

INTEGRATING GEOMORPHOLOGICAL AND ECOLOGICAL INDICATORS TO ASSESS COASTAL DUNE VULNERABILITY IN SOUTHERN BRAZIL

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ABSTRACT: Coastal dunes play a vital role in protecting human communities and ecosystems by acting as natural barriers against erosion of urban infrastructure, storm surges, and sea-level rise. However, these systems are increasingly degraded by urban expansion and climate change. In this study, we reassessed coastal vulnerability to erosion in the municipality of Imbé, southern Brazil – one of the fastest-growing coastal areas in the state of Rio Grande do Sul – 12 years after the implementation of a local Dune Management Plan. A geomorphological checklist method across 44 coastal segments (each 250 m long) was applied, scoring 25 variables grouped into four parameters: dune morphology, beach condition, adjacent land use, and anthropogenic pressure. Relative Vulnerability Index (RVI) values ranged from 28.0 to 69.6%, with 36% of the segments experiencing an increase in vulnerability classification compared to the 2012 baseline. Cluster analyses revealed distinct spatial patterns between seasons, with winter clusters better reflecting structural vulnerability and summer clusters influenced by tourism-related pressures. Concurrently, 30 active nests from three bird species (i.e. *Athene cunicularia*, n = 15; *Vanellus chilensis*, n = 13; and *Haematopus palliatus*, n = 2) were recorded and georeferenced along 11 km of coastline. Nest abundance is negatively correlated with dune area and width (Pearson's $r = -0.40$ and -0.35 , respectively), indicating that more degraded dune units supported fewer nesting birds. *A. cunicularia* emerged as a promising bioindicator due to its fidelity to nesting sites and preference for less fragmented dunes. These findings highlight the value of integrating physical and biological indicators to assess coastal vulnerability and suggest a cost-effective and ecologically informed framework for monitoring and managing sandy coasts under increasing environmental pressures.

Keywords: Avian reproduction; Bioindicators; Coastal erosion; Sandy beaches; Urbanization.

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1. INTRODUCTION

The coastline plays a critical role in protecting human communities, primarily through natural processes that mitigate the impacts of erosion and extreme weather events. Foredunes, for example, function as natural barriers against wind, tides, and flooding, thereby reducing damage to adjacent urban areas. However, the provision of these ecosystem services is increasingly jeopardized by climate change and unregulated coastal development. According to projections from the IPCC (2022), sea levels may rise between 0.29 and 1.1 m by 2100, depending on greenhouse gas emission scenarios, which would intensify erosion risks and threaten essential infrastructure and human settlements. In addition, extreme events such as storms and cyclones, becoming more frequent and intense, have already caused considerable destruction in coastal zones. Unplanned urbanization, often motivated by the economic value of beachfront property, further compounds these risks by replacing resilient natural ecosystems with more vulnerable artificial structures (You *et al.*, 2018). Collectively, these factors underscore the urgent need for integrated coastal management strategies aimed at mitigating impacts and preserving the protective functions of these ecosystems (Claussen, 2013; Harris & Ellis, 2025).

The biota of foredunes plays a vital role in maintaining and stabilizing these coastal environments. Pioneer vegetation, such as grass species adapted to high salinity and strong winds, is essential for dune stabilization, as their root systems help retain sediments and form natural barriers against erosion (Tomazelli, 1994; Hesp, 2000; Sigren *et al.*, 2014). The fauna associated with these ecosystems also depends directly on their stability, using dunes as habitats for feeding, breeding, and shelter. Among these organisms, birds stand out not only for their ecological associations with dune environments but also for their potential as bioindicators of dune geomorphology (Burger, 2023). The presence and behavior of birds provide valuable insights into dune configuration and dynamics, supporting the identification of appropriate management strategies to reduce coastal vulnerability. Their effectiveness as bioindicators stems from their sensitivity to changes in habitat structure and geomorphological processes, both of which reflect the overall stability and resilience of the system. Notably, the reproductive requirements of many bird species concerning dune morphology often align with the very conditions necessary to protect human communities from erosion and extreme events.

Coastal vulnerability assessment is a fundamental practice for the sustainable planning and management of coastal zones,

particularly in light of increasing urbanization pressures and the impacts of climate change. A variety of methodologies have been developed to identify and quantify the factors that render these areas more susceptible to erosion and other environmental hazards. Among these, beach cross-shore profiles are commonly used to monitor morphological and sedimentological variations, while evolutionary models, such as that of Hesp (1988), describe the stages of dune stabilization and degradation. Additionally, integrated vulnerability analyses (e.g., Williams *et al.*, 1993) offer a systematic framework to assess parameters related to dune morphology, beach conditions, adjacent land characteristics, and anthropogenic pressures. A notable practical application of this approach is the method adapted by Tabajara *et al.* (2013), which used the municipality of Imbé, on the southern coast of Brazil, as a case study. Based on a structured checklist, the method evaluates 25 variables grouped into four categories: dune morphology; beach conditions; characteristics of the 200 m adjacent to the shoreline; and usage pressure. Each variable is scored from 0 to 4, and these scores are then used to calculate a Relative Vulnerability Index (RVI), expressed as a percentage of the maximum possible score. The results revealed significant variation in RVI, ranging from 24 to 67%, with the northern coastal sectors exhibiting the highest vulnerability due to urban encroachment, reduced dune width, and sand loss. This approach effectively identified priority coastal sectors for intervention, particularly areas where urban expansion has encroached upon dune systems or where environmental degradation is most severe.

In Brazil, approximately 26% of the population (around 50 million people) live in the coastal region, spread across 280 municipalities along more than 7,000 km of coastline (IBGE, 2011; MMA, 2021). These figures underscore the strategic importance of coastal zones and the urgent need to monitor the consequences of human occupation and ecosystem alterations in order to prevent climate- and environment-related disasters. The southern coast of Brazil is characterized by an extensive, straight stretch of dissipative sandy beaches with medium-grain sediments. This region experiences low tidal amplitude and a high frequency of meteorological tides, making it particularly dynamic and sensitive to climatic and oceanographic influences. Population growth along this coast has shown heterogeneous patterns across its southern, central, and northern segments. According to 2022 census data from the Brazilian Institute of Geography and Statistics (IBGE, 2023), the northern coastal region of Rio Grande do Sul, which is the southernmost state in Brazil, recorded the highest annual population growth rates between 2010 and 2022, reaching nearly 2% per year, with some municipalities growing by as much as 4.79% annually. This

contrasts sharply with the state's average growth rate of only 0.15% over the same period. Of the ten municipalities with the highest population growth in the state, seven are located along the coast, and several have seen growth rates exceeding 50%, including the municipality of Imbé (51.81%). These demographic trends clearly illustrate the increasing anthropogenic pressure on coastal ecosystems, reinforcing the need for comprehensive assessments of coastline vulnerability and adjacent habitats in the context of ongoing climate change.

