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Loss and Gain in Mangrove Surrounding the Lençóis Maranhense National Park: An Integrated Approach Using Remote Sensing and SIG Data

Perda e Ganho do Manguezal no Entorno do Parque Nacional dos Lençóis Maranhenses: uma Abordagem Integrada Usando Sensoriamento Remoto e Dados SIG

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Abstract

Brazil harbors the second largest expanse of mangroves in the world, trailing only behind Indonesia. In a regional context, the state of Maranhão stands out, encompassing approximately 36% of Brazil's total mangrove area, including a portion located on the eastern coast in the Lençóis Maranhenses. This study played a crucial role in identifying the areas of gain, loss, and stability in the mangroves surrounding the Lençóis Maranhenses National Park over a historical period spanning from 1985 to 2019. The study provided detailed maps depicting spatial changes, such as migration and attenuation that occurred in the mangroves due to the influence of aeolian dunes and wind patterns in the region. This long-term analysis, the first of its kind to examine the annual expansion of forest loss in the remaining mangroves around the Lençóis Maranhenses in recent decades, revealed a reduction in the central mangrove areas between 1985 and 2019. This decline can be attributed not only to intense tourist activity and climate change but also to the movement and invasion of sand dunes in certain areas, as observed near the villages of Caburé and Paulino Neves (Pequenos Lençóis) in December 2022. Wind plays a fundamental role as a transformative agent in the local landscape. Through the analysis of wind roses using ERA5 reanalysis data and meteorological stations from the Aeronautics (São Luís and Parnaíba), it was possible to identify and characterize the prevalence of northeast trade winds in the Lençóis Maranhenses region during the years 1985 to 2019, with average speeds ranging from 6 to 8 m/s. The advancement of dunes onto the mangroves surrounding the Lençóis Maranhenses results in burial, reduction, and even migration of mangrove patches. Additionally, over the years, population growth and increasing tourism pressure along the banks of the Preguiças River have drawn attention to the need to implement control and conservation measures in the mangroves to prevent further disturbances in this environment.

Keywords: ERA5; Wind; Climate change

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Resumo

O Brasil abriga a segunda maior extensão de manguezais do mundo, atrás apenas da Indonésia. No contexto regional, destaca-se o estado do Maranhão, que abrange aproximadamente 36% da área total de manguezais do Brasil, incluindo uma porção localizada na costa leste nos Lençóis Maranhenses. Este estudo desempenhou um papel crucial na identificação das áreas de ganho, perda e estabilidade nos manguezais do Parque Nacional dos Lençóis Maranhenses ao longo de um período histórico de 1985 a 2019. O estudo forneceu mapas detalhados que descrevem mudanças espaciais, como migração e atenuação, que ocorreu nos manguezais devido à influência das dunas eólicas e ventos da região. Essa análise de longo prazo, a primeira desse tipo a examinar a expansão anual da perda florestal nos manguezais remanescentes ao redor dos Lençóis Maranhenses nas últimas décadas, revelou uma redução nas áreas centrais de mangue entre 1985 e 2019. Esse declínio pode ser atribuído não apenas à intensa atividade turística e às mudanças climáticas, mas também à movimentação e invasão de dunas em determinadas áreas, como observado próximo aos povoados de Caburé e Paulino Neves (Pequenos Lençóis) em dezembro de 2022. O vento tem papel fundamental como agente transformador da paisagem local. Através da análise das rosas dos ventos utilizando dados de reanálise ERA5 e estações meteorológicas da Aeronáutica (São Luís e Parnaíba), foi possível identificar e caracterizar a prevalência dos ventos alísios de nordeste na região dos Lençóis Maranhenses durante os anos de 1985 a 2019, com velocidades médias variando de 6 a 8 m/s. O avanço das dunas sobre os manguezais ao redor dos Lençóis Maranhenses resulta em soterramento, redução e até mesmo migração de manchas de mangue. Além disso, ao longo dos anos, o crescimento populacional e o aumento da pressão turística nas margens do Rio Preguiças têm chamado a atenção para a necessidade de implementar medidas de controle e conservação dos manguezais para evitar novas perturbações neste ambiente.

Palavras-chave: ERA5; Vento; Mudanças climáticas

1 Introduction

Mangroves are one of the most productive ecosystems on the planet, performing several ecological functions and economic interests, such as protecting against erosion and storm damage, providing critical habitats, supporting estuarine food chains, and sequestering five times the amount of carbon sequestered by tropical forests (Wang et al. 2004; Giri & Muhlhausen 2008; Ellison 2008; Das & Vincent 2009; Siikamäki et al. 2012). Mangrove ecosystems are usually found in tropical or warm temperate climate regions along the intertidal zone of coastal environments or estuarine margins (Amarasinghe & Balasubramaniam 1992; Duke 2006; Myint et al. 2008). Brazil has the second largest territorial extent of mangroves globally, after Indonesia. On a regional scale, the Maranhão state presents approximately 36% of the total area of brazilian mangroves, part of which is located on the eastern coast of the state, in Lençóis Maranhenses. Mangroves in this region are highly productive and provide several ecosystem services, such as improved water quality, reduced coastal erosion, support of coastal food webs, and forest products used in local economic development (IBAMA 2002; Vannucci 2003).

