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Papers

The Dunes Contribution to the Ecosystem Service of Coastal Protection on the Northern Coast of RS

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Abstract

Coastal dunes have a crucial role in offering the ecosystem service of natural coastal protection. This paper investigates the importance of dunes in providing the ecosystem service of natural coastal protection on the North Coast of the State of Rio Grande do Sul (RS) in southern Brazil. The *Integrated Valuation of Ecosystem Services and Tradeoffs* (*InVEST®) Coastal Vulnerability Model* was used to quantify the relative susceptibility to coastal erosion and flooding within the study area. First, the model was run to assess the susceptibility to coastal hazards considering the presence of dunes. Then, the model was run again without the presence of dunes. By comparing the results of the two model simulations, it was possible to identify where dunes contribute to reducing coastal exposure, which indirectly reflects their role in providing the ecosystem service of natural coastal protection. There are two main dune fields in the study area, one in the northern coastal sector and one in the southern sector, respectively in the municipalities of Torres and Cidreira. The index of exposure values produced by the two model simulations were very similar for locations along the Torres coastline. In contrast, along the coast of Cidreira, results from the model simulation without dunes produced higher exposure values than the simulation with the presence of dunes, suggesting that the dunes have an important role in offering natural coastal protection. Dunes are a natural barrier against coastal erosion and flooding, but they are not the only factor influencing the ecosystem service of coastal protection. In Torres, for instance, the local topography and the wind patterns contribute to reducing local exposure. The greatest threat in this sector is the urban sprawl.

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INTRODUCTION

Coastal erosion is a problem worldwide (Nguyen *et al.*, 2016), which has worsened due to rising sea levels, climate change and increased population density in coastal areas (Luijendijk *et al.*, 2018; Prates *et al.*, 2012).

Coastal habitats, including dunes and beaches, offer important ecosystem services, such as coastal protection, as they act as natural barriers against high wave energy and water levels, reducing erosion and flooding impacts. They also provide other ecosystem services of economic importance, such as tourism, recreation and amenity value (Alexandrakis *et al.*, 2015; Gopalakrishnan *et al.*, 2011; Landry *et al.*, 2020).

The artificialization or removal of dunes result in ecosystem services loss, increasing the susceptibility of low-lying areas to flooding, which can cause damage to seafront properties and infrastructure, leading to economic loss (Alexandrakis *et al.*, 2015; Gopalakrishnan *et al.*, 2011; Landry *et al.*, 2020; Martinho *et al.*, 2010; Tomazelli *et al.*, 2008).

The artificialisation of dunes or their replacement for hard engineering structures, such as seawalls and revetments, can reduce the aesthetic quality of the seafront and interfere with coastal processes in ways that enhance beach erosion in front and downdrift of the structures (Esteves; Santos, 2002; Huang *et al.*, 2007; Gopalakrishnan *et al.*, 2011; Landry; Hindsley, 2011).

In locations where the presence of dunes contributes to reducing exposure to coastal hazards, their absence is then likely to increase local physical vulnerability (Nguyen *et al.*, 2016; Romieu *et al.*, 2010). The loss of natural coastal protection is particularly concerning in less economically developed countries, where the most vulnerable people often occupy hazard-prone areas (Bonetti *et al.*, 2013; Cutter *et al.*, 2003; Kleinosky *et al.*, 2007; Masozera *et al.*, 2007).

Many indicators have been used to assess coastal vulnerability (Nguyen *et al.*, 2016), often aggregated in a coastal vulnerability index. The composition of coastal vulnerability indices can be complex as they integrate indicators of exposure, vulnerability and adaptive capacity (BID, 2010).