In southern Brazil, the coastal region provides critical habitat for both migratory and resident bird species that depend on its unique ecosystems for survival. These environments, defined by stabilizing vegetation and dynamic geomorphological features, offer essential shelter and food resources, particularly for species such as burrowing owls, American oystercatchers, and southern lapwings, which rely on nearby intertidal zones rich in benthic invertebrates. Given the close ecological association between these bird species and foredune habitats, alterations in these environments can have direct impacts on their populations. Monitoring avian use of foredunes, especially breeding activity, can therefore offer valuable insights into the stability and resilience of coastal ecosystems under increasing anthropogenic pressure and climate change. This is particularly relevant considering the potential use of these species, especially *Athene cunicularia*, as cost-effective bioindicators for the long-term monitoring of coastal vulnerability.

Therefore, this study aimed to assess foredune vulnerability to erosion in southern Brazil, using as a case study a municipality with one of the highest population growth rates in the region. In parallel, all bird nests located on foredunes were mapped and evaluated as potential bioindicators of coastal vulnerability. The findings have direct practical implications for the management of foredune systems, not only within the study area but also across other municipalities situated along the extensive, straight sandy coastline that characterizes southern Brazil. Moreover, the study provides novel insights into the use of avian reproductive activity as a cost-effective and ecologically relevant indicator of coastal vulnerability, particularly in the context of climate change adaptation and integrated coastal zone management.

1.1 Study area geological context and delimitation

The coastal plain of southern Brazil constitutes the emerged portion of the Pelotas Basin, an open marginal sedimentary basin (Barboza *et al.*, 2021). Late Quaternary sea-level variations were the primary drivers for the formation of the current lagoon-barrier depositional systems (Villwock *et al.*, 1986; Tomazelli

& Dillenburg, 2007). In this region the interplay between high sediment supply and wind conditions favorable to onshore accumulation has facilitated the development of dune fields and transgressive dune ridges on the Holocene Barrier System IV over millennial timescales (Barboza & Rosa, 2014). Currently, different sectors of this Holocene barrier exhibit progradational, retrogradational or aggradational behaviors, leading to varied small-scale morphologies (Dillenburg *et al.*, 2009; Watanabe *et al.*, 2023). Ultimately, negative sediment budget balances across both short and long temporal scales remain the primary cause of erosion along this coastline (Dillenburg *et al.*, 2004).

Within this morphological context, the present study was carried out in the municipality of Imbé, located on the northern coast of Rio Grande do Sul, southern Brazil. Bordered by the Atlantic Ocean, the area features open beaches that range from intermediate to dissipative, primarily shaped by wave action under a semidiurnal microtidal regime, with an average tidal amplitude of 0.30 m (Toldo *et al.*, 1993). During winter, meteorological tides can cause more pronounced variations, reaching up to 1.2 m (Almeida *et al.*, 1997). Owing to the homogeneous granulometric characteristics of the coastline, beach morphology in the region is largely governed by hydrodynamic energy, which influences the seasonal dynamics of the backshore extension (Weschenfelder & Zouain, 2002).

The area examined in this study corresponds to the same 11 km stretch of coastline analyzed in the dune vulnerability assessment by Tabajara *et al.* (2013). Its width extends from the swash zone (defined as the beach area between the minimum and maximum water run-up after wave breaking) to 200 m inland from the shoreline (Figure 1).

2. METHODS

2.1 Assessment of vulnerability levels to erosion in foredunes

The vulnerability of dunes is defined as a set of conditions that induce dune erosion and ecosystem manipulation (Davies *et al.*, 1995). To evaluate dune vulnerability to erosion along the coastline of the municipality of Imbé, the checklist method proposed by Williams *et al.* (1993, 2001) and adapted by Tabajara *et al.* (2013) was applied during two field campaigns: one in July 2022 (winter) and another in January 2023 (summer) (Figure S1). This method characterizes and delineates dune areas according to their degree of vulnerability. It also helps identify specific weaknesses in the system by assigning scores from 0 to 4 to each variable across 50,000 m² per sampling unit.

