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Temporal dynamics and land use in the marine protected area of Baía do Iguape in Northeastern Brazil

Dinâmica temporal e uso da terra na área marinha protegida da Baía do Iguape, no Nordeste do Brasil

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ABSTRACT

This study investigated land-use dynamics in a protected area and how dams and hydroelectric as anthropic tensors of spatial changes in mangrove areas, in addition to evaluating the spectral response for vegetative vigor, efficiently use radiation in the photosynthetic process and the flux of atmospheric carbon by vegetation indices. The temporal mapping and the transition of land use were evaluated between 1986 and 2020, using images from the Landsat 5 and Landsat 8 satellites using a visual interpretation technique. Spectral analysis of mangroves was performed using vegetation indices. The results showed that the establishment of the protected area decreased the rate of conversion from natural to anthropic areas, allowing natural areas to increase by 332 ha, driven by the increase in mangroves by 240 ha. Mangroves, dense ombrophilous forests, and grasslands are the classes that most transit between categories temporally. The combination of the dam and power generation reduced the flow to the estuary, causing an increase in saline intrusion, which contributed to the increase in the mangrove area in areas distant from anthropic activities, suggesting the maintenance of the protected area and the greater flow of atmospheric carbon.

Keywords: estuaries; anthropic tensors; remote sensing.

RESUMO

Este estudo investigou a dinâmica de uso da terra em área protegida e de que forma barragens e usinas hidrelétricas atuam como tensores antrópicos de mudanças espaciais em áreas de manguezais, além de avaliar a resposta espectral para o vigor vegetativo, o uso eficiente da radiação no processo fotossintético e o fluxo de carbono atmosférico por meio de índices de vegetação. O mapeamento temporal e a transição de uso foram avaliados entre 1986 e 2020, com imagens dos satélites Landsat 5 e Landsat 8, utilizando a técnica de interpretação visual. A análise espectral dos manguezais foi conduzida com o auxílio dos índices de vegetação. Os resultados mostraram que o estabelecimento da área protegida diminuiu o ritmo de conversão de áreas naturais para antrópicas, permitindo que as áreas naturais aumentassem em 332 ha, impulsionadas pelo aumento do manguezal em 240 há; manguezais, florestas ombrófilas densas e áreas campestres são as classes que mais transitam entre categorias temporalmente. A combinação de barramento e geração de energia diminuíram a vazão para o estuário, causando o aumento da intrusão salina, que contribuiu para a expansão da área de manguezal em regiões distantes das atividades antrópicas, sugerindo a manutenção da área protegida e o maior fluxo de carbono atmosférico.

Palavras-chave: estuários; tensores antrópicos; sensoriamento remoto.

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Introduction

Changes in land-use patterns are a key factor in increasing carbon dioxide (CO_2) emissions (Hörtenhuber et al., 2018). Research estimates that 13% of the total carbon dioxide emitted into the atmosphere between 2007 and 2016 came from agriculture, forestry, and other forms of human use. In addition, global carbon dioxide emissions have increased by 40% since the industrial revolution (Pachauri and Meyer, 2014; Shukla et al., 2019). Song et al. (2018) estimated that between 1982 and 2016, about 60% of landscape changes stemmed from direct human use; the remaining 40% indirectly correlate with climate change. In this scenario, tropical regions are the most modified.

The deforestation rate of the mangrove ecosystem is three to five times higher than that of other tropical systems (Duke et al., 2014; Romañach et al., 2018). Lucas et al. (2014) reported estimates of 16.1 million ha of mangrove forests existing in the world in 1990. This amount decreased to 13,776,000 ha in 2000 and increased to 15,600,000 ha in 2010. According to the last estimate for the year 2018, this ecosystem has 15,200,000 ha distributed worldwide. Of these, 38.7% occur in Asia, 20.3% in the Caribbean and Latin America, 20% in Africa, 11.9% in Oceania, 8.4% in North America, and 0.7% in European waters (Duke et al., 2014; Bunting et al., 2018).

Mangroves are tropical and subtropical forest ecosystems established in coastal and estuarine regions. These areas have high productivity, mainly of organic matter in terrestrial and aquatic ecosystems (Primavera et al., 2019). The ecosystems include plant, animal, and microbial populations, coexisting and interacting in the same physical environment, which are affected by estuarine regions and tidal dynamics (Schaeffer-Novelli et al., 2000; Duke et al., 2014; Kathiresan, 2021).

In Brazil, mangroves are listed as Permanent Preservation Areas and inserted into protected areas as conservation units (UCs). A total of 120 UCs have mangroves in their territories; 17 of these occurring in Bahia State (Brasil, 2000; 2012; Leão et al., 2018). These ecosystems are covered by the National Coastal Management Plan (Brasil, 1988; 1997) and are protected by the Brazilian Law for the Protection of the Atlantic Forest, which regulates the use, suppression, and protection of vegetation (Brasil, 2006).

