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Research Paper

Interaction between Vegetation and Coastal Dunes: The Greening Phenomenon in the Peró Dune Field, Cabo Frio (RJ)

Interação entre Vegetação e Dunas Costeiras: o Fenômeno do Greening no Campo de Dunas do Peró, Cabo Frio (RJ)

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Abstract: The Peró dune field, located in Cabo Frio (RJ), has undergone significant morphological transformations associated with vegetation expansion over previously unvegetated sandy areas, a process known as greening. This study investigates the relationship between vegetation changes and geomorphological processes linked to this phenomenon, using multitemporal NDVI data (1984–2023), Sentinel-2 imagery (2015–2024), and high-resolution surveys with remotely piloted aircraft. The results indicate a marked increase in NDVI values over recent decades, with a 134.6% rise in the annual average between 1992 and 2023. Seasonal patterns reveal higher NDVI values during the rainy period, especially from November to February, with January and December standing out, while June recorded the highest values among dry-season months. Sentinel-2 imagery confirmed vegetation expansion in the central and southern sectors of the dune field, previously dominated by exposed sediments. High-resolution mapping shows dense patches of invasive species, the formation of human-use trails, and vegetation growth on the leeward faces of parabolic dunes, which tends to reduce the natural migration.These results indicate the combined action of environmental and anthropogenic drivers in intensifying greening, with important consequences for the conservation of this coastal environment, including the risk of accelerated stabilization of mobile dune fields, habitat homogenization, and loss of coastal geodiversity.

Keywords: *Greening*; Vegetation cover; NDVI; Climate variability; RPA.

Resumo: O campo de dunas do Peró, localizado no município de Cabo Frio (RJ), vem passando por transformações morfológicas significativas devido à expansão da vegetação sobre áreas antes ocupadas por sedimentos livres, fenômeno conhecido como *greening*. Este estudo investigou as relações entre alterações na vegetação e processos geomorfológicos associados, utilizando dados multitemporais de NDVI (1984–2023), imagens Sentinel-2 (2015–2024) e levantamento aerofotogramétrico. Os resultados indicam aumento dos valores de NDVI ao longo das últimas décadas, com elevação de 134,6% na média anual entre 1992 e 2023. A análise sazonal demonstrou maiores índices durante os períodos chuvosos, principalmente entre novembro e fevereiro, com destaque para os meses de janeiro e dezembro, enquanto junho apresentou os maiores valores entre os meses secos. As imagens Sentinel-2 confirmaram o avanço expressivo da vegetação nas áreas centrais e sul do campo dunar, antes dominadas por sedimentos expostos. O mapeamento detalhado mostra manchas densas de espécies invasoras, formação de trilhas de uso humano e o crescimento da vegetação sobre as faces de sotavento das dunas parabólicas, que tende a reduzir sua migração natural. Esses resultados indicam a atuação combinada de fatores ambientais e antrópicos na intensificação do *greening*, com importantes consequências para a conservação desse ambiente costeiro, como o risco à acelerada estabilização dos campos de dunas móveis, homogeneização de habitats e perda da geodiversidade costeira.

Palavras-chave: *Greening*; Cobertura vegetal; NDVI; Variações climáticas. ARP.

1. Introduction

Coastal dunes are extremely sensitive and spatially limited ecosystems, frequently the most impacted by human activity (Carter, 1988). Formed within the recent Quaternary geomorphological context, especially the Late Pleistocene and Holocene, coastal dunes are ephemeral, highly dynamic landforms whose morphology results from the nonlinear interaction among aeolian, sedimentary, and biological processes, the latter acting as one of the main stabilizing agents during their development (Hesp, 2002; Baas & Nield, 2007; Pereira et al., 2010; Luna et al., 2011). These landforms consist of fine to very fine sandy sediments, generally sourced from the nearshore/subtidal zone, associated with intermediate to dissipative beaches and characterized by high wind energy that reworks and transports surplus material landward across the coastal plain. Accordingly, the morphodynamics of these systems expresses a metastable equilibrium sustained by the volume and nature of the sediment source, the intensity and persistence of winds exceeding the entrainment threshold, and the role of plant communities in trapping these sediments (Fernandez et al., 2017; Da Silva & Hesp, 2013). These elements combine in a sensitive balance and can transform the entire system whenever any of these drivers are altered by anthropogenic pressures or by the intensification of climate change.

In recent decades, the rapid expansion of vegetation cover on coastal dunes has become the focus of numerous investigations worldwide, owing to its effects on the natural dynamics of these systems (Da Silva & Hesp, 2013; Petrova et al., 2023; Gao et al., 2023, 2024). This phenomenon, known as greening, is characterized by the replacement of exposed sandy surfaces by arboreal, shrub, or herbaceous vegetation (Jackson et al., 2019). Although in many cases such vegetation plays an important role in protecting against aeolian erosion (and, on foredunes, and against coastal erosion), its excessive expansion can produce adverse impacts, such as large-scale dune stabilization, thereby compromising the capacity for natural transgression in the face of sea-level rise and storm-event frequency (Jackson et al., 2019).

The advance of vegetation over mobile dunes tends to reduce their mobility and geomorphological dynamism, producing more uniform dune fields with lower environmental diversity (e.g., fewer areas of exposed sand). This stabilization impoverishes the mosaic of microhabitats characteristic of transitional dunes, eliminating niches for psammophilous species and reducing local number of plants species and arthropods typical of active sandy environments, as shown by Brunbjerg et al. (2014), Brunbjerg et al. (2015), and Petrova et al. (2023). Studies on the resilience of these environments indicate that biological diversity and the diversity of functional responses are key to an ecosystem's capacity to withstand disturbance (Elmqvist et al., 2003); accordingly, habitat homogenization driven by greening tends to erode the functional diversity of dune systems and reduce their resilience to external disturbances and to impacts on typical environmental drivers.

Among the factors associated with vegetation growth are temperature, atmospheric CO_2 concentration and other greenhouse gases, precipitation, wind regime, and sediment availability (Jackson et al., 2019; Petrova et al., 2023) (Fig. 1). Temperature constrains the annual growing season; CO_2 directly influences plant development via photosynthesis, while other atmospheric gases may act indirectly. Precipitation supplies the water and soil moisture required for germination and growth, especially during the wet season. The wind regime governs sand-transport capacity, and reductions in beach–dune sediment supply favor surface colonization and stabilization. Coastal erosion is also a key component and relates directly to this phenomenon: at the global scale, Luijendijk et al. (2018) estimate that ~25% of sandy shorelines experience sediment loss, contributing to sediment deficits across the coastal plain and thereby intensifying greening.