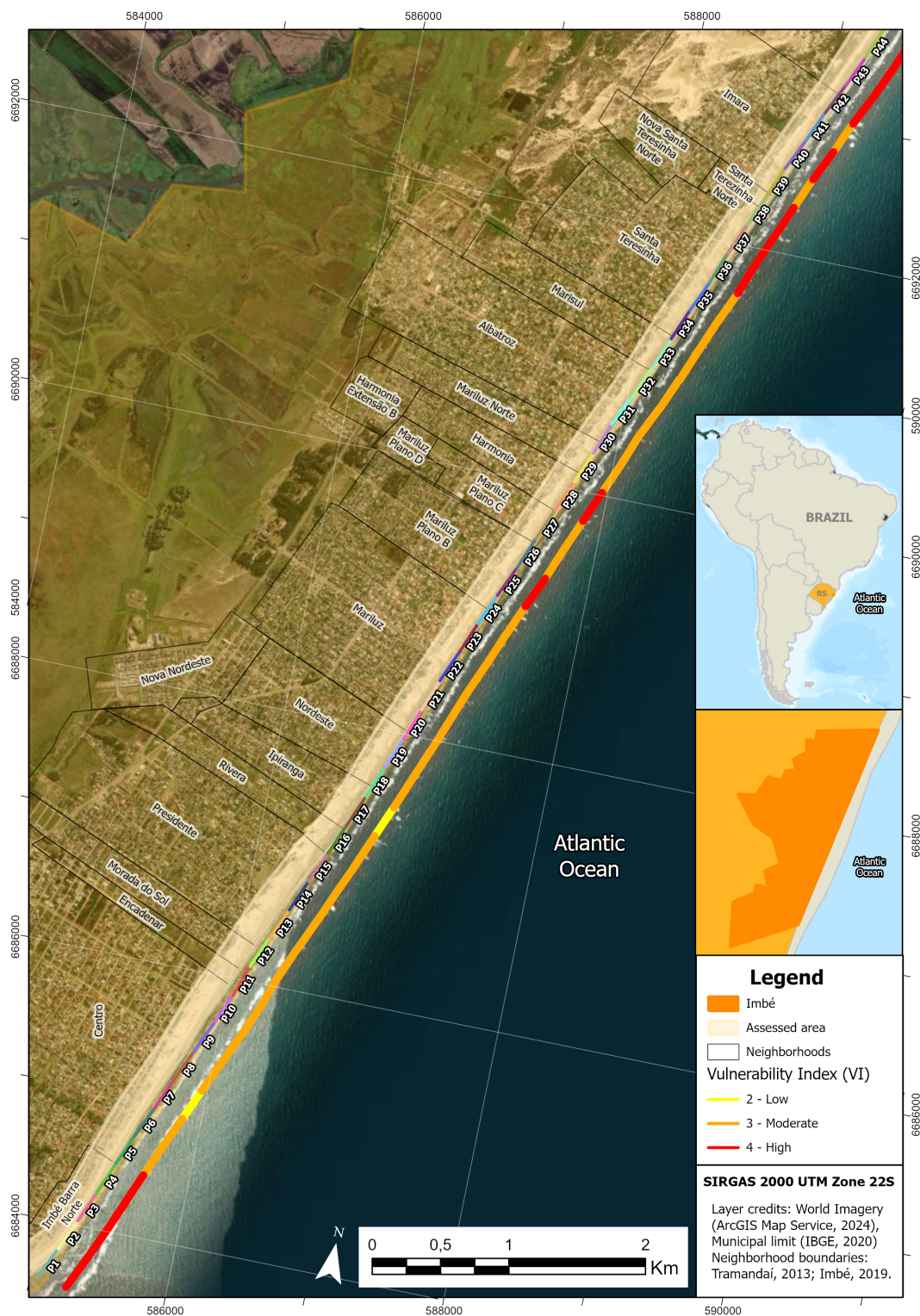


Figure 1. Location of the study area, showing neighborhood boundaries, delineation of landscape units, and their respective winter Vulnerability Index (RVI) classifications. Base map: World Imagery (ArcGIS Map Service, 2024); municipal boundary data: IBGE (2020).

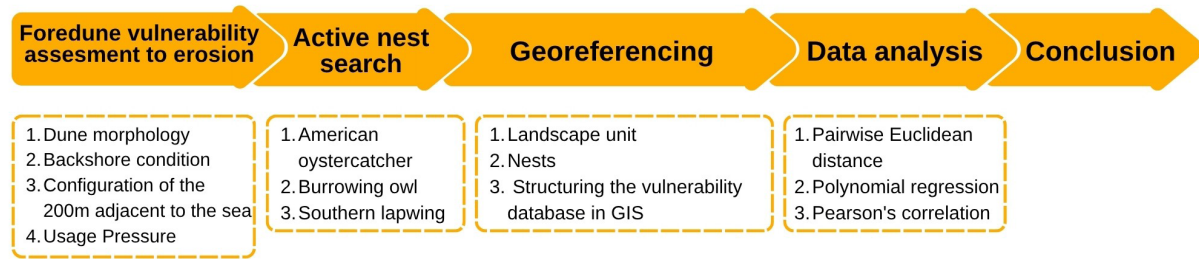


Figure 2: Methodological workflow applied in the assessment of coastal vulnerability and bioindicator analysis.

Table 1. Parameters used in the checklist. Source: Franchini (2010).

Parameter	Importance	Variables
Dune Morphology	Geomorphological condition (extent and sediment volume) determines the resilience of foredunes.	Surface area (m ²); dune width (m); height of the tallest dune (m); scarp and slope on the marine-facing side.
Backshore Condition	The backshore condition is related to the sand supply for foredunes (development of the dune's marine-facing slope).	Backshore width (m); sand supply; breaches in the beach face; width of breaches in the beach face; presence of embryonic dunes.
Characteristics of the 200 m Adjacent to the Sea	Synthesizes the biophysical characteristics and processes that interfere with local sediment dynamics (such as fragmentation of the system by blowouts).	Percentage of blowout areas, sand loss from the system to the continent; percentage of breaches in the dune system; percentage of vegetation on the seaward side of the dune; recent sand deposition; percentage of impermeable coverage; presence of exotic vegetation; and number of drainage/runoff outlets.
Usage Pressure	Evaluates anthropogenic interference in the balance of foredunes.	Number of vehicle access points; pedestrian path density; percentage and stage of urbanization; urbanization position; number of kiosks; and number of property owners.

The four parameters and their associated variables are presented in Table 1. For the checklist application, the coastline of Imbé was divided into 44 segments (Figure 1), each with a latitudinal length of 250 m, referred to as sampling units. These units were numbered and surveyed from south to north, beginning at the city center and ending in the Balneário Imara area, during both the winter and summer assessments (Figure 2). Although the segmentation approach followed the method used by Tabajara *et al.* (2013), one additional sampling unit was included in the present study due to a 250 m northward shift in the municipal boundary marker. Subsequently, each sampling unit was assigned a vulnerability index from 1 (very low) to 5 (very high), following classification criteria adapted from Laranjeira (1997).

2.2 Active nest search

The census of nests for three bird species that nest directly on the substrate was conducted through active visual searches, carried out biweekly between October and December 2022 (spring in the southern hemisphere). Both direct evidence (e.g., observation of nests and chicks) and indirect evidence

(e.g., pairs exhibiting territorial defense behaviors such as vocalizations and low flights) were used to identify active nests of *Athene cunicularia* (burrowing owl), *Haematopus palliatus* (American oystercatcher), and *Vanellus chilensis* (southern lapwing) during the four sampling efforts. During this phase, the entire 11 km coastline of the municipality was surveyed on foot using a zigzag search pattern, the most effective method for ensuring complete visual coverage of the area, even in the presence of blind spots caused by substrate irregularities (Bibby *et al.*, 1992). All active nests were georeferenced for subsequent spatial analysis and mapping.

2.3 Data analysis and georeferencing

Using a Geographic Information System (GIS) environment, the 44 landscape sampling units were georeferenced along with the coordinates of the identified nests (Table S1). To avoid double-counting, only the highest number of nests observed per species within each sampling unit across the four campaigns was recorded. Checklist variables requiring an overhead perspective - such as dune surface area and system width - were analyzed using orbital

imagery from the Wide Field Multispectral and Panchromatic Camera (WPM) aboard the CBERS-4A satellite (image acquisition date: July 2nd, 2022). These data were processed with ArcGIS Pro 10.3 (ESRI®). Calculations of dune area and width were conducted within the UTM planar coordinate system, referenced to the SIRGAS2000 datum, zone 22S. Checklist data collected during field assessments were organized in Microsoft Excel 2007®, where Relative Vulnerability Indices (RVI) were calculated. All datasets and outputs were subsequently georeferenced and converted into shapefile vector formats. Classification values of each checklist variable were plotted using local polynomial regression (loess), implemented via the *ggplot2* package in R (Cleveland *et al.*, 1992; Wickham, 2016; R Core Team, 2022). Additionally, a Pearson correlation matrix was constructed, and correlograms were generated using the *corrplot* package (Wei & Simko, 2021). Finally, pairwise Euclidean distances were calculated between sampling units based on checklist variables, and a dendrogram was created using the *tidyverse* package (Wickham *et al.*, 2019).