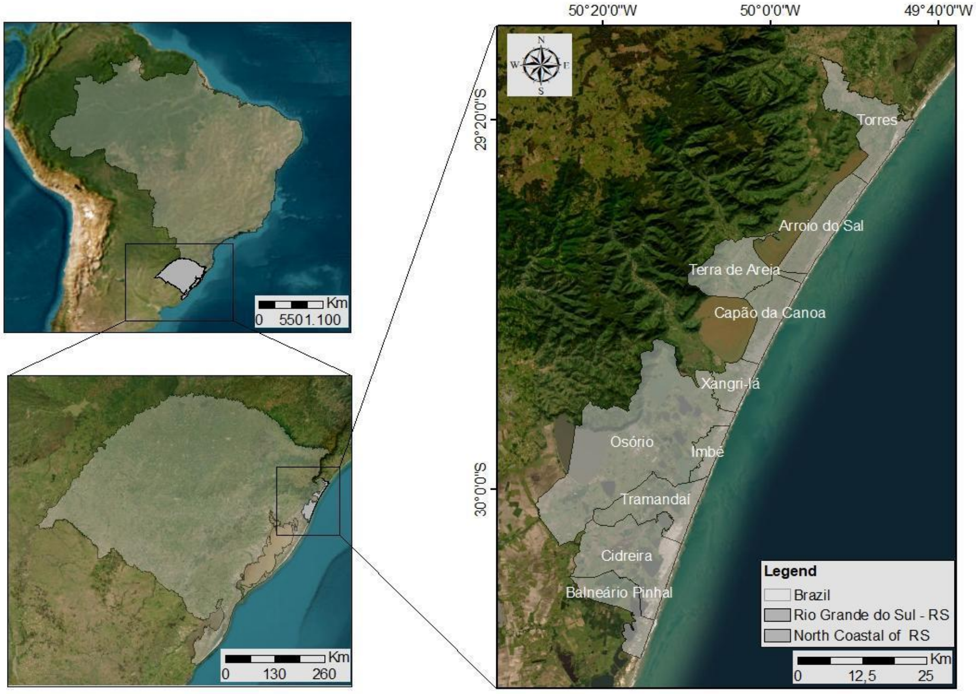
The suite of open-source models offered by the *Integrated Valuation of Ecosystem Services and Tradeoffs* (*InVEST®) includes the Coastal Vulnerability* model (Invest, 2023), which has been applied at a range of scales to produce a coastal vulnerability index and assess the role of coastal ecosystems in reducing exposure to coastal hazards, such as erosion and flooding (Ballesteros; Esteves, 2021; Ruheili; Boluwade, 2023; Zhang *et al.*, 2020).

This study uses the *InVEST Coastal Vulnerability* model to assess the importance of dunes in providing the ecosystem service of natural coastal protection along the North Coast of the State of Rio Grande do Sul (RS) in southern Brazil. This is achieved by comparing the results of a model simulation that includes the presence of dunes with another that disregards the presence of dunes.

STUDY AREA

The North Coast of the State of RS consists of ten coastal municipalities: Balneário Pinhal, Cidreira, Tramandaí, Imbé, Osório, Xangri-Lá, Capão da Canoa, Terra de Areia, Arroio do Sal and Torres (Figure 1).

Figure 1 - Location of the municipalities within the study area on the North Coast of the State of Rio Grande do Sul (RS) in southern Brazil.



Source: The authors (2023).

The study area sits between 29º17' and 30º18' latitude South and between 49º44' and 50º24' longitude West. It is delimited in the south by the boundary of Balneário Pinhal and in the north by the Mampituba River, which marks the northern boundary of the state of RS. The South Atlantic Ocean lies to the east of the study area and the western boundary is shaped by changes in geology, topography and drainage system that define the municipalities' administrative boundaries (FEPAM, 2000). Together, these coastal municipalities have a total area of 3,700 km² and a shoreline length of 120 km, about one-fifth of the RS shoreline, which is about 618 km long (FEPAM, 2000, 2021a, 2021b).

The North Coast of RS was formed mostly in the late stages of the Quaternary Period, associated with a depositional lagoon-barrier system known as Barrier IV, which developed in the final stages of the last post-glacial marine transgression in the Holocene, around 5,000 years BCE (Dillenburg *et al.*, 2000).

Regarding demographic characteristics, the North Coast of RS is dominantly urbanised, with an estimated fixed population of 198.235 inhabitants, which increased by 25.38% in the last decade (IBGE, 2022). In the summer, the seasonal population reaches 340.436 inhabitants due to the flow of tourists and second homeowners in search of sun and sea (Germani *et al.*, 2020; Rio Grande do Sul, 2021).

In 2021, real estate sales increased considerably in some municipalities, such as a 65% rise in Torres, 50% rise in Imbé and 34% increase in Tramandaí (Rodrigues, 2020). The real estate boom is noticed in the expansion and density of the urban fabric of these municipalities (IBGE, 2023). The processes of population growth and urban expansion led to urbanisation and beachfront development along more than 77% of the coastline length, with 55% of the buildings located in dune areas (Esteves *et al.*, 2003; Esteves, 2004).

Factors such as urbanisation, associated with changes in soil compaction and infiltration rates, the concentration of drainage creeks around the coastline and an increasing frequency of storms and floods are contributing to coastal erosion on the North Coast of RS. These changes are leading to the loss of frontal dunes and higher water table levels (Calliari *et al.*, 2010; Vianna *et al.*, 2015), which enhance the risk of flooding.

MATERIALS AND METHODS

Model description and application

This study used the *InVEST Coastal Vulnerability Model* (version 3.12.1) to produce a relative index of exposure to coastal erosion and flooding for the study area and to estimate the population in areas categorised as showing higher exposure levels. The index calculates a ranking that identifies the locations that have relatively higher or lower susceptibility to coastal erosion or flooding when compared to other locations within the study area (Invest, 2023).

The model follows the approach used in the widely used coastal vulnerability index methods proposed by Gornitz (1990) and Hammar-Klose and Thieler (2001). However, the InVest exposure index innovates by allowing to account for the natural protection offered by the presence of coastal habitats. Therefore, the model indirectly maps the ecosystem service of coastal protection, where the higher the index of exposure ranking, the lower the supply of the ecosystem service of coastal protection.