According to Janzen (1985) and Krauss et al. (2008), despite presenting several potentialities, this environment is considered fragile. Unlike terrestrial forests, they need understory plants to tolerate harsh environmental conditions, especially in cases of extreme weather events; in other words, the variations or intensifications of atmospheric gradients are one of the main factors affecting the dynamics of this ecosystem, in addition to anthropogenic factors (Lee 1999; Das & Vincent 2009; Siikamäki et al. 2012). In this context, Dos Santos et al. (2019) characterized the wind over the Lençóis Maranhenses as an important climate variable and one of the main ones responsible for the dynamics of the local dunes, with winds that blow from the northeast with an average speed of 70 km/h. Remote sensing data have been widely used to monitor and understand changes in land use and land cover, as well as the distribution of mangrove vegetation in recent decades, offering important advantages, such as the indirect observation of mangroves that are generally difficult to access. Some authors such as (Green et al. 1998; Giri et al. 2007; Giri et al. 2010; Clinton et al. 2014; Rodriguez et al. 2017, Cavanaugh et al. 2018, Osland et al. 2018; Songsom et al. 2019), evaluated mangrove swaths using remote sensing techniques and obtained satisfactory results. Another alternative for studying the climatic factors that regulate the mangrove dynamics is the use of atmospheric reanalysis data, databases that assimilate in situ measurements provided by meteorological radars and sensors aboard satellites (Couto et al. 2015). Thus, reanalysis data are excellent tool for analyzing the climate, mainly by solving problems associated with the calibration of sensors, low density of meteorological stations, discontinuity of time series, defects in equipment, and collection or measurement errors, much of them usually present in meteorological stations's data located surroundings the Lençóis Maranhenses National Park (LMNP) area.

Given the importance of obtaining information on climate and understanding the distribution of mangroves and their possible relationships with the dune dynamics, these become crucial elements to provide decision makers with the necessary tools for the development of policies and strategies aimed at the management and prevention of mangrove forests in the eastern coast of Maranhão. This study contributes to such understanding by identifying areas of gain, loss, and stability in the surrounding mangrove forests in the LMNP for the beginning and end of the historical series (years 1985 and 2019), providing explicit maps of the spatial changes (migration and attenuation) that occurred in the mangroves owing to the influence of the aeolian dune input and the wind regime in the region. This will aid decision makers to define priority areas for the management, restoration, and preservation of the mangrove ecosystem.

2 Materials and Methods

2.1 Study Area

The LMNP is in the northeast region of Brazil, more precisely in the coastal area of the eastern side of the Maranhão state. The LMNP has an area of 155,000 ha according to the Decree N°. 86,060 of June 2, 1981, and it was formed by one of the most expressive dune fields in the world, with temporary and perennial lagoons associated with restinga vegetation, warm water rivers, deserted beaches, and exuberant mangroves (IBAMA 2002). The study area is in the surroundings of LMNP, near the course of Preguiças River (Figure 1, in detail), where four genera and seven common mangrove tree species are found, namely: *Rhizophora mangle, Rhizophora racemosa, Rhizophora Harrisonii* (red mangrove), *Avicennia germinans, Avicennia chaueriana* (black mangrove), *Laguncularia racemosa* (white mangrove), and *Conocarpus erectus* (button mangrove) (Mochel et al. 2001).

2.2 Dataset

This study was based on datasets related to mangroves, dunes, and surface winds, as illustrated in Figure 2. For the years 1985 and 2019, a remote sensing database encompassing land use and land cover was utilized. These data were obtained from Collection 5 at a scale of 1:250,000, acquired through the Google Earth Engine platform, using the script from the Brazil Annual Land Cover and Land Use Mapping Project (MapBiomas). This dataset was generated by classifying Landsat satellite images, with spatial and temporal resolutions of 30 meters and 16 days, respectively (Wulder et al. 2019). Despite the challenges faced by the scientific field of remote sensing regarding spatial and temporal limitations of data, it's important to note that the MapBiomas data exhibit a remarkable overall accuracy of 94.80% and discrepancies in allocation and area of only 2.80% and 2.40%, respectively (Silva Junior et al. 2020).

The original MapBiomas land use and land cover maps for the study area underwent classification using the class codes and legends available in Collection 5. Subsequently, the "mangrove" class was analyzed in both considered years, designating the 1985 mangrove belt as the past and the 2019 mangrove belt as the present. Additionally, the "beach and dunes" class present in the MapBiomas land use and land cover maps was similarly isolated and studied to comprehend its dynamics and influence on the mangrove ecosystem. To conduct spatial analysis of loss, stability, and gain, the tools of QGIS 3.18 LTR software were employed, including operations like symmetric difference, intersection, and difference. These analyses were conducted on a regular pixel grid, with a spatial resolution of 30 kilometers. Results related to mangroves were quantified in terms of area (km²) for each pixel in the years 1985 and 2019. Furthermore, the corresponding area (km²) of the "Pequenos Lençóis" dune, situated near the analyzed mangrove in the city of Paulino Neves, was classified and calculated due to its natural spatial influence between the years 1985 and 2019.