3. RESULTS

3.1 Classification of the coastline by vulnerability index

Winter results showed that, of the 44 coastal segments evaluated, two were classified as vulnerability level 2, 29 as level 3, and 13 as level 4. No segments received the minimum (1) or maximum (5) classification. Only 4.5% of the coastline fell into level 2, indicating segments with less pronounced erosive changes. The remaining 95% were classified as levels 3 or 4, reflecting more evident signs of degradation. Of these, 30.95% corresponded to landscape units where dunes lacked mechanisms of resistance to erosion, while 69.05% showed intermediate conditions.

Cluster analysis based on winter data resulted in six distinct groups of landscape units (Figure 3). In summer, three clusters were identified (Figure 4). The units classified with the lowest vulnerability levels were not grouped together but rather distributed across different clusters in both seasons. In both seasonal assessments, the first cluster included units where dunes were absent, either due to replacement by built structures such as a boardwalk (units P1–P4) or road infrastructure (units P42–P44). Between winter and summer, changes in vulnerability classification were limited. In summer, only unit P17 remained at level 2. Units P7 and P29, previously level 4, shifted to level 3. While small variations were noted across parameters, most units retained their original classification. The observed variations affected cluster composition.

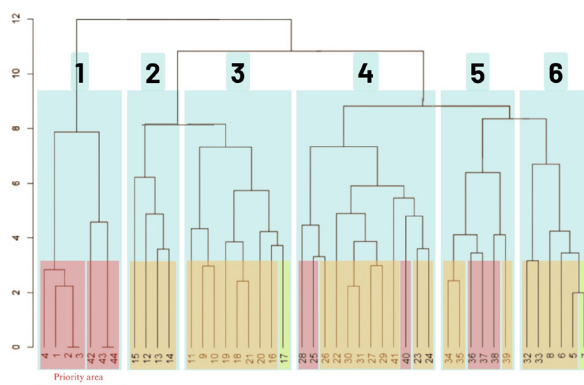


Figure 3: Euclidean distance dendrogram of the variables analyzed in the dune erosion vulnerability checklist applied in winter 2022. Aquamarine rectangles indicate clusters of landscape units based on similarity of vulnerability profiles. Red, orange, and yellow rectangles denote landscape units classified with Relative Vulnerability Index (RVI) levels 4, 3, and 2, respectively.

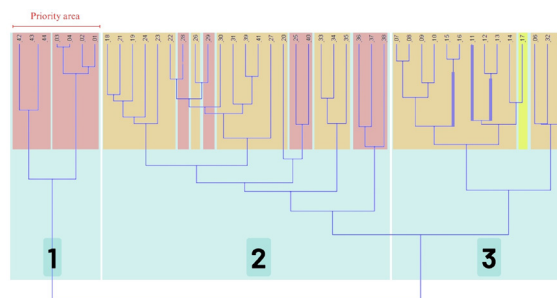


Figure 4: Euclidean distance dendrogram based on the variables analyzed in the dune erosion vulnerability checklist applied during the summer of 2023. Aquamarine rectangles delineate clusters of landscape units. Color-coded rectangles represent the vulnerability classification of each unit: red for level 4, orange for level 3, and yellow for level 2.

Among the remaining segments, two main clusters were identified. One encompassed units P18 to P41 (excluding P32), which shared characteristics of narrow and fragmented dunes. The other included units P05 to P17 and unit P32, which had wider dune areas (Figure 4).

(Figure 3) comprised only level 3 units. These segments were characterized by high erosive scarps and steep slopes, with low coverage of impermeable surfaces within the 200 m buffer (Figure 6A–C). Cluster 3 contained mostly level 3 units and one at level 2. These areas also had high scarps but greater impermeable surface coverage (Figure 6D–E). Cluster 5 included an equal number of level 3 and 4 units, with a mean RVI of 60.17% (SD: 3.11%). These segments had highly fragmented foredunes with narrow dune widths (Figure 7A). Cluster 6 was composed mainly of level 3 units and one at level 2, with relatively wide dune areas. The mean RVI for this group was 44.33% (SD: 3.14%). Cluster 4 included mostly level 3 units, and three classified as level 4. These segments had small remaining dune fragments and a mean RVI of 57.25% (SD: 3.94%).



Figure 5: Sampling units grouped within the area identified as a priority for coastal management interventions. A-D: dune absence due to replacement by a boardwalk in the southern sector. E-H: dune loss caused by erosion and the encroachment of the Interpraia Road in the northern sector.



Figure 6: Records of sampling units with dunes characterized by steep slopes and erosional scarps. A-C: units from Cluster 2, highlighting the low percentage of impermeable surface within 200 meters inland from the shoreline. D-E: units from Cluster 3, characterized by a higher percentage of impermeable coverage in the same adjacent area. E - Google Earth Pro Satellite image (June 2023) of sampling unit P18-P20 from Cluster 3.



Figure 7: Google Earth Pro Satellite images (June 2023) of sampling unit clusters 5 and 6. A: sampling units belonging to similarity Cluster 5. B: sampling units comprising Cluster 6, as identified by the Euclidean distance analysis.

3.2 Relationship between the checklist and bird nest abundance

To examine the relationship between predictor variables of dune erosion vulnerability and the number of bird nests per landscape unit, data from the winter vulnerability assessment were used. A total of 30 nest sites or territorial pairs exhibiting nest defense behavior were georeferenced, including 2 nests of *Haematopus palliatus* (American oystercatcher), 13 of *Vanellus chilensis* (southern lapwing), and 15 of *Athene cunicularia* (burrowing owl) (Figure 8, Table S2). Of these, 86.67% were located in the southern half of the municipality. Nest distribution across coastal sectors varied by species. Most *A. cunicularia* nests (11) were found in the foredune, along with one *H. palliatus* and one *V. chilensis* nest. In the dune field, a total of six nests were recorded: three of *V. chilensis*, two of *A. cunicularia*, and one of *H. palliatus*. In the urban portion of the coast, 11 nests were observed, including 9 of *V. chilensis* and 2 of *A. cunicularia*.

Among the checklist parameters, dune morphology (IVA) exhibited the highest positive correlation with the overall vulnerability classification of the sampling units (Figure 9A). Within this parameter, the variables with the strongest correlations to vulnerability levels were dune area and dune width (Figure 9B). When the relationship between the number of nests and dune morphology variables was evaluated, negative correlations were observed for dune area ($r = -0.40$) and dune width ($r = -0.35$). These results indicate that units with smaller dune areas and widths tended to contain fewer nests (Figure 10B).