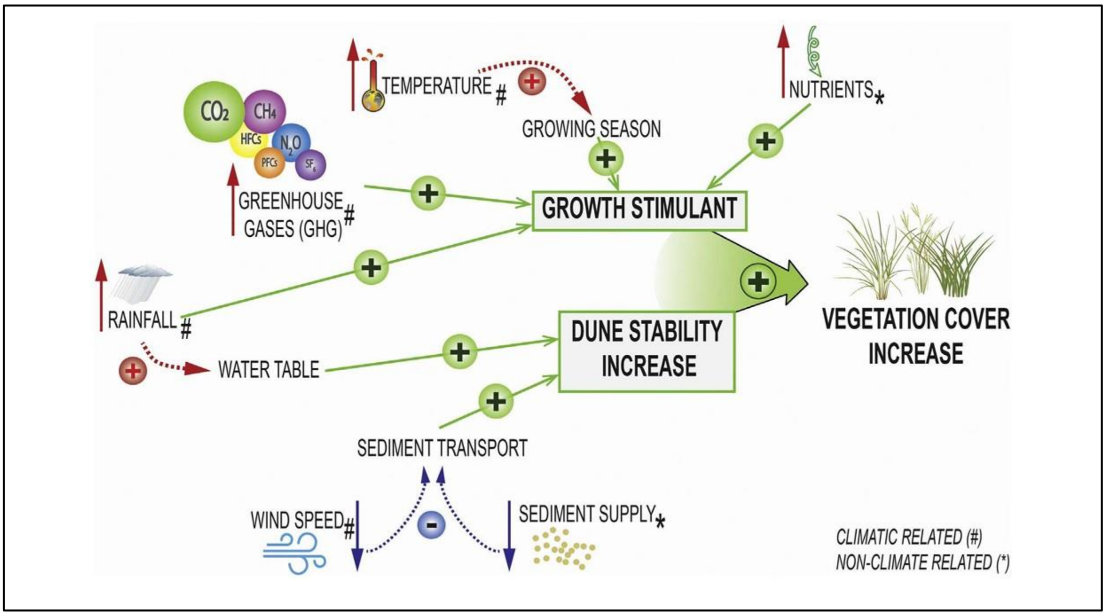


Figure 1. Environmental factors associated with vegetation increase in coastal dunes. Jackson et al., (2019).

At the global scale, Jackson et al. (2019) emphasize that several environmental drivers have shifted toward conditions more favorable to vegetation expansion in coastal dune systems, especially owing to changes in climatic and atmospheric regimes (Fig. 2). By contrast, at local to regional scales, this dynamic is governed primarily by the availability of sandy sediments, which directly constrains the potential for colonization and persistence of pioneer vegetation cover (Short & Hesp, 1982; Hesp, 1988, 2013; Gao et al., 2024). In other words, while global climate change operates as a broad-scale regulator influencing atmospheric cycles and extreme events (Carter, 1991; Jackson et al., 2019), regional climatic seasonality plays a central role in controlling vegetative expansion. Wet periods provide greater water availability for growth, stabilization, and densification, whereas dry periods, marked by reduced precipitation and higher aeolian transport capacity, tend to restrict or even reverse vegetation cover, resulting in greater dune mobility.

In this context, variability associated with the El Niño Southern Oscillation (ENSO) influences factors such as precipitation and temperature in southeastern South America (including southeastern Brazil), producing contrasting seasonal anomalies between El Niño and La Niña (Grimm, 2003; Tedeschi et al., 2016). Accordingly, La Niña conditions, typically weaker winds and higher precipitation, tend to reduce aeolian sand transport, favoring vegetation accumulation on dunes (greening). Conversely, El Niño, with reduced rainfall and stronger winds, tends to trigger the opposite effect, constraining plant growth. This influence also propagates to the wind field and the South Atlantic wave climate, altering beach–dune sediment supply and, consequently, the mobility and vegetative colonization of more interior dune systems (Hesp, 2002; Ramos et al., 2021).

Beyond these natural aspects, there is broad consensus that local anthropogenic interventions play a decisive role in triggering and intensifying greening (Jackson et al., 2019; Gao et al., 2020; Petrova et al., 2023). The most recurrent drivers include: (i) land-use and land-cover change; (ii) artificial stabilization programs that introduce pioneer exotic grasses or trees; and (iii) increased surface roughness resulting from urban infrastructure—all capable of reducing dune mobility and favoring vegetation densification over areas formerly dominated by sand surfaces (Tribe & Kennedy, 2010; Gao et al., 2022, 2024). Added to these factors is atmospheric nitrogen deposition from urban and industrial pollution, which acts as a diffuse fertilizer, accelerating vegetation growth and reinforcing dune stabilization (Provoost et al., 2011; Petrova et al., 2023).