In contrast, dams constitute a group of fixed projects that can change mangrove dynamics. Freshwater dams modify the hydrological system and allow for a greater entry of salinity. This affects flora and fauna, the transport of sediments and materials of greater diameter in river channels, as well as the intensity and influence of tides (Wolanski et al., 2001; Scharler and Baird, 2000; Wolanski et al., 2001; Cunha et al., 2016). In Bahia State, these situations may have occurred in the mangroves of the Iguape Bay. This is because the Pedra do Cavalo Dam (BPC) was installed in 1985 and the Pedra do Cavalo Hydroelectric Plant (UHPC) was implemented in 2005, changing freshwater flow to the local estuary and increasing salinity (Genz and Lessa, 2015; Silva et al., 2015). According to Kodikara et al. (2017), mangrove seeds in high salinity concentrations have lower performance, lower survival rate, and lower average growth than seeds in medium to low salinity. This situation may thus affect the regeneration and composition of mangrove forests.

Factors such as these can change ecosystems. In this sense, studies involving natural areas and energy matrices should be developed to understand the environmental impacts on the Brazilian landscape, biodiversity, and energy supply, reinforcing the importance of the Iguape Bay region in the Brazilian northeast. According to Couto (2014), the effects of the change in freshwater flow should be investigated because damming operations in this region have altered the salinity level of the estuary. The author concluded that, in a year of drought and aridity, salt intrusion travels through the estuary for about 18 km at high tide and about 16 km at low tide in the region.

In this study, we assessed land-use dynamics in a protected area and how dams and hydroelectric plants act as anthropic stressors of spatial changes in mangrove areas. Studies in UCs have pointed out the pressure of anthropic activities on ecosystems and the consequent reduction of natural areas (Fengler et al., 2012; Pinto and Toppa, 2017). We further assessed vegetative vigor, efficient use of photosynthetic radiation, and atmospheric carbon flux through vegetation indices. This study identifies the spectral conditions of mangrove vegetation in the extension of the Iguape Bay Marine Extractive Reserve (RESEX) in the Brazilian northeast.

Materials and Methods

The study took place in the RESEX, located west of the Todos os Santos Bay (BTS) between the cities of Maragogipe and Cachoeira, in Bahia State. The region is approximately 100 km away from the capital Salvador, in northeastern Brazil (Figure 1). The reserve includes the lower reaches of the Paraguaçu River, Iguape Bay, and Paraguaçu channel (Brasil, 2000).

The RESEX was the first Marine Conservation Unit to be created in Bahia in the 2000s. It covers an expanded area of 10,074.42 ha (Brasil, 2000; 2009). The Iguape Bay is characterized by fine sandbanks along the direction of the current. These sandbanks are exposed at low tide and extend through tidal channels and depths between 5 and 10 m (Lessa et al., 2000). The climate of the region is hot and humid, with a rainy season from autumn to winter. The relative humidity indicates a rainy season from April to September and a dry season from October to March (Genz, 2006).

In terms of vegetation, the region occurs in the phytogeographic domain of the Atlantic Forest and is represented by mangrove forests. Species like *Rhizophora mangle* L. (red mangrove), *Laguncularia racemosa* Gaertner (white mangrove), and *Avicennia schaueriana* Stapf and Leechman (black mangrove) predominate in these regions in different amounts (Ornellas et al., 2020). Fragments of dense Atlantic rainforest in different stages of conservation also occur in the upland portions of the RESEX (Oliveira et al., 2020).

Multitemporal mapping of the reserve included multispectral images from satellites LandSat 5, TM sensor, and LandSat 8, OLI sensor. Both have a spatial resolution of 30 m and were acquired online and free of charge for the years 1986, 2000, 2005, and 2020 in the US Geological System database. The images were georeferenced and reprojected to the SIRGAS 2000 reference system, 24 south zone.

The criteria for the selection period considered the chronological sequence of the operation of the Pedra do Cavalo dam in 1986, the creation of the RESEX Iguape Bay in 2000, the operation of the hydroelectric plant in 2005, and the most recent period of activity in 2020. Images from the months close to winter (June and July) were prioritized. The only exception was for the year 2000, due to lack of images without clouds over the study area. In this case, we used an image from February, in the summer.