Hourly wind data at 10 m were obtained from the ERA 5 reanalysis (https://cds.climate.copernicus.eu/), the fifth and most recent generation of atmospheric reanalysis from the European Center for Medium-Range Weather Forecasts (ECMWF) in global climate, with a spatial resolution of 0.25° x 0.25° for the period 1980 to 2020. ERA5 data were extracted for the same grid points of the meteorological stations of São Luís and Paraíba, respectively (lat: 02°35′19″S and lon: 044°14′11″W; lat: 02°53′37″S and lon: 041°43′55″W).

For the wind analysis, Matlab© (Campus Wide License – CWS) data processing software was used to generate wind roses that represent the wind speed and direction for the region of interest and to compare the wind speed between simulated (ERA5) and measured data (in situ). Wind data at 10 m (U and V wind components) were used. The time series used consists of 40 years (1980-2020) of hourly and punctual data from the ERA5 reanalysis. Two aeronautical meteorological stations were used, from São Luís and Parnaíba, located at the extremes of the LMNP.

In addition, an on-site technical visit was carried out from December 14 to 18, 2020 to identify the mangrove species and their distribution in Lençóis Maranhenses, near the Preguiças River in the villages of Vassouras, Canto do Atins, Praia de Atins (Moana) and Caburé, all villages in the municipality of Barreirinhas, Maranhão.

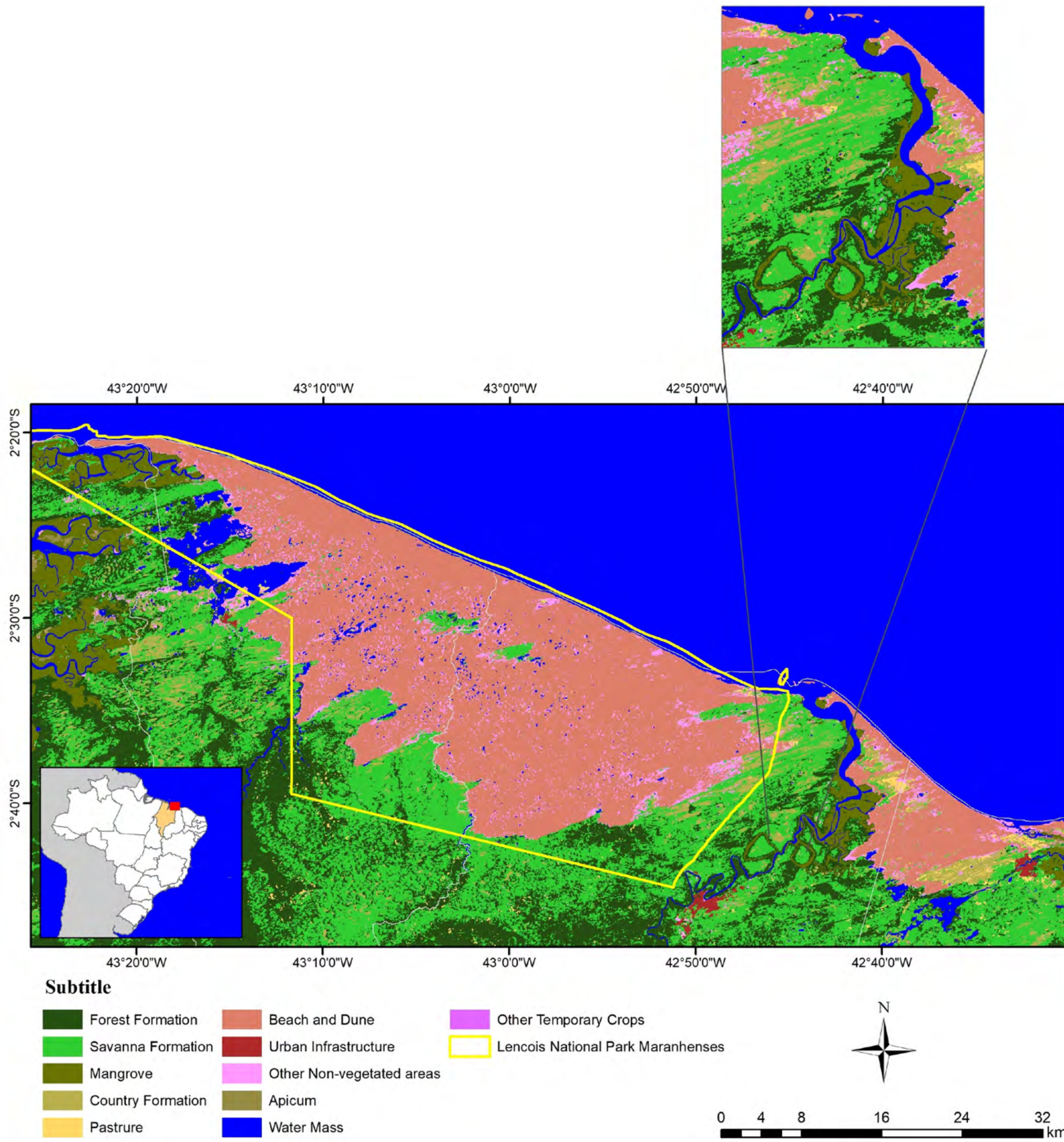

Figure 1 Map of the study area highlighting the mangroves evaluated around the Lençóis Maranhenses National Park (PNLM). Classification of land use and land cover according to the MapBiomas Project 5 and the location of the mangrove spots visited near the villages of Vassouras, Caburé, Praia de Atins and Canto do Atins.