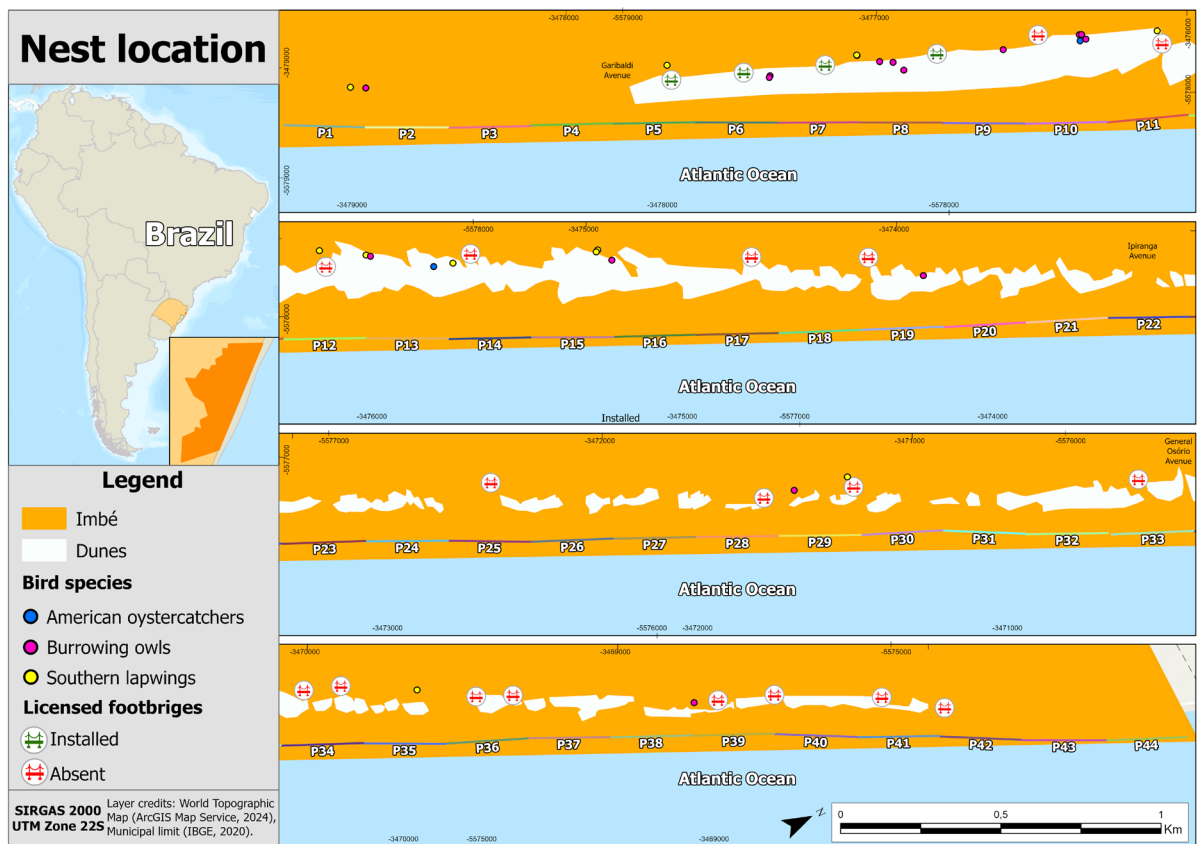


Figure 8: Spatial distribution of bird nests recorded between October and December 2022 in Imbé (RS), Brazil.

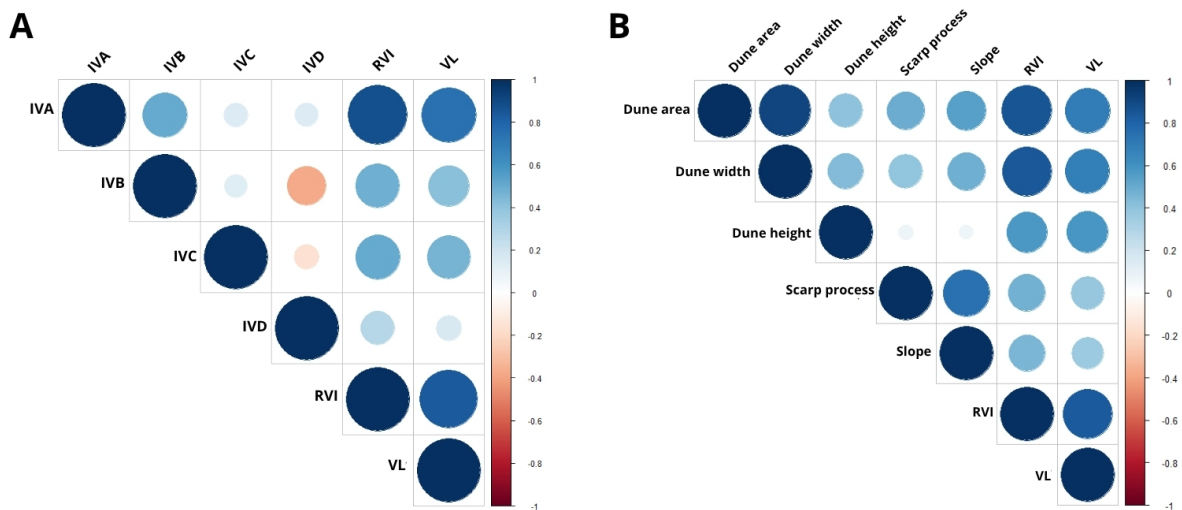


Figure 9: Pearson correlation matrix. A: correlogram showing relationships between the checklist parameters, Relative Vulnerability Index (RVI), and Vulnerability Levels (VL) along the coastline of Imbé, RS. B: Correlogram showing correlations between the individual variables of the dune morphology parameter and both RVI and VL. Checklist parameter acronyms: IVA = dune morphology; IVB = beach conditions; IVC = characteristics of the 200 m adjacent to the sea; IVD = usage pressure.