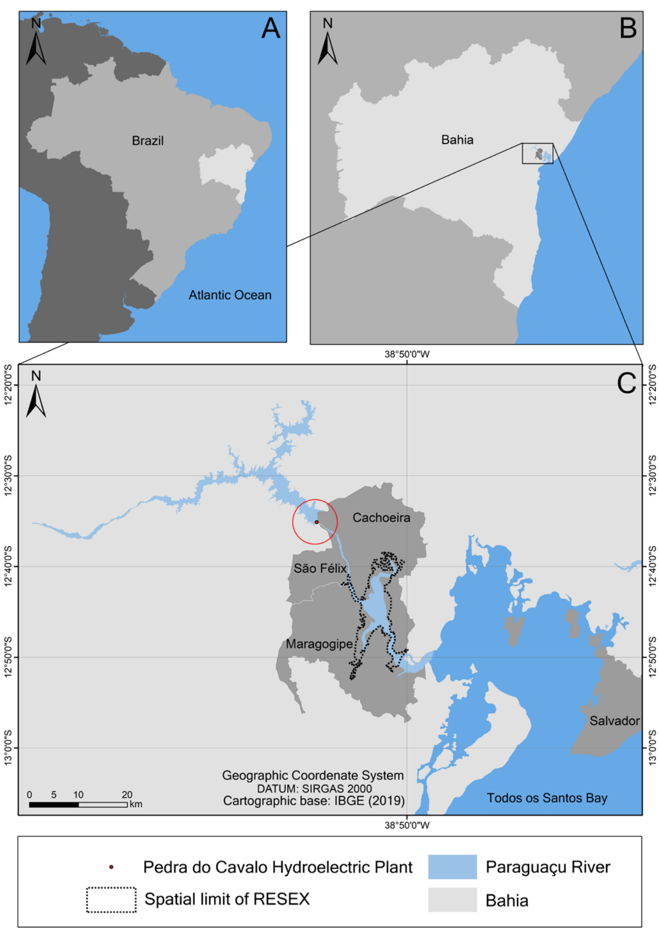

Figure 1 – Location of the study area. (A) Location of Bahia State in Brazil and South America; (B) Highlight of the position of the RESEX Iguape Bay in Bahia State; (C) Location of the RESEX in the Todos os Santos Bay, with emphasis on the upstream and downstream of the Pedra do Cavalo Hydroelectric Plant.
Source: Prepared by the authors from data collected in the research.

Compositions of spectral bands of the electromagnetic spectrum of green, red, and blue were performed. Images of each period were then classified by an unsupervised method through visual interpretation of the spatial limit of the area. Next, we proceeded to the identification of the categories with the patterns of geometry, texture, shape, size, tonality, and location of the target in the landscape (Panizza and Fonseca, 2011). Land use categories were determined according to the Technical Manual of Land Use for classification level III (IBGE, 2013).

Quantitative and spatial transitions were investigated in order to understand the changes caused by the dam operation (1986–2020), the creation of the RESEX (2000–2020), and the operation of the Pedra do Cavalo Hydroelectric Plant (2005–2020) in relation to the current period. Land-use mappings were processed using a cross-tabulation tool and analyzed in meters per hectare.

The Land Modeler Change module was applied to detect spatial transitions in the land use of mangroves from the damming of the hydroelectric station (2005) to the present day (2020). The aim was to understand the transformations in this ecosystem and its relationship with other categories of land use, as well as areas of loss, gain, and persistence of mangrove forests.

For vegetation analysis, the spectral bands in the mangrove areas identified temporally in each land use mapping were segmented. The spectral bands were processed in matrix operations considering the ratio between spectral bands for application of the following spectral indices of vegetation: Normalized Difference Vegetation Index (NDVI), proposed by Rouse et al. (1974); Photochemical Reflectance Index (sPRI) and Carbon Flux (CO_2Flux), both proposed by Rahman et al. (2000).

The most recent mapping and the mangrove areas of the reserve were confirmed and validated with fieldwork. Then, mapping categories were identified with the terrestrial truth using a sampling grid of 50 random points. The points had the collection of geographic coordinates recorded in a spreadsheet and a photographic record for verification, comparison, and adjustment of the mapping when necessary. All methodological procedures in GIS were performed using the ArcGis 10.8 software (ESRI, 2019).

Results and Discussion

In the period between 1986 and 2020, the RESEX Iguape Bay underwent intense transformations in the landscape. This was evidenced by the changes in land-use dynamics, especially driven by agricultural and urban expansion. Figure 2 shows the distribution of each land-use category in the different selected periods.

The comparison of the region between the first and the last period of the analysis showed a reduction in anthropic areas. This reduction stemmed from the decrease of 264 ha of grassland (31.34%), despite the increase of 60 ha of agricultural areas (493.19%). Natural areas in mangroves increased by 240 ha (9.05%) and forest areas increased by 52 ha (21.13%).

The dense Atlantic rainforest initially presented 246 ha, having an increase of approximately 52 ha in 2020, with greater effect in the north, southeast, and southwest regions of the RESEX. However, the region bordering the RESEX presents piassava (*Attalea funifera* Mart.) extraction without adequate management of the flora through opening of gaps and removal of vegetation. This interferes with the species' structure, distribution, composition, and richness, in addition to preventing the forest from reaching advanced stages of succession (Lima, 2005; Schaadt and Vibrans, 2015; Oliveira et al., 2020). The mangrove category, however, concentrates the largest area of natural vegetation in the RESEX, with 2,660 ha in 1986 and increasing to 2,901 ha in 2020.

Tables 1–3 present an analysis of the transition between the period when the dam started operations (1986), the creation of the RESEX (2000), and the operation of the Hydroelectric Plant (2005) in relation to 2020, highlighting the most important annual temporal changes. The changes observed in the periods under study are mainly due to loss and gain of natural areas, with dense Atlantic rainforest and mangroves being replaced by grassland and agricultural areas.