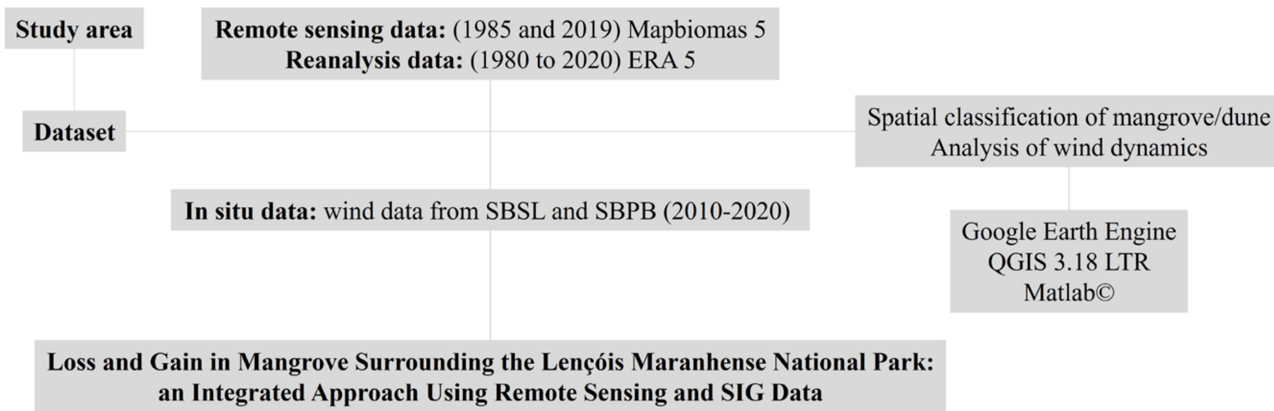

Figure 2 Methodological flowchart.

3 Results

The study area analyzed had a mangrove forest cover of 21% in 1985 and 22% in 2019 (Figure 3A), while the dune covers near the mangrove in Lençóis Maranhenses extended to 57% in 1985 and 78% in 2019 (Figure 3B), resulting in a difference of 15.34 km² of dune expansion between the years. This movement of the dunes over time led to a decrease in mangrove forest and changes in the local landscape. Analysis of mangrove and dune classes for gain, stability, and loss revealed areas with dune growth and mangrove decline due to mangrove burial and mortality in both years (Figure 4A-B). There was a total loss of 8.27 km² (8%) of mangrove area between 1985 and 2019, but a gain of 3.74 km² (4%) was also observed in 2019 compared to 1985. Additionally, 26.32 km² (26%) of the mangrove area remained stable throughout the years. The analysis of the dune class (Figure 5A-B) yielded results like those of the mangrove class, with 31.92 km² (32%) of dune growth between 1985 and 2019. Although there was dune movement in response to seasonal winds, 73.96 km² (74%) of the dunes remained stable during the analyzed years. Therefore, the first long-term analysis of the annual expansion of forest loss in the remaining mangroves around Lençóis Maranhenses in recent decades reveals that this region, continuously exposed to high tourist activity and climate change, has experienced a reduction in the core mangrove areas between 1985 and 2019.