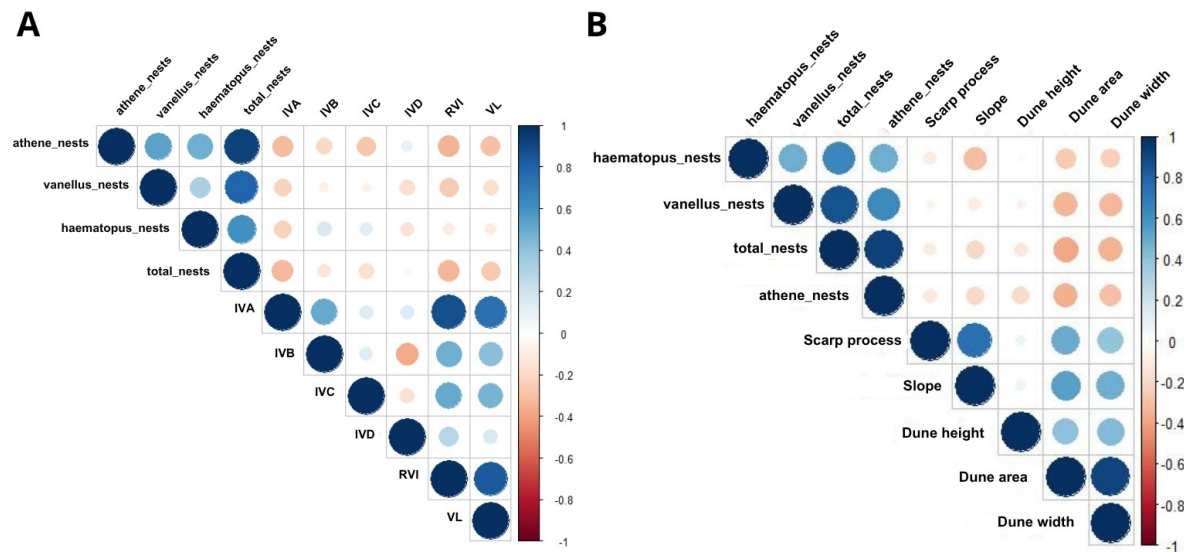


Figure 10: Pearson correlogram showing the relationships between the checklist parameters assessed in winter 2022 and the total number of bird nests, as well as nests of each species observed during spring and early summer 2022 in Imbé (RS), Brazil. B: Pearson correlogram between the individual variables of the dune morphology parameter (IVA), assessed in winter 2022, and the total and species-specific nest counts. Circle size indicates the strength of the correlation; color denotes direction, blue for positive and red for negative correlations.

4. DISCUSSION

This study provides an updated and spatially explicit diagnosis of coastal dune vulnerability in the municipality of Imbé, 12 years after the implementation of the local Dune Management Plan. The results indicate that 36% of the coastline has experienced an increase in vulnerability classification since the previous assessment, accompanied by significant changes in dune morphology and a reduction in natural buffering capacity. These findings underscore the need for periodic reassessment and offer clear evidence of ongoing degradation in dune systems. At the local scale, this research directly informs the refinement of coastal management strategies by identifying the most erosion-prone sectors and the specific vulnerability drivers in each landscape unit. More broadly, the study contributes to conceptual and methodological advancements by integrating a standardized geomorphological checklist with data on avian reproductive activity, presenting a dual-assessment approach that is both ecologically grounded and operationally feasible. Compared to widely adopted approaches such as the Coastal Vulnerability Index (Thieler & Hammar-Klose, 1999), the integrated checklist used here adds a biological dimension that captures ecosystem functionality and resilience, not just geomorphological exposure.

The importance of foredunes as natural barriers against sea level rise and storm surges is further emphasized in regional flood modeling studies for Imbé and Tramandaí. According to Silva *et al.* (2020), projected sea level rise scenarios could inundate up to 60% of the urbanized areas in these municipalities by 2100 under extreme emission trajectories. The presence and integrity of dune systems are thus crucial not only for biodiversity and sediment retention but also for reducing flood risks to coastal infrastructure and populations at different temporal scales.

The most erosion-prone coastal dune segments were concentrated at the southern and northern extremes of the municipality, where dunes had either been replaced or lost their capacity for inland migration due to public infrastructure such as boardwalks and roads (Pedroza *et al.*, 2013). In these priority areas, storm-induced erosion has already damaged access ramps, recreational decks, and roadways. In other highly vulnerable zones, such as the neighborhoods of Harmonia (P28), Mariluz Plano B (P25), and Santa Terezinha (P35–P38), the primary driver of vulnerability was dune morphology, particularly the fragmentation caused by pedestrian paths, vehicle tracks, and drainage channels. These segments also exhibited the narrowest dunes, directly related to unregulated urban encroachment (FEPAM, 2000; FEPAM, 2022; Quiroz-Villanueva *et al.*, 2022; FEPAM, 2024).

In the central part of the coastline, specifically segments P34 to P39 (Cluster 5), management interventions such as the implementation of macro-drainage studies and the fencing of pedestrian accesses are needed to support sediment retention and lateral dune recovery. In these locations, seasonal stormwater runoff intensifies lateral erosion, exacerbating the vulnerability of the dune system (Ferreira *et al.*, 2021). Elevate walkways represents a strategic tool for minimizing fragmentation while maintaining beach accessibility (Tabajara *et al.*, 2013). Until 2024, only five of twenty-two licensed and planned elevated walkways were constructed.

While Cluster 3 contains wide dunes, it is under intense human pressure due to its central location in the city. Although some elevated walkways have been installed, informal trails continue to undermine vegetation cover, especially on the seaward dune face. Nonetheless, this segment maintained a medium vulnerability classification (level 3), suggesting that moderate intervention measures such as fencing and environmental education could be sufficient to prevent further degradation. Many of the segments identified in this study as highly vulnerable had already been flagged in the 2012 Dune Management Plan (Tabajara *et al.*, 2013), which proposed, for example, sediment removal and urban cleaning instead of dune restoration. As a result, prior actions may have inadvertently reduced sediment stocks and intensified dune erosion (Seagrass, 2012). In Imara (P42–P44), no mitigation measures were implemented in the past decade, despite prior recommendations to relocate the Interpraías Road and restore the dune system. This lack of action has led to progressive erosion and infrastructure damage.

This pattern of inadequate planning aligns with findings from other studies. Pedroza *et al.* (2013) and Quiroz-Villanueva *et al.* (2022) documented similar processes on the Mexican Pacific coast, where anthropogenic infrastructure near dunes increased erosion by disrupting sediment dynamics and fragmenting vegetation. These parallels reinforce the conclusion that ineffective coastal management can directly exacerbate natural vulnerability, leading to irreversible ecosystem degradation.

Although the classification of most units did not change significantly between seasons, cluster composition varied, particularly in response to the “use pressure” parameter (D), which is influenced by seasonal population growth due to tourism. Parameters related to dune morphology and beach conditions (A and B) remained relatively stable, likely due to sediment accretion during summer months (Weschenfelder & Zouain, 2002; Martinho *et al.*, 2010). However, the distribution

of beach kiosks and pedestrian access varied considerably between seasons, altering the clustering of units. Summer clusters revealed spatial standardization in use profiles of contiguous units, while winter data provided a clearer picture of structural vulnerability in the absence of high tourist pressure. This highlights the robustness of the checklist as a tool that incorporates both environmental and cultural seasonality, while also indicating the importance of incorporating additional variables, such as tourism intensity, to capture finer seasonal dynamics (Ciccarelli *et al.*, 2017; Barros & Baldraia, 2023).