The assessment of the transition between land-use classes from the start of the operation of the dam to the year 2020 shows the modification of a total of 716.13 ha in the RESEX. During these 34 years, 60 ha of dense Atlantic rainforest became grassland and 29 ha were destined for agriculture, a combined loss of 89 ha. Forest areas are deforested and converted into grassland; these areas are transformed into crops slowly. Notwithstanding, this transformation also occurs in the opposite direction through the abandonment of grassland and subsequent regeneration of forests.

Deforestation in the Iguape Bay may relate to plant extraction by traditional communities without any management strategy, reducing habitat availability (Oliveira et al., 2020).

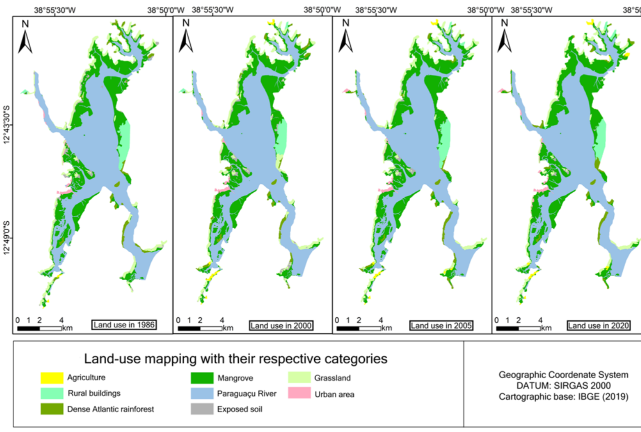

Figure 2 – Land use for the Iguape Bay Extractive Reserve, Bahia, Brazil. (A) 1986, (B) 2000, (C) 2005, (D) 2020.
Source: Prepared by the authors from data collected in the research.

This pattern of deforestation and fragmentation reduces fragments in advanced successional stages (Molin et al., 2017).

The way urban development was organized in the cities included in the RESEX led to the closing of cigar and oil palm factories in the 1980s and 1990s. Therefore, the population started to occupy mangrove areas (Prost, 2007; Nascimento, 2018). These urban areas are characterized by precarious and irregular housing in regions of landfills over mangroves. The environments lack basic sanitation and face spatial conflicts regarding land protection. Moreover, the area was included in the Federal Plan Luz Para Todos in 2005. This allowed the existence of electricity and the provision of basic services to schools and medical centers, which accelerated development, albeit to a less extent (Zagatto, 2013).

Table 1 – Quantitative transition between 1986 and 2020 for land-use classes.

Previous class – 1986 (ha)	Subsequent class – 2020 (ha)								
	Rural buildings	Dense Atlantic rainforest	Agriculture	Mangrove	Grassland	Urban area	Exposed soil	Total (1986)	Transition
Rural buildings	263.61	28.08	0	16.56	0	9.36	3.69	321.30	57.69
Dense Atlantic rainforest	3.87	125.01	29.88	18.90	60.66	0	0	238.32	113.31
Agriculture	0.00	0	11.79	0.54	0	0	0	12.33	0.54
Mangrove	6.39	3.15	2.43	2,521.08	15.39	3.33	6.21	2,557.98	36.90
Grassland	42.93	125.37	25.83	125.73	485.55	22.14	1.44	828.99	343.44
Urban area	0.27	0	0	10.89	0.81	54.63	0.54	67.14	12.51
Exposed soil	4.41	12.87	2.52	117.72	12.42	1.80	38.25	189.99	151.74
Total (2020)	321.48	294.48	72.45	2,811.42	574.83	91.26	50.13		

Source: Prepared by the authors from data collected in the research.

Table 2 – Quantitative transition between 2000 and 2020 for land-use classes.

Previous class – 2000 (ha)	Subsequent class – 2020 (ha)								
	Rural buildings	Dense Atlantic rainforest	Agriculture	Mangrove	Grassland	Urban area	SExposed soil	Total (2000)	Transition
Rural buildings	254.70	0.27	0	11.97	0.45	9.45	0	276.84	22.14
Dense Atlantic rainforest	2.97	123.30	11.61	25.92	89.82	0	0	253.62	130.32
Agriculture	0	0	43.11	1.71	7.11	0	0	51.93	8.82
Mangrove	3.42	6.57	5.49	2,560.68	13.14	2.07	0.90	2,592.27	31.59
Grassland	58.95	158.67	6.66	122.76	434.07	20.34	1.62	803.07	369
Urban area	0	0	0	14.40	0.54	58.23	0.36	73.53	15.30
Exposed soil	1.44	4.77	5.58	82.89	30.78	0.54	44.91	170.91	126
Total (2020)	321.48	293.58	72.45	2,820.33	575.91	90.63	47.79		

Source: Prepared by the authors from data collected in the research

Table 3 – Quantitative transition between 2005 and 2020 for land-use classes.