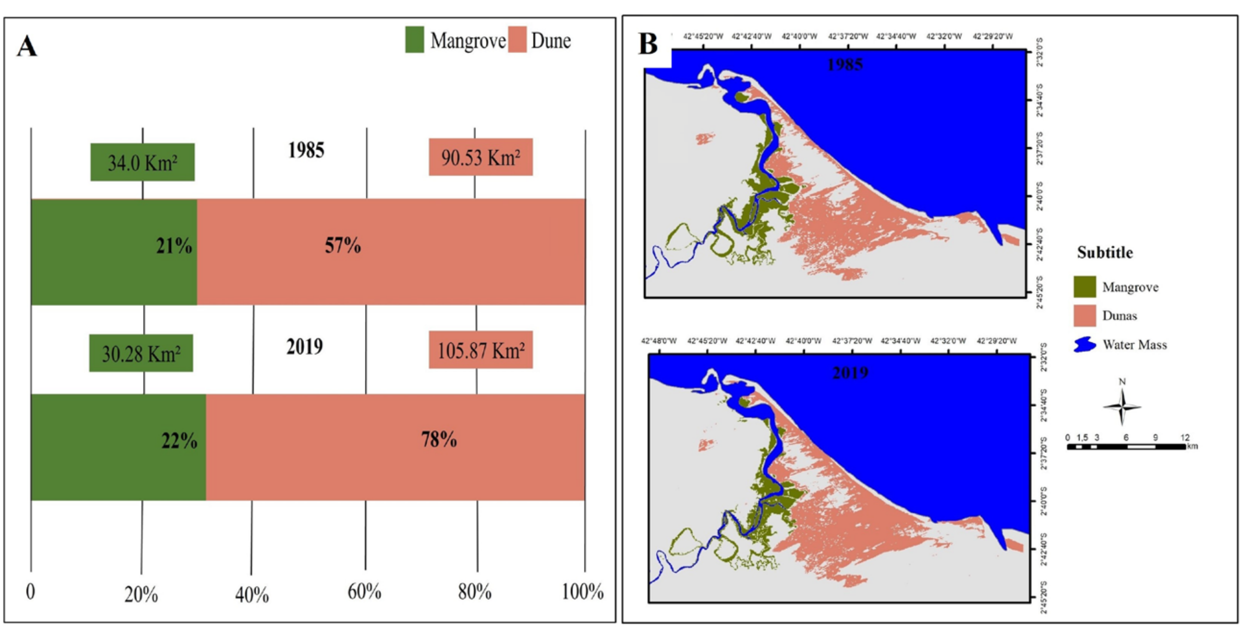

Figure 3 A. Mangrove and dune classes during the study period as a percentage of total land cover in each year; B. Annual mangrove and dune forest cover in 1985 and 2019 in the surrounding areas of the Lençóis Maranhenses National Park (LMNP), Brazil.

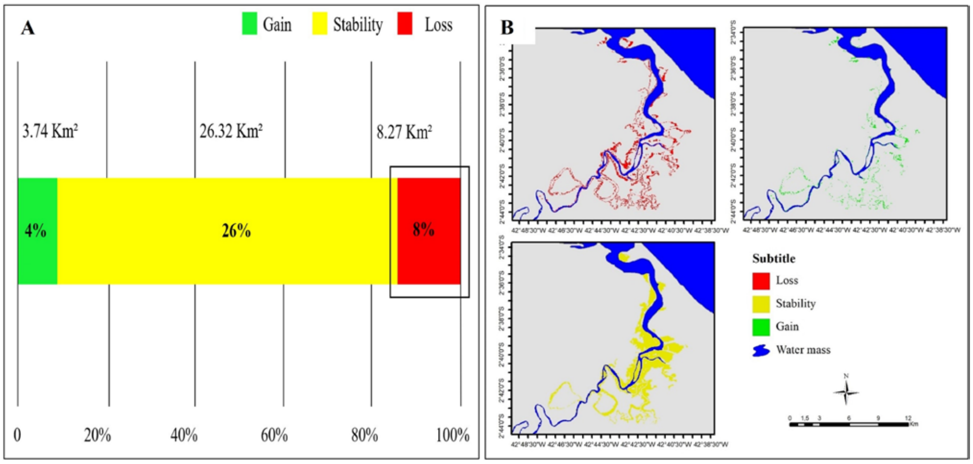

Figure 4 A-B. Annual area of the mangrove class as a percentage of land cover in 1985 and 2019. The figures represent the gain (green), stability (yellow), and loss (red) of mangrove area in different color scales. National Park (LMNP), Brazil.

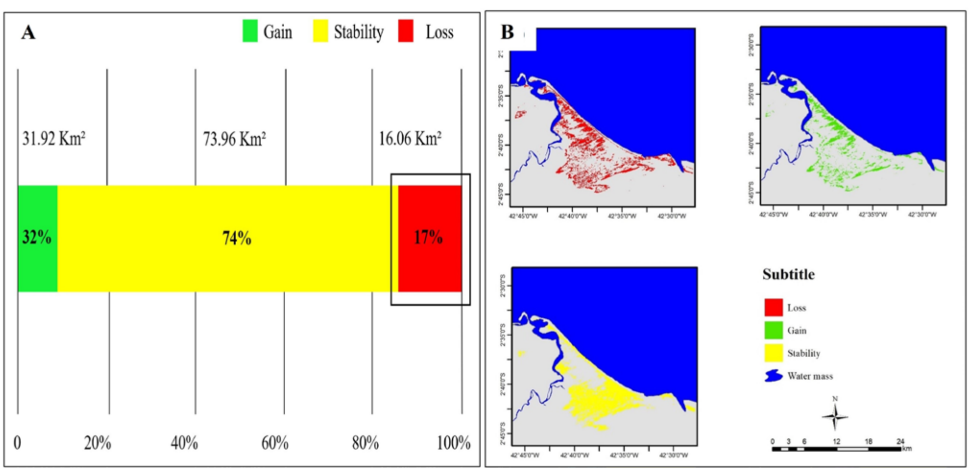

Figure 5 A-B. Annual area of the dune class as a percentage of land cover in 1985 and 2019. The figures represent the gain (green), stability (yellow), and loss (red) of the dune area in different color scales.

Additionally, this loss in the remaining mangrove core may also be attributed to the movement and encroachment of sand dunes in certain areas, as observed on-site near the villages of Caburé and Paulino Neves (Pequenos Lençóis) in December 2020, with winds acting as the primary influencing agent and transformer of the landscape in the region. According to Dos Santos et al. (2019), in a study conducted in the region from December 2015 to January 2017, it was observed that certain dunes located south of Caburé Beach have higher elevations and are shaped by northeast winds, which significantly affect the transport of sandy sediments from the coast to the mainland. Consequently, these factors have influenced the coastal erosion process at Caburé Beach.