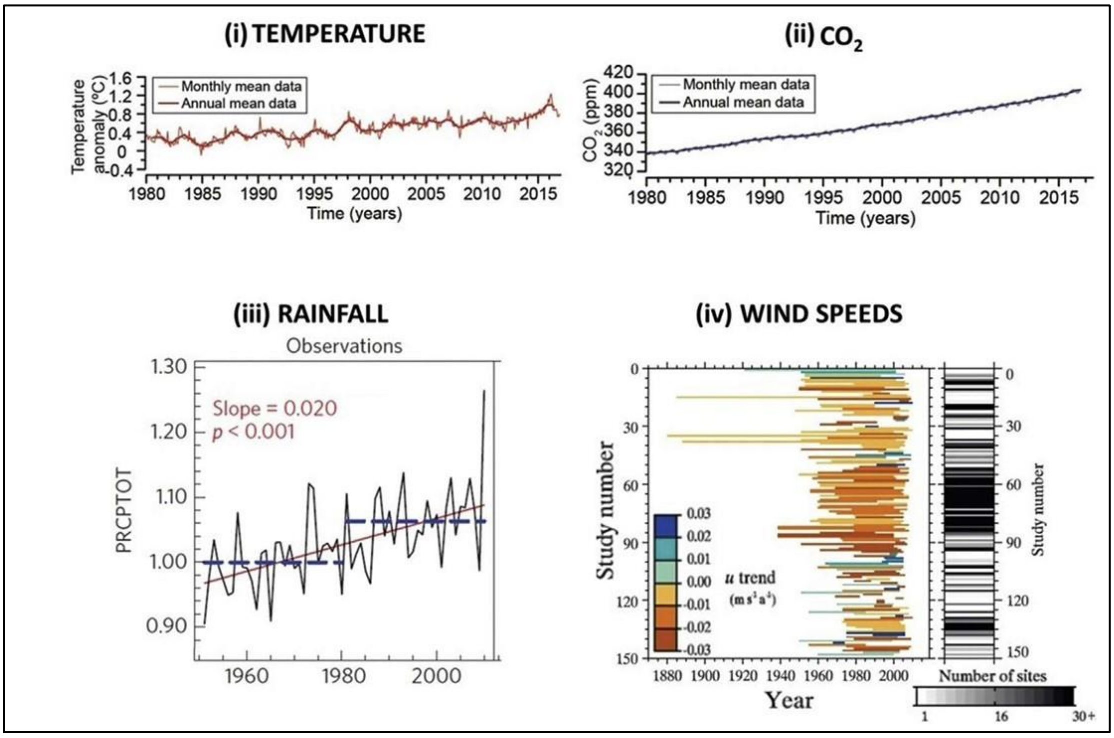


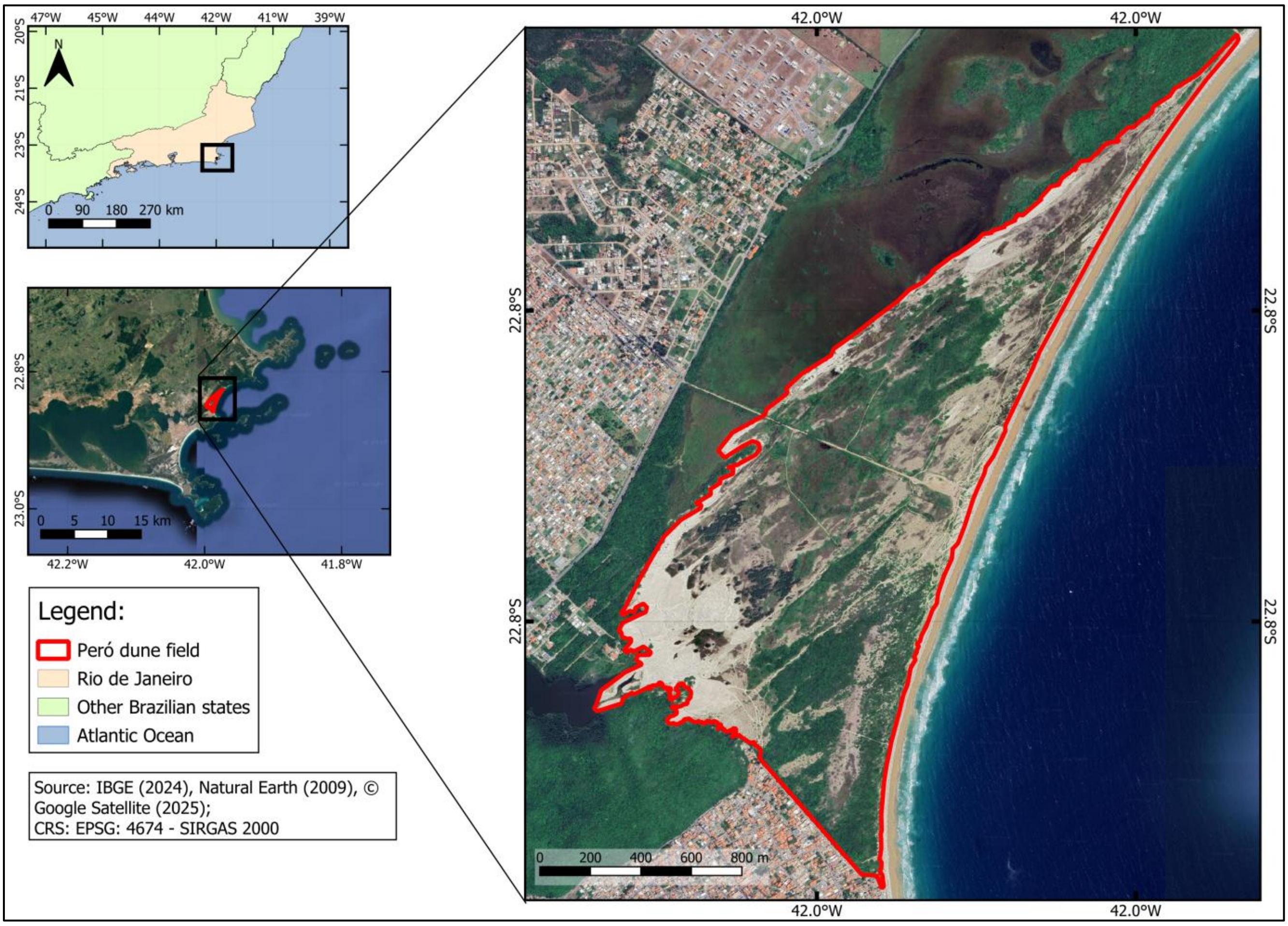
Figure 2. Global trends in climate variables. Jackson *et al.* (2019).

In the Peró dune field, located in the Baixadas Litorâneas region of Rio de Janeiro state, the process of vegetation expansion is observed, raising concerns about the advance of the greening phenomenon in the area. Previous studies, such as Muehe et al. (2010) and Mansur & Carvalho (2011), have already documented the growth of shrub vegetation since the mid-twentieth century, suggesting significant ecological changes in the local dune systems.

Given the multiple drivers associated with greening, it is essential to investigate whether the vegetation expansion observed in the Peró dune field is indeed related to this phenomenon. Such analysis contributes to understanding local ecological and geomorphological dynamics and to assessing possible implications for the stability and resilience of this coastal ecosystem. Accordingly, the main objective of this study is to determine the pattern of vegetation-cover dynamics in the Peró dune fields over the last few decades. To this end, we analyze vegetation expansion in the area, evaluate the transformations brought about by increased cover, and correlate the intensity of this growth with the seasonal variability of selected physical parameters in the region, regarded as key drivers of this phenomenon.

2. Study Area

Between the headlands of Cabo Frio and Búzios transgressive dune fields occour, with particular emphasis on the Peró dune field, located along the central stretch of the coastline between the municipalities of Cabo Frio and Armação dos Búzios (Pereira et al., 2010; Fernandez et al., 2017). Covering 214.27 hectares, it is the second largest in the region, surpassed only by the Dama Branca dune field (Pereira et al., 2010). Figure 3 shows the location of the Peró dune field.



Source: IBGE (2024), Natural Earth (2009), © Google Satellite (2025);
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Figure 3. Location map of the Peró dune field (RJ). Prepared by the authors.

The region contains the most significant assemblage of active aeolian landforms in southeastern Brazil, standing out for its sediment volume, variety of forms, and shoreline-oblique orientation (Castro et al., 2003). Table 1 summarizes the main natural controls associated with the formation of these systems.

Natural controls	Descriptions
Climate	- Köppen–Geiger classification: Hot Semi-arid (BSh) (Barbieri, 1984). - Presence of a Coastal Upwelling Zone, which affects the occurrence of convective rainfall (Martin & Suguio, 1989; Turc et al., 2010). - Low precipitation and evaporation rates (Barbieri, 1984; Martin & Suguio, 1989). - Dry winter and wet summer (Freitas et al., 2005). - Prevailing NE winds; during cold fronts, S and SW winds (Barbiere, 1985).
Vegetation	- High physiognomic and floristic diversity, with a high degree of endemism (Bohrer et al., 2009). - Phytogeographic enclave (Coe et al., 2007; Coe & Carvalho, 2013). - Features resembling the Northeastern Brazilian caatinga, with predominance of cacti and bromeliads (Mooney et al., 1995; Coe et al., 2007). - Center of Plant Diversity of the Neotropical Region (Araujo, 1997; Bohrer et al., 2009). - Xeromorphic floristic composition, adapted to climatic constraints (Araujo, 1997).

	- Introduction of invasive exotic species, such as Casuarina equisetifolia L. (Bohrer et al., 2009).
Geomorphological and geological aspects	- Geological domains comprising crystalline basement and coastal sedimentary deposits (Da Silveira et al., 2021). - Lower incidence of orographic rainfall due to the distance from the Serra do Mar (Barbieri & Coe Neto, 1999). - Cabo Frio Tectonic Domain (CTFD), from the Neoproterozoic to the Quaternary (Heilbron et al., 2000). - Three physiognomic units: coastal plains; low hills and coastal islands; and continental hills (Araujo, 1997).
Morphodynamics stage associated with dune formation	- Dune formation on beaches with intermediate and dissipative morphodynamic stages (Fernandez et al., 2020). - The main source of fine sediments is the continental shelf (Muehe & Valentini, 1998). - Sediment transport is essential for the maintenance and evolution of dune fields (Fernandez et al., 2020).