Previous class – 2005 (ha)	Subsequent class – 2020 (ha)								
	Rural buildings	Dense Atlantic rainforest	Agriculture	Mangrove	Grassland	Urban area	Exposed soil	Total (2005)	Transition
Rural buildings	288.72	26.73	0	16.29	0.36	0	0.81	332.91	44.19
Dense Atlantic rainforest	3.06	165.42	2.16	20.52	46.62	0	0	237.78	72.36
Agriculture	0	0	49.59	3.69	5.22	0	0	58.50	8.91
Mangrove	4.41	9.45	2.52	2,614.95	19.26	2.97	1.53	2,655.09	40.14
Grassland	24.30	88.92	17.91	111.78	495.45	21.42	1.44	761.22	265.77
Urban area	0	0.54	0	13.50	0	67.23	0.54	81.81	14.58
Exposed soil	1.17	0.90	0	51.93	8.73	0	45.81	108.54	62.73
Total (2020)	321.66	291.96	72.18	2,832.66	575.64	91.62	50.13		

Source: Prepared by the authors from data collected in the research.

The analysis of the spatial transition between the creation of the RESEX and the year 2020 showed the modification of 703.17 ha of land. The categories of grassland, exposed soil, and dense Atlantic rainforest had the highest transition values.

The comparison of Tables 1 and 2 shows that the urban area has expanded less in the period under study. The increase in urban area over the course of 20 years stemmed from the structuring of existing urban areas. In addition, the creation of the RESEX seems to have contributed to reducing the expansion of the urban class. Thus, the importance of creating this protected area is in the reduction of anthropic areas and maintenance of natural areas.

In agriculture, this area is transited mainly with grassland, originally already degraded for the practice of pasture and small fractionation of forest area. Recent studies on agricultural expansion scenarios in Brazil indicate that the expansion of this activity reduces natural vegetation areas (Criscuolo et al., 2005; Coelho et al., 2007; Rudorff et al., 2010; Trevisan et al., 2018). The establishment of the RESEX seems to have curbed the expansion of agriculture in the Iguape Bay despite the consolidation of existing areas.

The lack of services for the poorest population has had negative effects on mangroves close to the urban perimeter. When analyzing a fishermen's neighborhood inside the RESEX, Ornellas et al. (2020) observed that it was built on grounded mangroves. Solid waste collection in this region does not meet the demand of the population, and the houses do not have access to sanitary sewage. People thus carry out all disposals directly into the mangrove, also removing the vegetation to build fences. These activities have had negative impacts on mangrove forests, resulting in a biotic homogenization effect of *Laguncularia racemosa* Gaertn (white mangrove) in the forests of urban areas (Ornellas et al., 2020).

The analysis of the spatial transition between the start of the operation of the Hydroelectric Plant and the year 2020 showed that the total area modified in the RESEX was 508.68 ha. The classes' grassland, dense Atlantic rainforest, and exposed soil again had the highest transition values.

During this period, the dense Atlantic rainforest was replaced by mangroves. One forest ecosystem was thus being replaced with another, characterizing the establishment of coastal human biomes (anthropobiomes) within the RESEX (Ellis and Ramankutty, 2008). This transition seems to correlate with the increase in salinity in Iguape Bay, allowing mangroves to advance into the forest. For Teh et al. (2008), the increase in salinity promotes the development of mangroves in areas previously colonized by nonhalophytes. Furthermore, in the case of the Iguape Bay, the human changes caused by the implementation of the Hydroelectric Plant also significantly affect the reduction of flow and the increase in salinity, which may consequently affect mangroves (Church and White, 2006; Cañedo-Argüelles et al., 2013; Herbert et al., 2015).

A similar study carried out by Pelage et al. (2019) determined the effects of the increase in salinity from anthropic impacts in three estuaries in Pernambuco (Suape-PE, Santa Cruz-PE, and Sirinhaém-PE). Two of the three estuaries had an increase in mangrove forests. The authors relate this increase to the establishment of large-scale human activities in the vicinity of mangroves, affecting the salinity and the sediment profile in these areas. Lacerda et al. (2007) studied the estuary of the Pacoti River in Ceará State. The authors observed that the construction of the dams of the Pacoti and Gavião reservoirs increased mangrove areas in the region, a fact that may also have occurred in the Iguape Bay. This evidences the importance of studies on anthropic impacts on estuarine mangroves in northeastern Brazil to ensure the protection of this ecosystem from disturbances associated with anthropic stressors.

The increase in the mangrove areas of the RESEX may thus correlate with changes caused by energy generation from 2005 onward. The installation of the Pedra do Cavalo dam in 1985 affected the environmental conditions of the waters of the bay. The average daily flow used to cover 2–5 h with pulses ranging from 50 to 60 m^3/s^{-1} (Genz and Lessa, 2015). However, a minimum flow of 11 m^3/s began to take place in 1997 as required by the environmental license (Genz et al., 2008). The operation of the Pedra do Cavalo Hydroelectric Plant in 2005 modified the water discharge operation policy. The plant started to operate two turbines using a minimum flow of 80 or 160 m^3/s^{-1} depending on environmental conditions (Genz and Lessa, 2015).