In their study on tourist activities in the Lençóis Maranhenses, Silva (2008) also observed the presence of sand dunes near the Pequenos Lençóis and Caburé, which encroach upon the mangroves due to the constant hydrodynamics of the winds. The reports from this study revealed that the sand field expands each year, leading to the destruction of vegetation, particularly the mangroves. The mangrove species observed in the field during this study, which are most affected by the accumulation of sand, include Rhizophora mangle, found on the shores of Atins and Caburé beaches, and *Avicennia germinans*, found near Caburé Beach, in different stages of development and senescence (Figure 6A-B).

Figure 6 Mangrove species in the senescence phase caused by the input of sand: A. *Rizophora mangle* observed at Atins Beach; B. *Avicennia germinans* observed near the Caburé village.

Although not the focus of this study, it is necessary to discuss the relevance of the physiological characteristics of the species that make up the mangrove ecosystem in the region to understand how physical factors enhance or limit the distribution and development of these species in this environment. For instance, the mangrove species *Avicennia germinans* may exhibit a high susceptibility to the effect of sand on its roots due to the presence of pneumatophores, structures that grow above the ground and assist in gas exchange for the plant. While this mangrove species is highly tolerant to saline stress, the high amount of sand considerably limits its growth and contributes to its mortality. Therefore, it is understood that the mangroves in the region have been migrating to adjacent areas that offer favorable conditions for their development, which justifies the loss and gain of new mangrove areas.

The results of the temporal analysis of ERA5 Vm (Figure 7A, black line) demonstrated a seasonal pattern like that of the São Luís meteorological station (Figure 7A, red line), capturing the most significant wind amplitudes. However, at certain points, the observational data indicated a tendency to overestimate Vm, particularly towards the end of the time series (Figure 7A). This discrepancy suggests that the ERA5 reanalysis was unable to fully adjust the Vm values during that specific period. On the other hand, the behavior of ERA5 was like the measurements taken at the Parnaíba meteorological station (Figure 7B), despite a slight underestimation of Vm values by the ERA5 model.

Figures 8 illustrate the prevailing wind directions at the surface meteorological stations of the Aeronautics and ERA5, represented by the wind rose. There is good agreement among the results (Figure 8A-B). Specifically, the São Luís meteorological station exhibited a smaller amplitude, with predominantly northeast winds up to approximately 60°, compared to the ERA5 reanalysis, which showed predominantly northeast winds up to around 85°. This difference reflects the pattern observed in Figure 7, where the model underestimated the in situ Vm values. Additionally, it can be noted that the in-situ measurements taken at the Parnaíba meteorological station (Figure 8C) indicated a predominance of Vm from the southeast, between approximately 90° and 132°, while the values provided by the ERA5 reanalysis (Figure 8D) exhibited a predominance of Vm from the northeast, around 90°.

The wind roses showed that in 2019 there was greater constancy in the direction of the winds, with a predominance of trade winds from the northeast acting on the LMNP region (Figure 9). The northeast wind acts perpendicularly to the coastline in the region, which reflects in the largest migration rates of the dunes when compared to the mangrove. When considering the whole period from 1980 to 2020 the average speeds range from 6 to 8 m/s in the region.

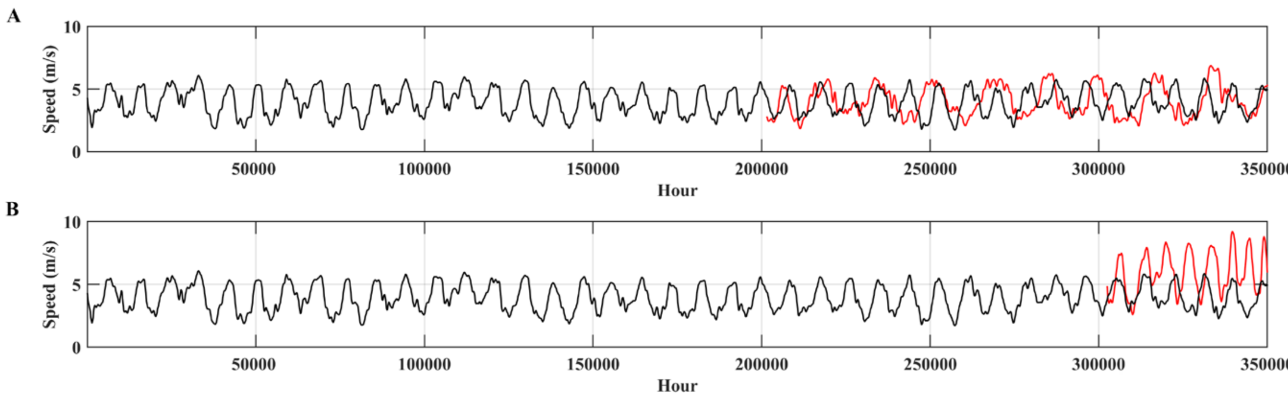

Figure 7 Time series with monthly low-pass filter (January 1980 to December 2020) of Vm measured by the Aeronautic's surface meteorological stations (red line) and Vm simulated by ERA5 reanalysis (black line): A. São Luís station 02° 35' 13'' S 044° 14' 10'' W; B. Parnaíba station 02° 53' 35'' S 041° 43' 47'' W.