One of the key innovations of this study was integrating ecological indicators into vulnerability assessment. The correlation between dune morphology and nesting distribution supports the interpretation that dune area and width are limiting factors for avian reproductive success, as narrower and more fragmented dunes hosted fewer nests. Most nests were concentrated in the southern half of the study area, which had the broadest and least disturbed dunes. Among the species observed, *Athene cunicularia* (burrowing owl) emerged as the most promising bioindicator, given its nesting fidelity, preference for nest building in dunes, and tolerance to moderate human disturbance (Orsi *et al.*, 2021; CEMAVE, 2025a). In contrast, *Vanellus chilensis* (southern lapwing) nested opportunistically in more urbanized areas, and *Haematopus palliatus* (American oystercatcher) was observed in insufficient numbers to support firm conclusions (McGowan & Simons, 2006; Nol & Humphrey, 2012; Delfino & Carlos, 2020; CEMAVE, 2025b; CEMAVE, 2025c).

These findings are consistent with the broader literature on habitat compression and reproductive avoidance by sensitive coastal bird species (Gjerdrum *et al.*, 2005; Defeo *et al.*, 2009; Canabarro & Fedrizzi, 2010). Therefore, it is proposed that long-term monitoring of *A. cunicularia* nesting activity could serve as a proxy for assessing the evolution of dune vulnerability. Since these birds often reuse nesting burrows across reproductive cycles, mapping and revisiting these sites offer a cost-effective alternative to repeated application of the full checklist method. Additionally, targeted studies in areas with higher densities of *H. palliatus* could clarify its utility as a complementary indicator species (Nol & Humphrey, 1994; Sanders *et al.*, 2004).

Despite its utility, the proposed method may have limited applicability in coastal systems with high tidal amplitude or sediment dynamics strongly influenced by estuarine inputs. In such contexts, tidal variation can significantly alter dune-beach interactions, influencing sediment supply and wave energy, and should be considered in future adaptations of the checklist

(Williams *et al.*, 1993; Fairley *et al.*, 2020). Likewise, future refinements could benefit from incorporating more precise proxies for human pressure, such as visitation frequency, spatial intensity of foot traffic, or metrics of tourist infrastructure density (Ciccarelli *et al.*, 2017).

Finally, this study highlights the importance of coastal governance and the effectiveness of simple structural interventions. The installation of walkways not only reduces dune fragmentation but also enhances habitat availability for nesting birds. Conversely, unmanaged pedestrian access contributes to erosion through the formation of stormwater runoff paths. These findings suggest that relatively low-cost interventions, when strategically implemented, can yield significant conservation benefits. As sea level rise and coastal urbanization intensify globally, integrating biotic indicators into standard vulnerability assessments may enhance our ability to monitor and manage the resilience of sandy beach ecosystems (IBGE, 2023; IPCC, 2022; Silva *et al.*, 2023; Cosby *et al.*, 2024).

5. CONCLUSIONS

This study demonstrates that the municipality of Imbé is undergoing a progressive degradation of its coastal dune systems, with 36% of the evaluated segments showing increased vulnerability over the past decade. The combination of a standardized geomorphological checklist and avian nesting data enabled the identification of both structural and ecological indicators of vulnerability, with particular emphasis on dune width, fragmentation, and the spatial distribution of nests by species with different sensitivities to human presence. Among them, *Athene cunicularia* proved to be a reliable and low-cost bioindicator for long-term monitoring.

The findings reinforce the relevance of dune systems not only as ecological assets but also as critical infrastructure for climate adaptation, especially in light of projected sea level rise and flood risk scenarios for the region. The integration of biotic and abiotic metrics within vulnerability assessments is shown to be a valuable approach for improving coastal zone planning and prioritizing management interventions.

In practical terms, this study provides updated spatial information that can support the revision of the local Dune Management Plan and the implementation of targeted measures such as the installation of elevated walkways, restriction of informal access paths, and restoration of fragmented dune stretches. As coastal pressures intensify across the globe,

the methodology and insights presented here may serve as a replicable model for other sandy beach environments facing similar socio-environmental challenges.

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SUPPLEMENTARY MATERIAL

Table S1. Code and UTM coordinates of the evaluated landscape sampling units (from P01 to P44).