Table 1. Environmental and geomorphological factors conditioning the formation and evolution of coastal dunes in Cabo Frio (RJ). Prepared by the authors.

Beyond the aspects mentioned above, anthropogenic influence has intensified with the accelerated urbanization of the Baixadas Litorâneas region, directly threatening all dune ecosystems located between Cabo Frio and Cabo Búzios. Major pressures include the introduction of invasive exotic species such as Casuarina (Casuarina equisetifolia L., also known as Australian pine), livestock grazing in dune areas, urban expansion, and inadequate management practices (Konlechner et al., 2015; Moulton et al., 2018; Lopez & Hesp, 2023). Another relevant anthropogenic impact stems from the pressure exerted by large, high-end tourism–real estate developments. The lands occupied by the dune fields have been systematic targets of such large-scale projects, as in the case of “Club Med Peró”, a development that, in the early twenty-first century, sought to establish itself near the dune field and envisaged occupying virtually the entire contiguous area, from the landward side of the foredunes to the aeolian features farthest from the shoreline (Saleme, 2016).

3. Materials and Methods

The methodology was structured into two main stages: (3.1) a multitemporal analysis of the Normalized Difference Vegetation Index (NDVI) and (3.2) fieldwork involving direct observation and an aerophotogrammetric survey using a remotely piloted aircraft (RPA) to generate high-resolution imagery. The integration of remote sensing, geoprocessing, and field data collection was fundamental to ensure the robustness of the analyses of vegetation dynamics associated with the dunes.

3.1. Multitemporal analysis of the Normalized Difference Vegetation Index (NDVI)

NDVI is an index used to estimate vegetation cover and to detect changes in land use/land cover patterns (Shimabukuro, 1998). It is generated by applying mathematical operations to satellite sensor bands for image enhancement (Melo et al., 2011). For this study, data were obtained from the Climate Engine platform and from Sentinel-2 imagery, processed in GIS environments such as QGIS and Google Earth Engine (GEE). NDVI is computed as follows, where NIR denotes near-infrared reflectance and Red denotes red reflectance:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \tag{1}$$

The Climate Engine platform draws on Landsat 5, 7, 8, and 9 imagery (30 m spatial resolution), providing a data record from 1984 to 2023. From this source we generated NDVI time series and trend plots for the available period. We also examined NDVI values for the wet months (November–February) and the dry months (June–September), enabling an assessment of seasonal and long-term (interdecadal) variations in vegetation cover. The analysis considered 222 observations for the selected months between 1984 and 2023. The series is nonetheless discontinuous owing to variations in data availability on the platform.

Complementarily, we extracted Sentinel-2 imagery (10 m spatial resolution), suitable for finer-scale mapping. These images, spanning 2015–2024, were used to analyze in detail the spatial distribution of vegetation cover. Two scenes per year were selected, one representative of the dry season and one of the wet season, in order to capture seasonal variability and the effects associated with climatic events such as El Niño and La Niña. The data were processed and analyzed in GIS to produce maps and to evaluate the spatial distribution and density of vegetation through time.

3.2. Aerophotogrametric Survey

Two field campaigns were conducted for this study:

- 20-22 May 2024: exploratory reconnaissance of the study area, photographic recording of points of interest, and an initial assessment of indicators relevant, such as dense patches of exotic vegetation, trails, blowouts, active deflation features, and the identification of priority area(s) for mapping.
- 2-4 September 2024: planning and execution of the aerophotogrammetric survey with a remotely piloted aircraft (RPA), including the establishment of ground control points (GCPs) for georeferencing with GNSS (Global Navigation Satellite System) equipment to ensure higher positional accuracy. The dry-season window was chosen to (i) minimize ephemeral greening of seasonal herbs and thereby avoid overestimating vegetative cover; (ii) maximize visual contrast between exposed sand and vegetated nuclei for improved segmentation; (iii) operate under low cloudiness and reduced soil moisture, enhancing photogrammetric quality and the sharpness of tie points for Digital Elevation Model (DEM) processing; and (iv) document the system’s state of higher potential mobility.

The imagery acquired enabled mapping of the dune field and the generation of 3D modeling (DEM) for morphological characterization of the area, analysis of vegetation patterns, and documentation of the diversity of forms present in the region. The use of RPA for aerophotogrammetry plays an important role in the rapid surveying of large areas at high spatial resolution and low operational cost (Guisado-Pintado et al., 2019). Low-altitude flights yielded centimeter-scale orthomosaics and digital surface models capable of capturing micro-relief, anthropogenic trails, and vegetation nuclei with a level of precision unattainable with medium-resolution orbital sensors.

The survey was carried out under few-cloud conditions and wind speeds below 10 m s^{-1}. The DJI Air 2S RPA covered 48 ha, focusing on the innermost portion of the deflation plain, where the dune megaform is established (the largest transgressive dune feature on the plain, formed by the coalescence of smaller dunes), along with several semi-fixed dunes, in the central–southern sector of the Peró beach arc. The area was selected due to the concentration of environmental indicators related to vegetation expansion observed during the first campaign and also reported by Muehe et al. (2010). An autonomous-flight app was used to load the flight plan with the following image-acquisition parameters: altitude 100 m, 70% sidelap and 80% frontlap, and ground sample distance (GSD) < 10 cm.

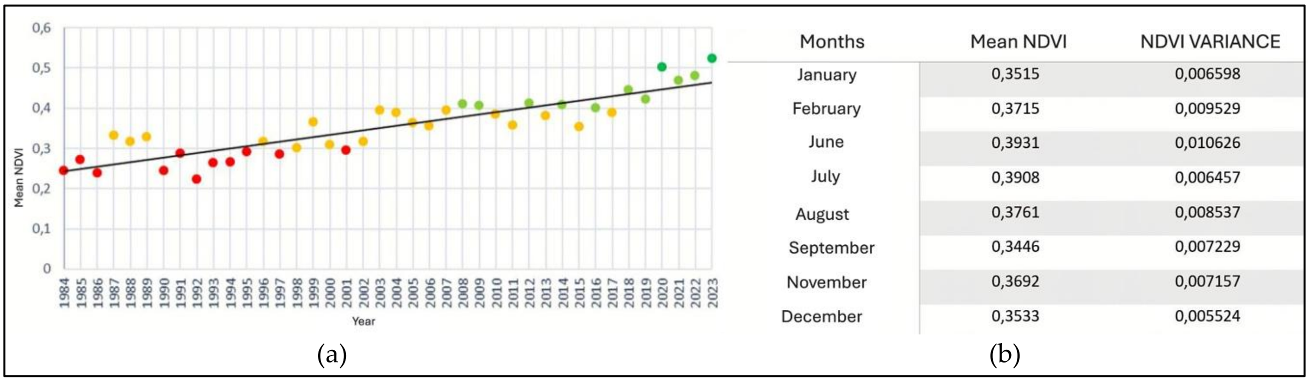
We established 15 geodetic GCPs, split between control and check points, all georeferenced with GNSS receivers. RTK (Real-Time Kinematic) mode was used to achieve high real-time positional accuracy, significantly reducing coordinate errors. The vertical RMSE obtained was ≤ 25.3 cm, meeting Class A of the Brazilian Standard for Cartographic Accuracy for Digital Cartographic Products (PEC-PCD) for mapping scales up to 1:5,000 (Brazil, 1984).