Genz and Lessa (2015) and Silva et al. (2015) evaluated, respectively, the impact of dams and plants on the circulation of the Paraguaçu River and the spatiotemporal behavior of salinity in the estuary of the Iguape Bay. These authors concluded that the damming of the river allowed greater entry of salinity into the estuary and changed the ecological conditions for the existing species.

Therefore, from the decrease in the flow of the Paraguaçu River downstream of the Pedra do Cavalo Hydroelectric Plant depicted in Figure 3, one can observe the dynamics of loss, gain, and persistence of the mangrove (Figure 3A), as well as the transition between dense Atlantic rainforest and mangrove between 2005 and 2020 (Figure 3B).

For the period under study, mangrove vegetation lost 132 ha to other land-use classes. In turn, 2,614 ha of mangrove forests persisted and 253 ha were gained from the conversion of other classes. Transitions between dense Atlantic rainforest and mangroves were quantified in 15 ha. In turn, 9 ha of land were converted from mangrove to forest. However, the increase in salinity in the estuary and the increase in mangroves do not necessarily mean an increase in the provision of ecosystem services (Lam et al., 2020).

Increased salinity can slow down the process of nitrogen removal, carbon storage, and other nutrient cycles. It can also affect the natural function of mangroves as aquatic nurseries and reduce fish populations (Herbert et al., 2015). Furthermore, the scenario of future sea-level rise may be problematic with the greater inflow of seawater from the Todos os Santos Bay and, consequently, into the Iguape Bay (Church; White, 2006; Havens, 2017).

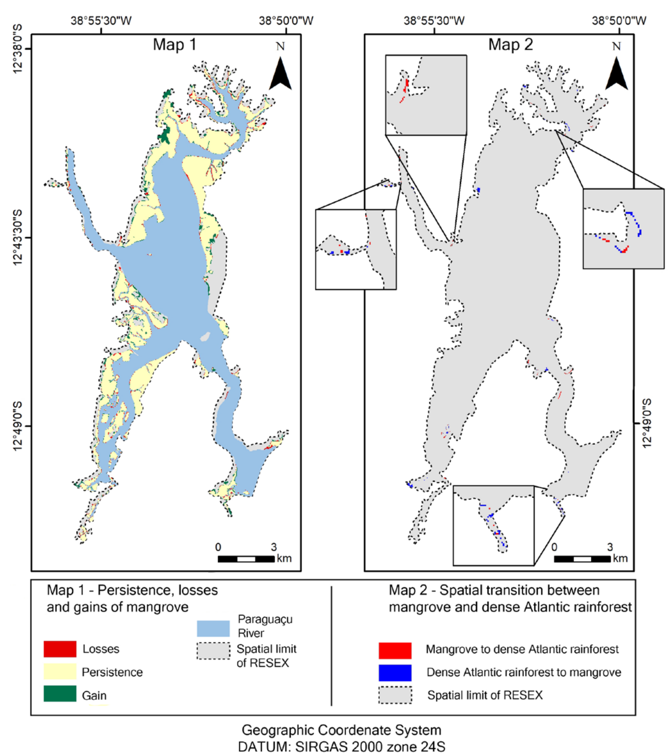

Figure 3 – (A) Spatial mapping of losses, gains, and persistence for mangroves, (B) spatial transition between mangroves and dense Atlantic rainforest.
Source: Prepared by the authors from data collected in the research.

The mangrove category represents the highest class, of utmost importance for the RESEX. Therefore, the present study analyzed vegetative vigor, efficient use of photosynthetic radiation, and atmospheric carbon flux through vegetation indices. In Figure 4, one can spatially visualize the vegetative vigor of mangrove areas from the spectral scale of the NDVI.

Since 1986, the maximum value presented in the score has been between 0.40 and 0.66. This indicates that mangrove forests in the area have high vegetative vigor. In 2000, the discrete measures of the scores differed. Genz (2006) argued that changes in scores due to the temporality of the indices can be explained by the high temperature and low rainfall in the area in the summer period, while the other images relate to the winter period. Decreased rainfall and high temperature also increase soil salt concentration and promote saline stress on biomass, reducing mangrove productivity (Noor et al., 2015; Feher et al., 2017). This situation occurs in the region under study, which has a dry summer and a wet winter.

Mangroves surrounded by urban areas and agriculture had a reduction in vegetative vigor, which also occurred in the center-west of the RESEX in 1986 and the north in 2005 and 2020, an issue confirmed in the field. In these regions, human activity acts as an anthropic stressor affecting plant development and energy consumption that were previously spent on mangrove development and regeneration (Duke et al., 2021).

Ornellas et al. (2020) confirmed this effect on RESEX when comparing the biomass of forests close to the urban area to that of distant and more conserved forests. The authors estimated a 17% biomass in urban forests. This value is lower than in conserved forests, showing a tendency to biotic homogenization by *Laguncularia racemosa*. Fernandes et al. (2018) observed that species *L. racemosa* is frequent in areas such as borders and channels of gaps, playing the role of pioneer species in revegetation. For Satyanarayana et al. (2002), the frequent access of the population to the forests also reduces mangrove biomass. Zhila et al. (2014) corroborated this statement by reporting that mangrove forests with better conservation conditions reach higher biomass values than anthropized forests.