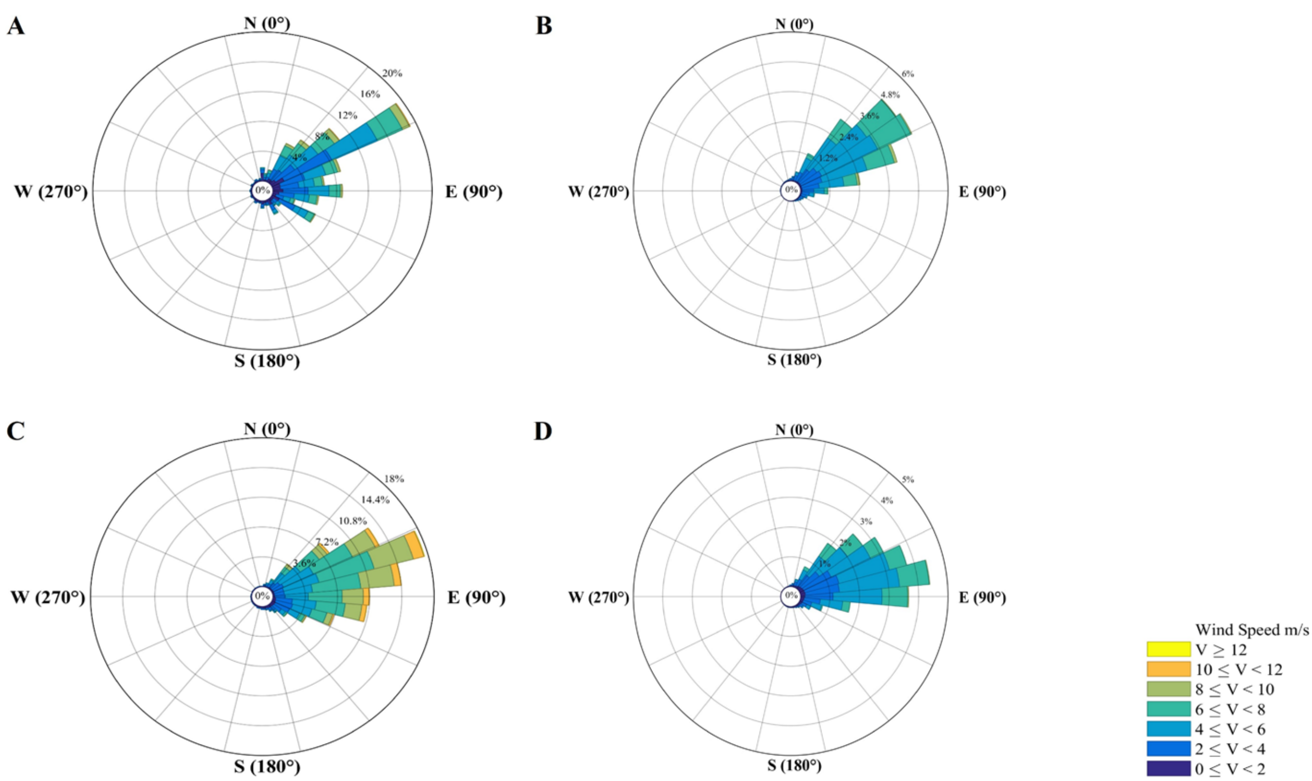

Figure 8 Vm directional histogram: A. Vm measured by the São Luís meteorological station; B. Vm simulated by the ERA5 reanalysis for the São Luís station; C. Vm measured by the Parnaíba meteorological station; D. Vm simulated by reanalysis ERA5 Parnaíba station.

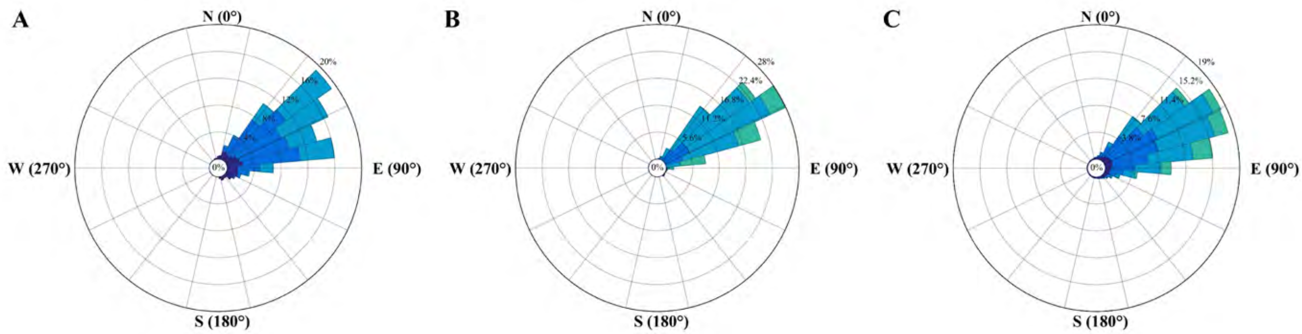

Figura 9 Directional histogram of Vm simulated by ERA5 reanalysis, measured from surface wind at 10 m for the study area: A. 1985; B. 2019; C. Period 1980-2020.