Photogrammetric processing was performed in Agisoft Metashape Professional (version 2.1.2). The workflow produced geospatial outputs including a dense point cloud, textured 3D models, surface models (DEM/DTM), and georeferenced orthomosaics compatible with GIS. These products supported the geomorphological analyses and vegetation mapping integrated in the GIS environment.

4. Results

4.1. NDVI temporal trends (1984-2003)

NDVI data show a strong increase over four decades (Figure 4A). The annual mean (Figure 4B) rose from 0.2232 in 1992 to 0.5236 in 2023, an increase of 134.6%. This steady rise indicates a gradual expansion of vegetation cover. Seasonally, June (0.3931) and July (0.3908) recorded the highest mean NDVI values, whereas September had the lowest (0.3446). Monthly variance was also highest in June (0.010062) and February (0.009529), suggesting greater oscillation in these months, while December showed the lowest variance (0.005524). Taken together, these figures confirm that vegetation has increased even during drought months, reinforcing evidence of greening in the dune system.



Months	Mean NDVI	NDVI VARIANCE
January	0,3515	0,006598
February	0,3715	0,009529
June	0,3931	0,010626
July	0,3908	0,006457
August	0,3761	0,008537
September	0,3446	0,007229
November	0,3692	0,007157
December	0,3533	0,005524

(a) (b)

Figure 4. (a) Variation of the annual mean NDVI from 1984 to 2023; (b) Monthly NDVI statistics. Prepared by the authors.

4.2. Seasonal variation of NDVI

Although the overall increase in NDVI is evident across the study period, it is important to consider intra-annual seasonal effects. Figures 5A and 5B show that monthly NDVI patterns reflect local climatic seasonality. June–September is represented in the dry-season panel (Fig. 5A), whereas November–February correspond to the wet-season panel (Figure 5B).

Within the dry season, June 2023 registered the highest NDVI value in the entire time series, along with the largest year-to-year increase; September recorded the lowest value (in 1992) and the smallest proportional increase. In the wet season, mean NDVI values were generally higher than in the dry months, indicating greater vegetation cover in response to rainfall. January and December stand out with higher indices, in contrast to November and February, which exhibited more homogeneous vegetative growth. Trend lines over time show NDVI increasing in all months of the year, with the largest gains in June and July. This indicates that vegetation has expanded even during less favorable periods (dry season), likely due to ongoing colonization by tolerant and invasive species, coupled with a more pronounced reduction in local aeolian intensity in the wet season (Figura 6), as presented by Pereira (2025) using TerraClimate data.

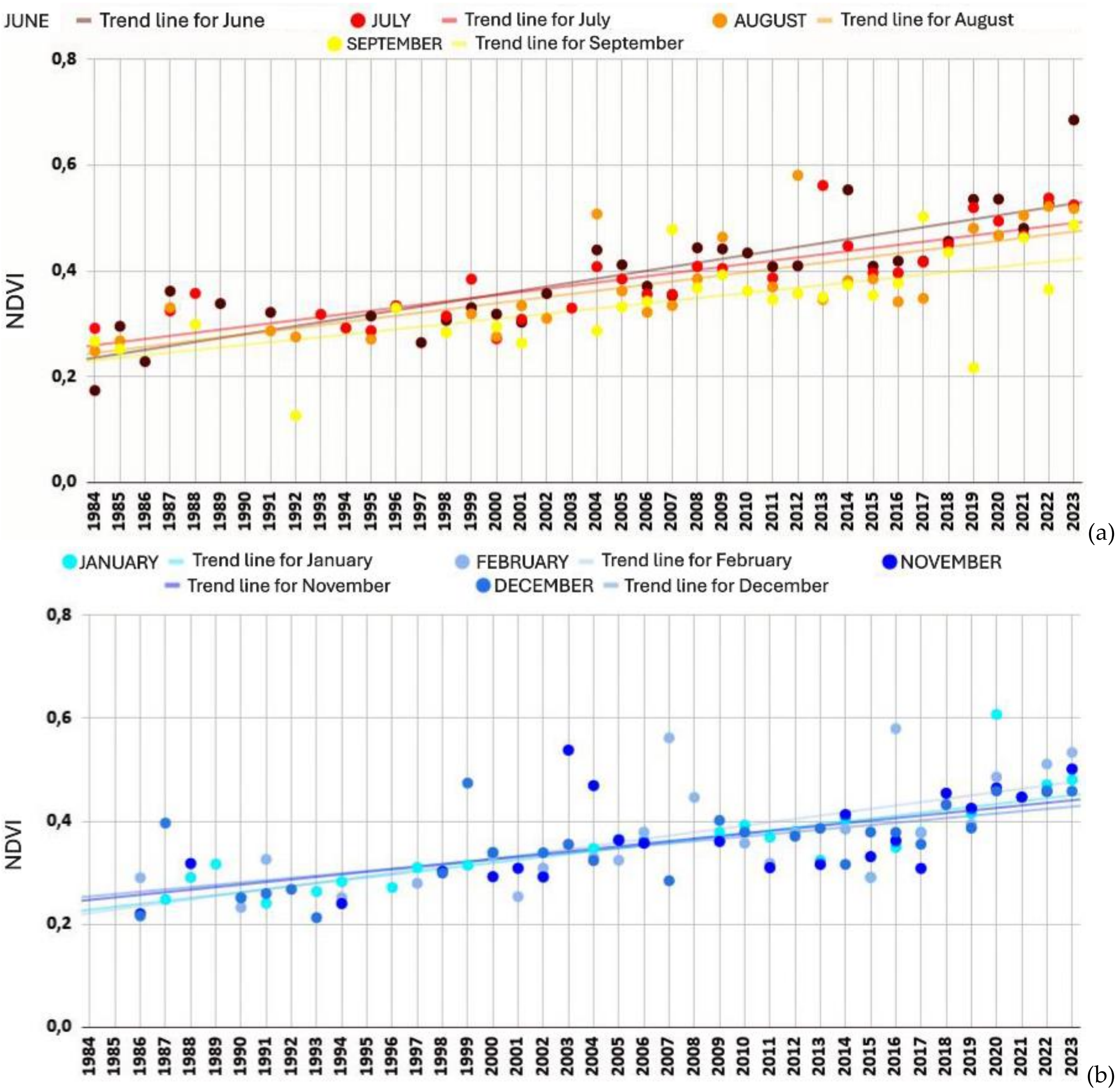


Figure 5. (a) NDVI variation (1984–2023) for dry-season months; (b) NDVI variation (1984–2023) for wet-season months. Prepared by the authors.