Vegetative vigor in RESEX mangroves decreased from 1986 to 2020. Thus, despite the mangrove forests in 2020 having 240 ha more than in 1986, they have lower vegetative vigor. As already informed, RESEX forests are subject to anthropic stressors of alteration of the Paraguaçu River flow, increase in salinity, landfill, and discharge of effluents and solid residues. Several authors present the NDVI as a successful method in the spatial assessment of the impact of anthropic stressors on mangroves (Nardin et al., 2016; Sari and Rosalina, 2016; Marins et al., 2020).

Regarding the efficient use of photosynthetic light (Figure 5), sPRI values were lower in 1986 and 2005. In turn, the years 2000 and 2020, especially the latter, present the highest sPRI values in the analysis. Low values may correlate with salinity, which is a variable capable of reducing mangrove sPRI as observed by Song et al. (2011).

The increase in values in 2020 may indicate that, after more than 20 years of changes in the RESEX estuary, mangroves are now adapting to the new environmental conditions. Furthermore, Ornellas et al. (2020) reported differences in abundance and structure between mangrove species in two areas of mangrove forest in the Iguape Bay with different conservation status. According to these authors, *L. racemosa* is the dominant species in the degraded area adjacent to the residential perimeter, while *R. mangle* predominates in the area furthest away from stressors and with higher conservation status.

The analysis of the atmospheric carbon flux of these regions showed that years 2000 and 2020 were distinguished by the lowest and highest values, respectively. Figure 6 shows the spatial distribution of these concentrations, with areas with positive values representing the atmosphere-plant carbon flux; the higher the value, the greater the amount of stored carbon (Rahman et al., 2000).

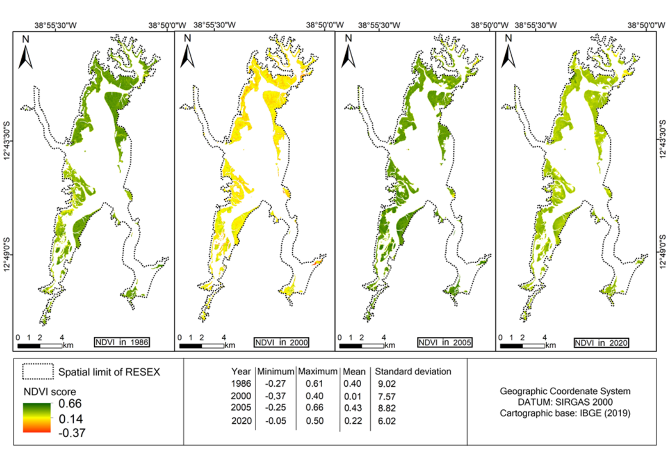

Figure 4 – Spatial distribution of the NDVI for the RESEX Iguape Bay between 1986 and 2020.
Source: Prepared by the authors from data collected in the research.

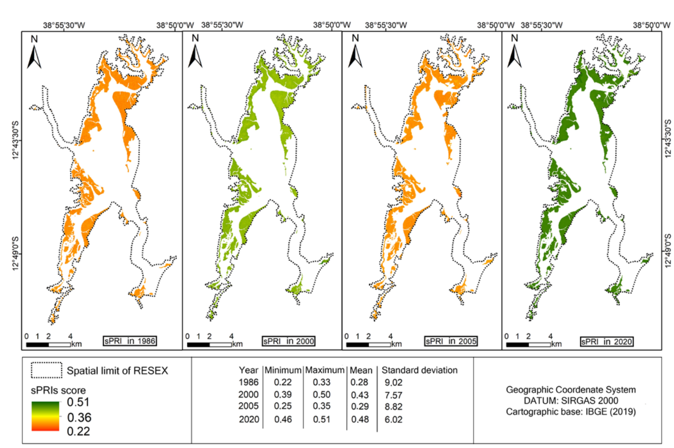

Figure 5 – Spatial distribution of sPRI for the RESEX Iguape Bay from 1986 to 2020.
Source: Prepared by the authors from data collected in the research.

According to the NDVI, between 1986 and 2020, the central and western regions of the RESEX had the lowest values of carbon flux. This is because these regions are close to crops and rural activities and, therefore, to the highest degree of anthropization. In other regions of the RESEX, the atmosphere-plant flux has an average score of 0.14 and a high variability. This indicates that the joint activity between photosynthesis and efficient use of atmospheric carbon differs in several stretches of mangrove, especially in areas of regeneration and gain of mangrove forests.

Field activities showed that forests with low vegetative vigor and in contact with agricultural areas have low trees, spaced from each other and with the presence of gaps allowing light to enter but without the presence of regenerating seedlings (Figures 7A and 7B).