Despite the influence of winds on the transport of sandy sediment to mangroves and their impact on this ecosystem, other important climatic variables that are vital to the functioning of this ecosystem should also be evaluated. Previous studies (Twilley & Chen 1998; Gilman et al. 2008) have emphasized the significance of regular levels of precipitation and temperature for the distribution and development of mangrove forests. Over the past five decades alone, mangrove areas have declined by approximately 40% worldwide (Hu et al. 2018). Much of this loss can be attributed to global climate changes and their consequences, such as sea-level rise (Kirwan & Megonigal 2013; Lovelock et al. 2015).

The observed changes in the landscape between the Preguiças River and Caburé Beach over the years bolster the hypothesis that escalating coastal erosion will heavily contribute to the advancement of sea-level towards the mainland and the disappearance of mangrove belts, thereby endangering the communities residing in these areas. Consequently, climate change stands as one of the primary factors impacting mangrove ecosystems. According to the Intergovernmental Panel on Climate Change (IPCC 2022), a 25% increase in precipitation rates is projected by 2050, accompanied by uneven spatial distribution and a temperature rise of 2-4°C by 2100, largely attributed to human activities (Knutson & Tuleya 1999; Walsh & Ryan 2000; Houghton et al. 2001).

Another concerning trend observed in our study is the correlation between higher sand deposition on mangroves, particularly in Atins and Caburé (indicating their edges), and increased levels of tourist activity, especially near the few remaining mangroves that still retain their preserved status. Fishing, timber extraction, and so-called “ecotourism” practices have deeply encroached upon the previously pristine forest, exposing the central regions of mangroves to fragmentation and detrimental edge effects, including alterations in the composition of plant and animal communities, as well as a progressively growing loss of diversity, which necessitate further investigation.

A letter published by Bezerra et al. (2022) addresses the vulnerability of mangroves in Brazil and worldwide, proposing dynamic conservation measures for this ecosystem that are crucial for our survival. Mangroves serve as the largest carbon sinks and regulators of atmospheric greenhouse gases, thereby impacting and subjecting us to the severe consequences of climate change. Management plans, socio-environmental education for local communities, and enforcement are among the measures that can help maintain the equilibrium of this ecosystem. It is imperative for the scientific, civil, private, and public communities to unite their efforts to mitigate the changes in the mangroves of the Lençóis Maranhenses. The constant influx of people in the Preguiças River and its extensive utilization for various activities, coupled with the natural influx of sand into its water body, should be curtailed through measures such as river siltation, meander breakage, and reduction of the transitional environment, all of which will significantly impact the mangroves in the region.

4 Final considerations

This study revealed that the advancement of dunes over the mangrove forest surrounding the Lençóis Maranhenses has resulted in the burial, reduction, and even migration of the mangrove patches. Therefore, it is important to adopt measures for the conservation of the region’s mangroves, which can be directed towards overall climate change control or focused on the study area. Additionally, measures are needed to halt degradation due to local effects on riverbanks and disturbance caused by tourist pressure. Environmental policies implemented in cooperation between the state of Maranhão, civil society, the private sector, and the scientific community are necessary and important for the conservation of primary and secondary mangroves in the PNLM region. Furthermore, in the context of the United Nations Framework Convention on Climate Change for the restoration of these ecosystems, this area would be recognized as a mangrove conservation hotspot, and the conservation of secondary mangrove forests is necessary to partially compensate for the historical loss of existing mangroves observed in the region.

Our findings revealed that mangroves depend not only on climatic factors for survival but also on the synergistic interaction between the remaining mangrove forest configuration and the communities living there as sources of artificial ignition in the landscape. However, over the years, population growth and increasing tourist pressure on the banks of the Preguiças River have drawn attention to the need for control and conservation measures for mangroves to prevent disturbance in this environment.

Lastly, our findings contribute to filling gaps in our understanding of the dynamics of the Maranhão mangroves and their characteristics. Specifically, we present results on gain, stability, and loss related to dune field dynamics over a 34-year period. Thus, in addition to the increased dune advancement in later years, future research must analyze the period after 2019 to elucidate the fragmentation of these mangroves and the loss of ecosystem services, such as carbon sequestration, during the recent increase in anthropogenic pressures and natural factors in Lençóis Maranhenses.

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Juliana Sales dos Santos: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **André Luís Silva dos Santos:** methodology; supervision. **Claudia Klose Parise:** methodology; writing; supervision. **Thalita Mirian Santos Furtado:** data analyses; validation. **Adilson Matheus Borges Machado:** data analysis; writing. **Ulisses Denache Vieira Souza:** funding acquisition; formal analysis. **Leonardo Gonçalves de Lima:** methodology, discussion; visualization. **Ana Carolina Sousa Santos:** fieldwork. **Milena da Silva Rocha:** fieldwork. **Denilson da Silva Bezerra:** discussion; visualization.

Conflict of interest

The authors declare no conflict of interest.

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