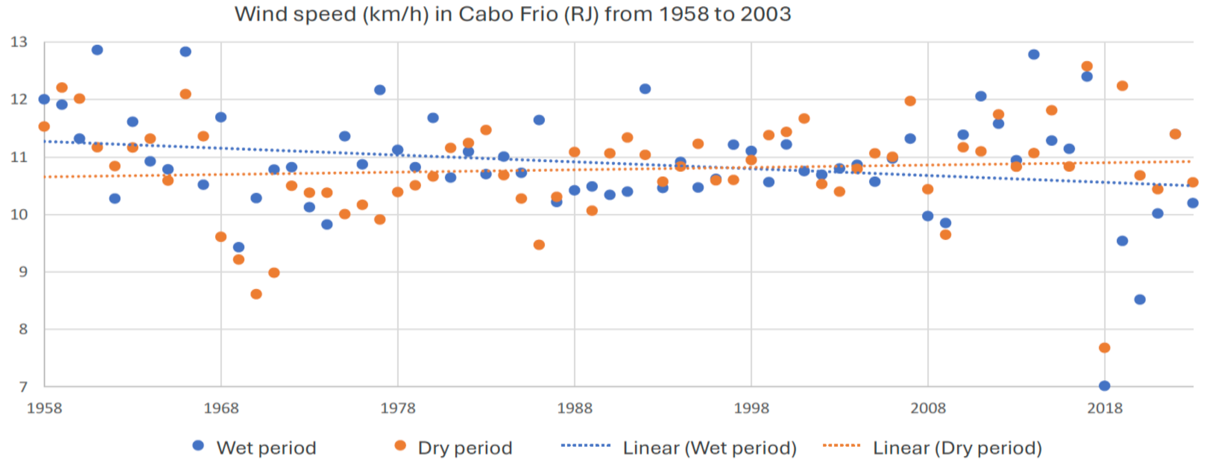


Figure 6. Time series of mean wind speed (km/h) in the wet and dry seasons for Cabo Frio, 1958–2023. Translated from Pereira (2025).

In general terms, between 1980 and 1990 NDVI values remained relatively low, increasing as the number of months with available data also grew. In more recent years, the contrast between dry and wet months appears attenuated. After 2000, greater interannual amplitude is evident, linked to global climatic events such as El Niño and La Niña, which directly influence water availability in many regions. Between 2015 and 2020, NDVI values stand out as higher, suggesting more favorable environmental conditions or a positive vegetation response to change.

4.3. Climatic seasonalities produced by El Niño and La Niña

Figure 7 presents the Oceanic Niño Index (ONI) time series provided by NOAA, analyzed here to investigate large-scale climatic influences. Irregular cycles of El Niño (positive values) and La Niña (negative values) were identified between 1950 and 2023. Intense El Niño events occurred in 1982–83, 1997–98, and 2015–16, and intense La Niña events in 1973–74, 1999–2000, and 2010–11. This climatic variability is reflected in the NDVI series, with accentuated interannual oscillations especially after 2000, when El Niño (2009–2010; 2015–2016) and La Niña (2007–2008; 2010–2011; 2011–2012; 2020–2021) episodes occurred in succession, reaching strong to very strong intensities.

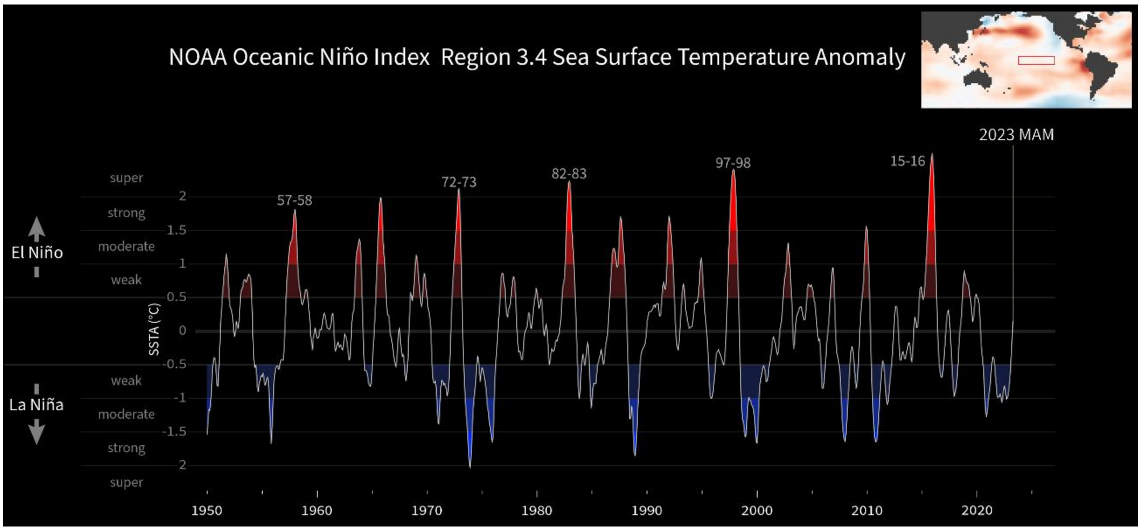
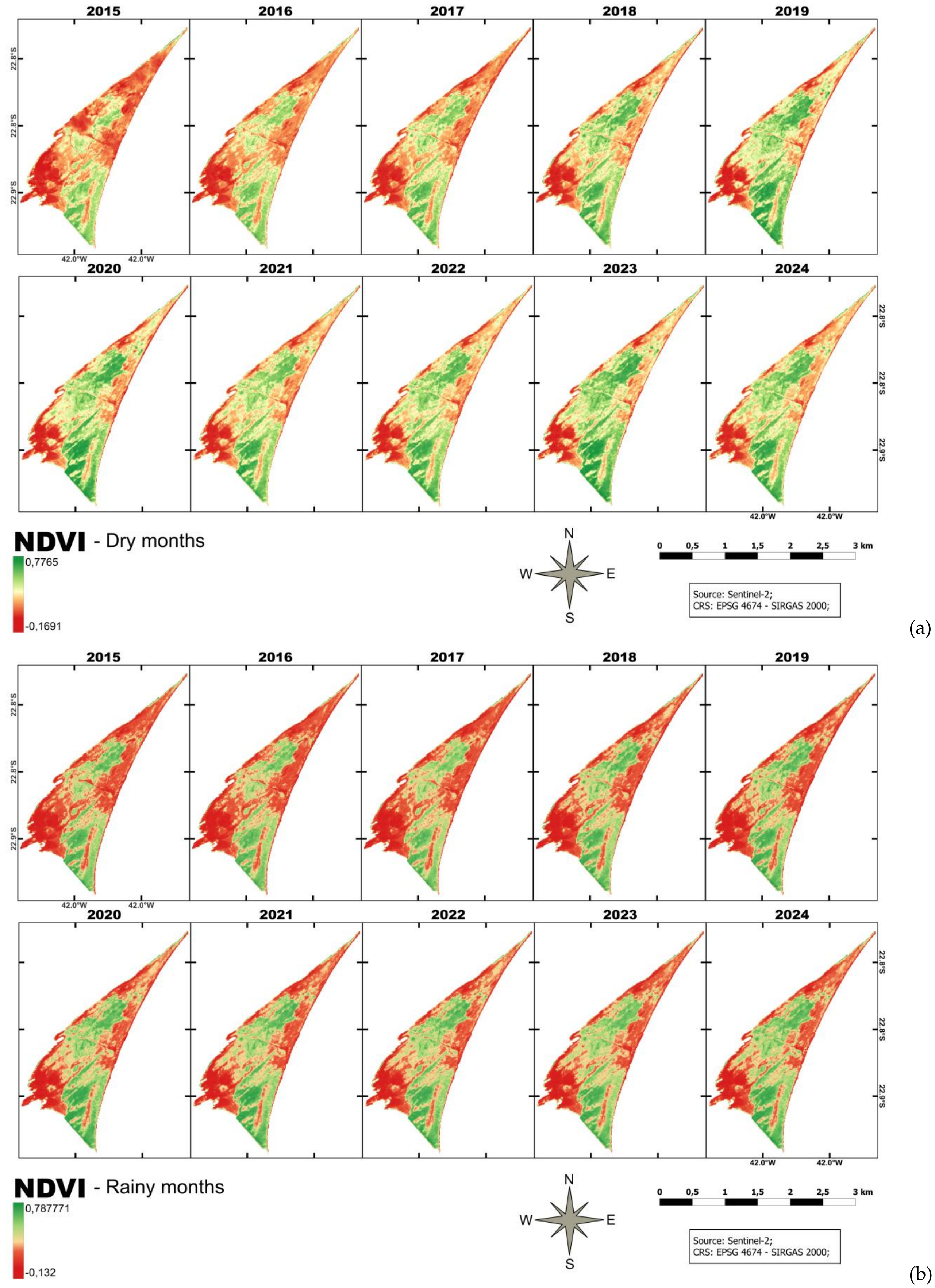