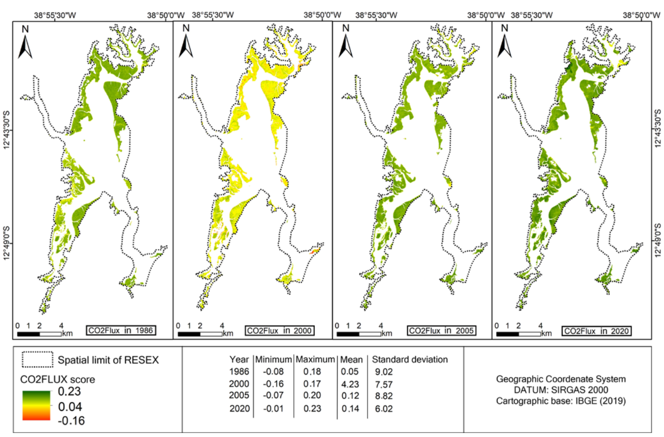

Figure 6 – Spatial distribution of CO_2FLUX for the RESEX Iguape Bay from 1986 to 2020.
Source: Prepared by the authors from data collected in the research.

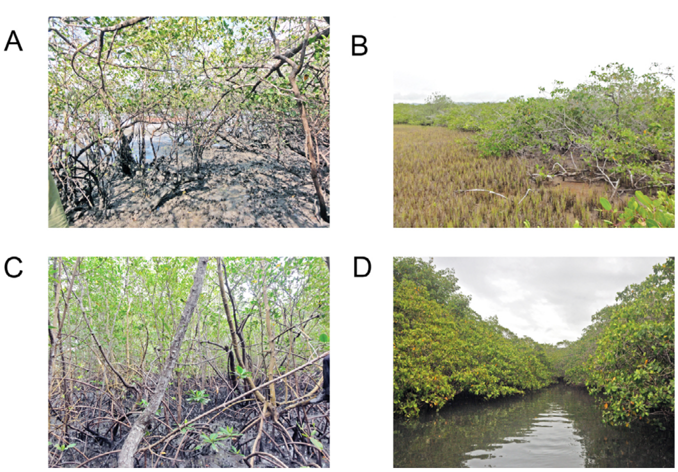

Figure 7 – Mangrove forests in the RESEX Iguape Bay, Bahia, Brazil. (A and B) Forests close to agricultural areas, showing lower values of vegetative vigor. (C and D) Mangrove forests with greater vegetative vigor.
Source: Prepared by the authors from data collected in the research.

In contrast, regions with high vigor, far from contact with human activities, show two important features. The first refers to regions with high density of regenerating individuals per unit of area, even in newly colonized areas. The second refers to regions of mangrove persistence, dense and ecologically stabilized, having well-developed, tall trees with a continuous canopy (Figures 7C and 7D).

This pattern of regeneration and colonization of new areas corroborates the findings by Twilley (2019). According to this study, colonization of new areas by mangrove individuals occurs quickly after the establishment of several individuals in the new area. This colonization considerably increases vegetative vigor, thus increasing radiation use and carbon capture. As the stand ages, the high density of individuals is replaced by few trees with large diameters.

It is important to promote actions so that urbanization activities are carried out away from mangroves. This would lead to conservation and sustainability for extractive communities, also meeting the objectives of the RESEX. Mangroves should be highlighted as spaces that constitute slow-cycling carbon storage, translating into possible reductions in anthropic CO_2 emissions. Moreover, these sites present conservation benefits for biodiversity (Siikamäki et al., 2012; Adame et al., 2018; Schaeffer-Novelli, 2018) and economic benefits for the local population dependent on natural resources.

Conclusions

Despite the various human activities, the damming, the energy generation, and the urbanization that take place in the RESEX, the UC has contributed to reducing the effects of disturbances in the mangrove. The establishment of the protected area seems to have decreased the conversion of natural to anthropic areas. Regarding mangrove indices, the results showed a reduction in vegetative vigor, photosynthetic use, and carbon flux as a result of large-scale human activities. It is noteworthy that the installation of the dam may have presented less damage than the installation of the hydroelectric plant.

The conservation and increase of mangroves were confirmed in areas far from human activities, suggesting maintenance of the protected area, as these places also have the highest atmospheric carbon flux. The replacement of forest areas by mangroves also indicates the establishment of coastal anthropobiomes that must be monitored in light of established environmental conditions.

Therefore, it is pertinent to monitor the effects of anthropic uses within protected areas and what impacts external enterprises associated with the hydrological flow can cause on mangrove vegetation. This would allow for establishing strategies to reduce the effects of anthropic stressors and to recover areas in the process of degradation. These strategies should aim at the ecological functioning of ecosystems, the conservation of the diversity of fauna and flora, and the maintenance of ecosystem services.

Contribution of authors:

ORNELLAS, J.L.: Conceptualization; Methodology; Validation; Formal Analysis; Investigation; Resources; Writing — Original Draft; Writing — Review & Editing. CAIAFA, A.N.: Methodology; Validation; Formal Analysis; Investigation; Visualization; Writing — Review & Editing. LOPES, E.R.N.: Conceptualization; Methodology; Validation; Formal Analysis; Writing — Review & Editing; Supervision.

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