Landscape sampling unit code	Start coordinates	End coordinates	Landmark
P01	22J 584950 6683627	22J 585089 6683755	Beira Mar Ave. - Bent Gonçalves St.
P02	22J 585089 6683755	22J 585198 6684001	Bent Gonçalves St. - Castelo Branco St.
P03	22J 585198 6684001	22J 585281 6684246	Castelo Branco St. - Santa Rosa Ave.
P04	22J 585281 6684246	22J 585363 6684461	Santa Rosa Ave. - Garibaldi Ave.
P05	22J 585363 6684461	22J 585445 6684707	Garibaldi Ave. - between the first and second elevated walkways
P06	22J 585445 6684707	22J 585527 6684953	Between the first and second elevated walkways - Between the second and third elevated walkways
P07	22J 585527 6684953	22J 585609 6685167	Between the second and third elevated walkways - Secret kiosk
P08	22J 585609 6685167	22J 585718 6685413	Secret kiosk - Carazinho Ave.
P09	22J 585718 6685413	22J 585801 6685658	Carazinho Ave. - near Não-Me-Toque Ave.
P10	22J 585801 6685658	22J 585883 6685873	Near Não-Me-Toque Ave. - the end of the Las Olas apartment complex
P11	22J 585883 6685873	22J 585992 6686150	The end of the Las Olas apartment complex - near Tancredo Neves Ave.
P12	22J 585992 6686150	22J 586074 6686334	Atlântida Ave.
P13	22J 586074 6686334	22J 586156 6686518	Presidente district
P14	22J 586156 6686518	22J 586265 6686794	Presidente district
P15	22J 586265 6686794	22J 586348 6687039	Presidente district
P16	22J 586348 6687039	22J 586430 6687254	Rivera district
P17	22J 586430 6687254	22J 586539 6687500	Ipiranga district
P18	22J 586539 6687500	22J 586621 6687715	Ipiranga District
P19	22J 586621 6687715	22J 586757 6687960	Ipiranga Ave. - near Nordeste Ave.
P20	22J 586757 6687960	22J 586839 6688175	Mariluz District
P21	22J 586839 6688175	22J 586948 6688389	Salvador do Sul St. - Alegrete St.
P22	22J 586948 6688389	22J 587057 6688635	Monteiro Lobato St.
P23	22J 587057 6688635	22J 587140 6688880	Mariluz Ave.
P24	22J 587140 6688880	22J 587249 6689095	Campo Bom St.
P25	22J 587249 6689095	22J 587331 6689341	Estrela St.
P26	22J 587331 6689341	22J 587440 6689524	Mariluz Plano B district
P27	22J 587440 6689524	22J 587549 6689801	Mariluz Plano C district
P28	22J 587549 6689801	22J 587631 6690015	Harmonia district
P29	22J 587631 6690015	22J 587713 6690230	Mariluz Norte district
P30	22J 587713 6690230	22J 587823 6690476	Harmonia Ave. - Mariluz Norte Ave.
P31	22J 587823 6690476	22J 587932 6690690	Albatroz district
P32	22J 587932 6690690	22J 588041 6690905	Albatroz district
P33	22J 588041 6690905	22J 588123 6691181	Marisul district
P34	22J 588123 6691181	22J 588205 6691396	Travessa 1 St. - General Osório Ave.
P35	22J 588205 6691396	22J 588314 6691611	General Osório Ave. - Pedro Alves St.
P36	22J 588314 6691611	22J 588397 6691856	Pedro Alves St. - Camargo St.
P37	22J 588397 6691856	22J 588479 6692102	Camargo St. - Capitão Manna St.
P38	22J 588479 6692102	22J 588615 6692316	Capitão Manna St. - Farroupilha St.
P39	22J 588615 6692316	22J 588697 6692562	Farroupilha St. - Piscinas's Bar
P40	22J 588697 6692562	22J 588780 6692777	Piscinas's Bar - near Parque Pajé
P41	22J 588780 6692777	22J 588889 6693022	Near Parque Pajé - Tapuia Ave.
P42	22J 588889 6693022	22J 588998 6693237	Tapuia Ave. - near Padre Cacique St.
P43	22J 588998 6693237	22J 589107 6693451	Estrada Interprias
P44	22J 589107 6693451	22J 589161 6693508	Estrada Interprias - municipal boundary sign

Table S2. Code and UTM coordinates of the nesting sites.

UTM E (m)	UTM N (m)	Species	Landscape sampling unit code
585524	6685001	<i>Athene cunicularia</i>	P07
585527	6684997	<i>Athene cunicularia</i>	P07
585622	6685326	<i>Athene cunicularia</i>	P08
585640	6685362	<i>Athene cunicularia</i>	P08
585672	6685381	<i>Athene cunicularia</i>	P08
585800	6685921	<i>Vanellus chilensis</i>	P10
585798	6685919	<i>Athene cunicularia</i>	P10
585800	6685925	<i>Athene cunicularia</i>	P10
585817	6685931	<i>Athene cunicularia</i>	P10
586022	6686458	<i>Vanellus +chilensis</i>	P13
586030	6686468	<i>Athene cunicularia</i>	P13
586131	6686630	<i>Haematopus palliatus</i>	P13
586146	6686689	<i>Vanellus chilensis</i>	P14
586289	6687110	<i>Vanellus chilensis</i>	P15
586331	6687135	<i>Athene cunicularia</i>	P16
587651	6690166	<i>Athene cunicularia</i>	P29
588625	6692434	<i>Athene cunicularia</i>	P39
585580	6685271	<i>Vanellus chilensis</i>	P08
585578	6685271	<i>Vanellus chilensis</i>	P08
585742	6685686	<i>Athene cunicularia</i>	P09
586745	6687981	<i>Athene cunicularia</i>	P19
585045	6683817	<i>Vanellus chilensis</i>	P01
588259	6691681	<i>Vanellus chilensis</i>	P35
585955	6686334	<i>Vanellus chilensis</i>	P12
585883	6686141	<i>Vanellus chilensis</i>	P11
586292	6687103	<i>Vanellus chilensis</i>	P15
585065	6683859	<i>Athene cunicularia</i>	P01
585374	6684729	<i>Vanellus chilensis</i>	P05
587682	6690333	<i>Vanellus chilensis</i>	P29
585814	6685912	<i>Haematopus palliatus</i>	P10

Landscape unit:

Reference point and/or coordinates

Section A - Dune Morphology					
	0	1	2	3	4
1 Dune surface area (m²)	>10000 []	> 7500 []	> 5000 []	> 2500 []	< 2500 []
2 Dune width (m)	> 50 []	> 40 []	> 30 []	> 20 []	> 10 []
3 Height of the tallest dune (m)	> 5 []	> 4 []	> 3 []	> 2 []	< 1 []
4 Scarp process	low []		moderate []		high []
5 Slope on the marine-facing side	smooth []		moderate []		marked []
TOTAL SCORE:					
Section B - Backshore Condition					
	0	1	2	3	4
1 Backshore width (m)	>100 []	> 80 []	> 60 []	> 40 []	<40 []
2 Sand supply	alto []		moderate []		low []
3 Breaches in the beach face	none []		some []		many []
4 Width of breaches	< 2 []		2 - 10 []		>10 []
5 Embryonic dunes	many []		some []		few []
TOTAL SCORE:					
Section C - Characteristics of the 200 m adjacent to the sea					
	0	1	2	3	4
1 Blowout areas (%)	< 5 []	> 5 []	> 10 []	> 20 []	>40 []
2 Sand loss to the continent	little []		some []		much []
3 Breaches in the dune system (%)	>0 []	> 5 []	> 25 []	>50 []	> 70 []
4 Vegetation on the seaward side (%)	>90 []	>60 []	> 30 []	>10 []	<10 []
5 Recent sand deposition	much []		some []		none []
6 Impermeable coverage (%)	little []		some []		a lot []
7 Presence of exotic vegetation	none []		some []		many []
8 Number of runoff outlets	0 []		1 []		2 or + []
TOTAL SCORE:					
Section D - Usage Pressure					
	0	1	2	3	4
1 Number of vehicle access points	0 []	1 []	2 []	3 []	4 []
2 Pedestrian path density	low []		medium []		high []
3 Stage of urbanization	none []	rustic []	horizontal []	mixed []	vertical []
4 Percentage of urbanization	<10 []	>10 []	30 - 50 []	>50 []	>70 []
5 Urbanization position	without []	final third []	post dune []	foredune []	backshore []
6 Number of kiosks	0 []	1 - 2 []	3 - 5 []	6 - 8 []	9 - 10 []
7 Number of property owners	one []		some []		many []
TOTAL SCORE:					

Figure S1. Checklist method proposed by Williams et al. (1993) and adapted by Tabajara et al. (2013).