Figure 7. El Niño and La Niña variability from 1950 to 2023. NASA (2023).

4.4. Spatial distribution of vegetation (Sentinel-2, 2015–2024)

Based on Sentinel-2 imagery acquired between 2015 and 2024, the distribution of NDVI over the Peró dunes reveals key aspects of vegetation dynamics in the region. The maps (Figures. 8A and 8B) show that during this period NDVI values ranged from 0.17 to 0.78 in the dry months and from 0.13 to 0.79 in the wet months, indicating a larger amplitude in the wet season. In both seasonal contexts, the lowest vegetation concentrations (lower NDVI) occurred in the southwestern sector of the dune field, suggesting areas of higher sand mobility. The highest indices were observed in the central and southern portions, where vegetation cover has expanded more intensely. These spatial patterns highlight localities with different degrees of stabilization and, consequently, different morphodynamics.

Additionally, comparison between dry and wet periods shows that, although seasonality modulates magnitude, the spatial patterns of higher or lower vegetation density remain fairly consistent. This suggests that denser vegetated nuclei remain relatively stable even in the dry season, due to cover densification/maturation and micro-environmental controls (greater surface roughness/aeolian sheltering and local soil-moisture retention), consistent with the dominance of tolerant and/or exotic species in the parts with highest values are found.



Source: Sentinel-2;
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Figure 8. (a) Spatial distribution of NDVI (2015–2024) in the Peró dune field during dry-season months; (b) Spatial distribution of NDVI (2015–2024) during wet-season months. Prepared by the authors.

4.5. Detailed spatial analysis (DEM and 2024 orthomosaic)

High-resolution analysis using an orthomosaic and DEM derived from the RPA survey provides fine-scale details of vegetation expansion and local factors. False-color imagery of vegetated areas (Figure 9) highlights dense Casuarina clusters—an exotic species with high tolerance (examples 9A and 9E). In other portions (examples 9B and 9F), vehicle and foot trails are visible, indicating vegetation removal and partial return of aeolian sediments. The enlarged images (9C, 9G) show grasses and herbs encroaching onto larger dune features, approaching the field's main aeolian landforms. Finally, cutouts 9D and 9H emphasize vegetation expansion on the lee faces of central parabolic dunes. In summary, vegetation cover is increasing across virtually the entire area, with notable development of Casuarina forest patches, human-made trails, and progressive stabilization of smaller dune

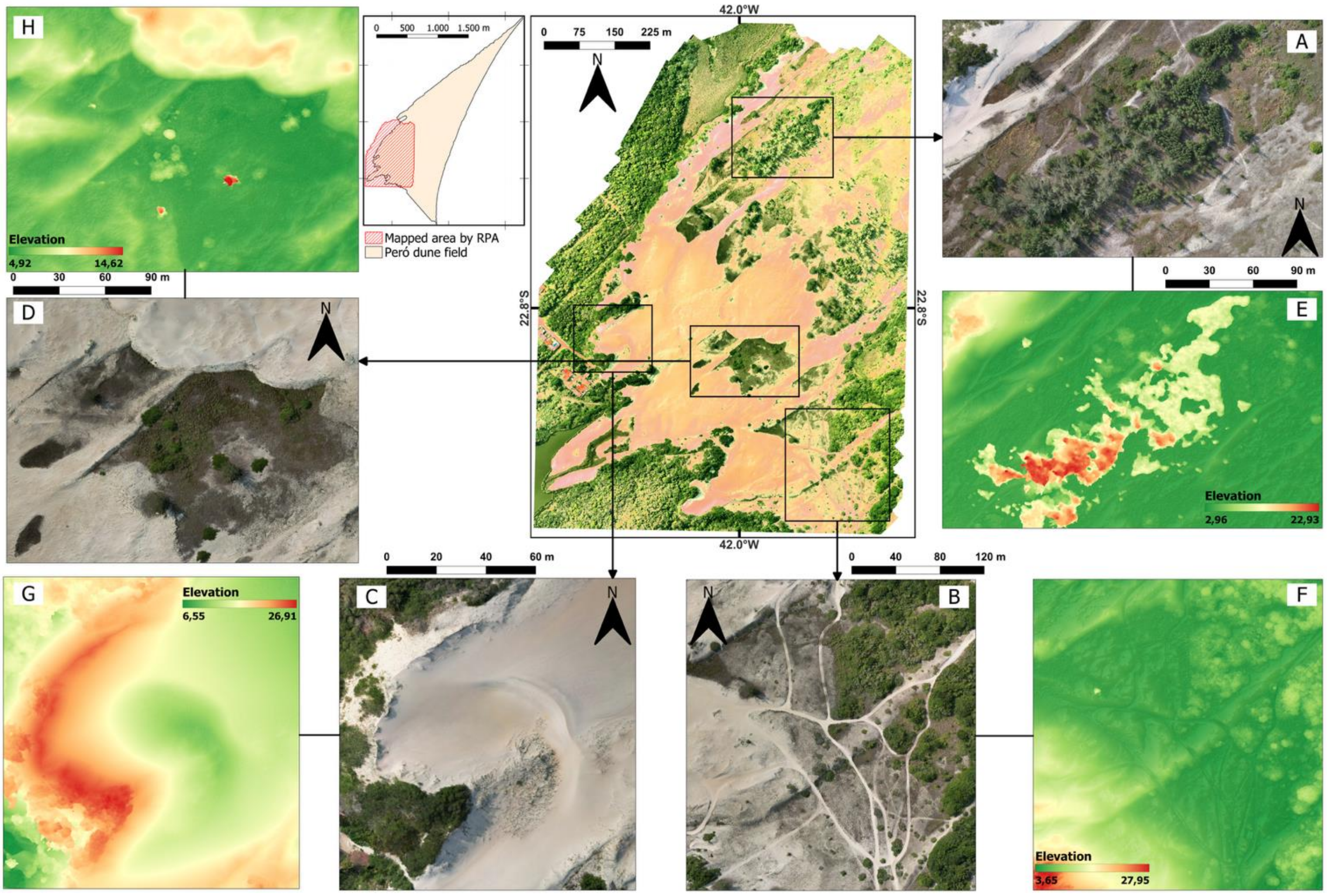

Figure 9. Central panel: orthomosaic with false-color DEM of the area mapped in the central–southern sector of the Peró dune field; black rectangles delimit windows A–H. Panels A–D (orthomosaics, natural color): (A) densification of a Casuarina forest; (B) aeolian reactivations associated with trails; (C) encroachment of grasses/herbs onto larger dune features; (D) vegetation expansion on the lee faces of parabolic dunes. Panels E–H (false-color DEM highlighting elevation variation): (E) Casuarina forest; (F) trail-induced aeolian reactivation; (G) encroachment of low vegetation onto dune features; (H) vegetation expansion on the lee faces of parabolic dunes. Prepared by the authors.

5. Discussion

The results of this study reveal a continuous and increasing expansion of vegetation cover in the Peró dune field, evidenced by a significant rise in NDVI from 1984 to 2023, especially after the 2000s. This pattern reflects a dynamic widely described in the international literature as greening: the replacement of sandy surfaces by more permanent vegetation, producing functional changes in dune systems (Jackson et al., 2019; Petrova et al., 2023). The occurrence of high NDVI values even in historically dry months (e.g., June and July) indicates a modification in the seasonal regime of vegetation cover, suggesting greater resilience of local vegetation to hydrological variability.

This vegetation advance should be understood as the outcome of multiple drivers. On one hand, médium-term climatic events such as El Niño and La Niña directly influence precipitation and wind regimes in southeastern Brazil, conditioning the degree of dune mobility or stabilization (Da Silva & Hesp, 2013). On the other, NDVI data and high-resolution RPA imagery reveal local anthropogenic interferences, such as trails, efforts to advance real-estate developments as documented by Saleme (2016) that affect the morphodynamics of the dune field by creating micro-environments favorable to vegetation establishment and spread. The literature indicates that, without adequate management strategies, these interventions can intensify dune stabilization, leading to the loss of distinct landforms and to biodiversity decline (Tribe & Kennedy, 2010; Gao et al., 2024).

The expansion of vegetation over areas formerly dominated by free/mobilizable sediment can profoundly affect local aeolian dynamics. Parabolic, barchan, and barchanoid dunes, formerly abundant on this plain (see Muehe et al., 2010), depend on the continuous interaction among sediment supply, wind action, and a controlled presence of vegetation. When vegetation becomes excessively dense, especially on the lee faces of features within the deflation plainas (shown in Figs. 8D and 8H) the system tends toward morphological stagnation (Hesp, 2013). This compromises internal sediment remobilization, weakens supply to more landward features, and alters the systemic functioning of the dune field. According to Yizhaq et al. (2013), smaller features tend to stabilize more rapidly, whereas larger dunes require greater sediment input and a longer response time to vegetation cover, corroborated here by the 3D analysis of the Peró megaform (Figs. 8C and 8G).

The differential behavior of NDVI through time, particularly the reduced seasonal contrast between dry and wet periods, suggests not only vegetation expansion but also functional homogenization of the ecosystem. Such loss of temporal variability may pose a risk to ecological resilience because the system's ability to cope with extreme events (storms and storm surge) and sea-level rise depends on the alternation between phases of mobility and stabilization (Carter, 1991; Elmqvist et al., 2003). By reducing mobility, greening hinders the natural landward migration of dunes in response to shoreline retreat, making the system more vulnerable to erosion and functional fragmentation.

The Peró case also illustrates how local anthropogenic elements act synergistically with regional atmospheric processes and global climate change, producing landscape modifications that may be misread as environmental "recovery" (due to increased biomass) but, in fact, indicate a functional imbalance. As discussed by Marzialetti et al. (2019) and Petrova et al. (2023), NDVI must be interpreted in context: vegetation growth does not necessarily imply ecological regeneration; it may reflect the expansion of homogenized and ecologically disruptive vegetation—assemblages that interrupt aeolian/sediment fluxes and severing the connectivity of the system linking the beach, primary (fore) dunes, and secondary (interior) dunes. The replacement of native species adapted to dune mobility by fast-growing, tolerant invasive exotics compromises structural integrity, floristic diversity, coastal geodiversity, and the ecosystem services associated with dune fields.

The presence of tolerant and exotic species such as casuarina is widely associated with accelerated dune stabilization in different coastal regions (Garzo et al., 2025) and is directly related to human pressures around natural dune systems (Bohrer et al., 2009). Analysis of Figures 8A and 8E revealed pronounced densification of Casuarina equisetifolia in the Peró dune field, where its rapid spread has been favored by more prolonged wet windows and lower aeolian energy for abrasive sediment transport. This expansion is not limited to Peró: Casuarina has spread to other aeolian systems in the Baixadas Litorâneas, such as the Massambaba fields and the Dama Branca dune complex, forming dense forest patches that interrupt the natural sediment flux from the beach. By altering aeolian transport and promoting excessive fixation, this species compromises the morphodynamics of lee-side dunes, suppresses native psammophilous species, and reduces ecological variability. Such a scenario raises concerns about the functional mischaracterization of these environments and about local biodiversity loss (CBD, 1992; Feagin et al., 2010).

6. Conclusions

In the Peró dune field, the intensification of greening, observed through the steady NDVI rise since the 1980s, reflects significant shifts in vegetation patterns driven by climatic factors and human interventions. This process, documented in many coastal systems worldwide, manifests locally as the expansion of vegetation over areas of formerly mobilizable sand, propelled by anthropogenic interferences such as the spread of Casuarina equisetifolia L. across the deflation plain.

The detailed analysis of NDVI seasonality, together with high-resolution imagery, enabled the identification of spatial and morphological patterns that point to a loss of functional performance in the dune system. In particular, the role of invasive exotic species and landscape-level anthropogenic alterations stands out as critical in modifying aeolian and sedimentary dynamics.

Given the singularity of this coastal environment, management approaches must integrate geomorphological, ecological, and climatic knowledge. Our results underscore the need for more critical interpretations of spectral indicators and remotely sensed vegetation patterns. The advance of greening in the Peró dune field expresses a multicausal process and should be interpreted as a symptom of deep environmental change, pointing to a regime shift: from mobile dune fields to anthropogenically amplified stabilization. This state is sustained by a positive feedback loop composed of vegetation densification (including exotics); greater roughness and aeolian sheltering; reduced effective sand transport; further densification, modulated by more prolonged wet windows and by periods of lower aeolian energy.

The integration of detailed spatial analyses, field observation, and global climatic indicators can provide a robust methodological basis for monitoring and managing these environments. As a final hypothesis, we propose that the Peró dune field is undergoing a functional transition phase, in which the balance between mobility and stabilization is being reconfigured, calling for targeted conservation policies and management to prevent the system's definitive functional mischaracterization.

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