The InVEST index of exposure allows the integration of seven biogeophysical variables: natural habitats, relief (in the form of a digital elevation model), wind exposure, wave exposure, storm surge potential, geomorphology (following Hammar-Klose and Thieler, 2001) and sea level change. The values of each variable are categorised into five classes ranked from 1 to 5, representing very low to very high exposure, respectively. The exposure index is the geometric mean of these rankings.

Data sources and structure

The input data for the InVEST Coastal Vulnerability model, as well as the variables used for the input data and their sources are illustrated below (Table 1). The ranking of the input variables, the ranking with the respective values, is available below (Table 2). The ranking and classification of the input data variables were based on the InVEST coastal vulnerability model guide (Invest, 2023).

Table 1 - Input variables required by the *InVEST* Coastal Vulnerability model, data used and sources.

Input variables	Data used	Data sources
Area of Interest (Vector) and Landmass (Vector)	Administrative boundaries of the municipalities in the North Coast of RS (Balneário Pinhal, Cidreira, Tramandaí, Imbé, Osório, Xangri-lá, Capão da Canoa, Terra de Areia, Arroio do Sal and Torres)	Instituto Brasileira de Geografia e Estatística (IBGE, 2020), the national agency for geographical and statistical data.
Winds and waves	Standard wind and wave data compiled from 8 years of WAVEWATCH III	Data available from the InVEST download package (2022).
Bathymetry (Raster)	Bathymetric data, 15 arcseconds (~450 meters)	Data used from Gridded Bathymetry - GEBCO (2022).
Relief (Raster)	Digital Elevation Model	Data from the United States Geological Survey - USGS (2020).
Edge of the continental shelf contour (Vector)	180m of continental shelf	Mapped by the authors based on studies by Calliari *et al.* (2009) and Castro *et al.* (2006).
Habitats and Geomorphology (csv and Vector)	Classification table (csv) of habitats and geomorphology (rank classification in Table 3), with their protection distance in meters, and with the corresponding Vector (shapefile separated polygons)	Data from the Economic Ecological Zoning of the State of RS
Population (Raster)	Average population density (people per square kilometer), 30m resolution	Data from the 2010 Census, available on Geoserver (2020).

Source: The authors (2023).

Table 2 - Ranking of exposure level according to the values of the biogeophysical variables.

Ranking	1 (very low)	2 (low)	3 (moderate)	4 (high)	5 (very high)
Geomorphology	----------	Medium cliff	Coastal plain	Lagoon	Beach
Relief	81 to 100 Percentile	61 to 80 Percentile	41 to 60 Percentile	21 to 40 Percentile	0 to 20 Percentile
Habitats	Coastal forests	Marshland	Low dunes	----	No habitat
Wave and Wind Exposure	0 a 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	80 to 100 Percentile
Storm Surge Potential	0 a 20 Percentile	21 to 40 Percentile	41 to 60 Percentile	61 to 80 Percentile	81 to 100 Percentile

Source: Adapted from the InVEST Coastal Vulnerability Model user guide (Invest, 2023).

The simulations did not include sea level change due to limited spatial data coverage, which prevents the use of this variable to assess relative differences across locations within the study area. The wind exposure is an index that combines, for 16 equiangular sectors of the compass rose, fetch distance, the mean wind speed of the 10% highest measured values over a relatively long time series and the percentage of all wind speeds that blow in the direction of each sector (Invest, 2023).

The natural habitats mapping was obtained from the Economic Ecologic Zoning (EEZ) of the RS (Table 1). The ranking values attributed to natural habitats can be defined by the user. Here, the habitat 'coastal forests', which include riparian and silviculture woodlands, received a ranking value of 1, marshlands were ranked 2, low dunes were ranked 3 and absence of habitats was ranked 5, representing the highest level of exposure (Table 2), or the lowest level of natural protection.

The type of geomorphology was also obtained from the EEZ, except for the medium cliffs, which were digitised by the authors based on information presented in the EEZ. As medium cliffs represent relatively higher ground, they were ranked 2 due to lower susceptibility to flooding, while coastal plains were ranked 3, lagoons 4 and beaches 5 (Table 2). Data manipulation was undertaken in ArcGIS/ArcMap version 10.5.1. RStudio software, version 4.1.0, was used for the statistical analysis of the results used in the graphs.

Assessing the role of dunes in reducing coastal erosion and flooding risk

To assess the role of dunes in reducing exposure to erosion and flooding, the Coastal Vulnerability model was run twice. The first simulation calculated the index of exposure, considering the presence of dunes. Then, the model was run again, this time without the presence of dunes. The dunes were considered to have a role in coastal protection at the locations where the index of exposure was higher in the simulation without dunes than in the simulation with dunes. This approach enabled the identification of the importance of dunes in reducing the susceptibility to erosion and flooding along the North Coast of RS.

RESULTS

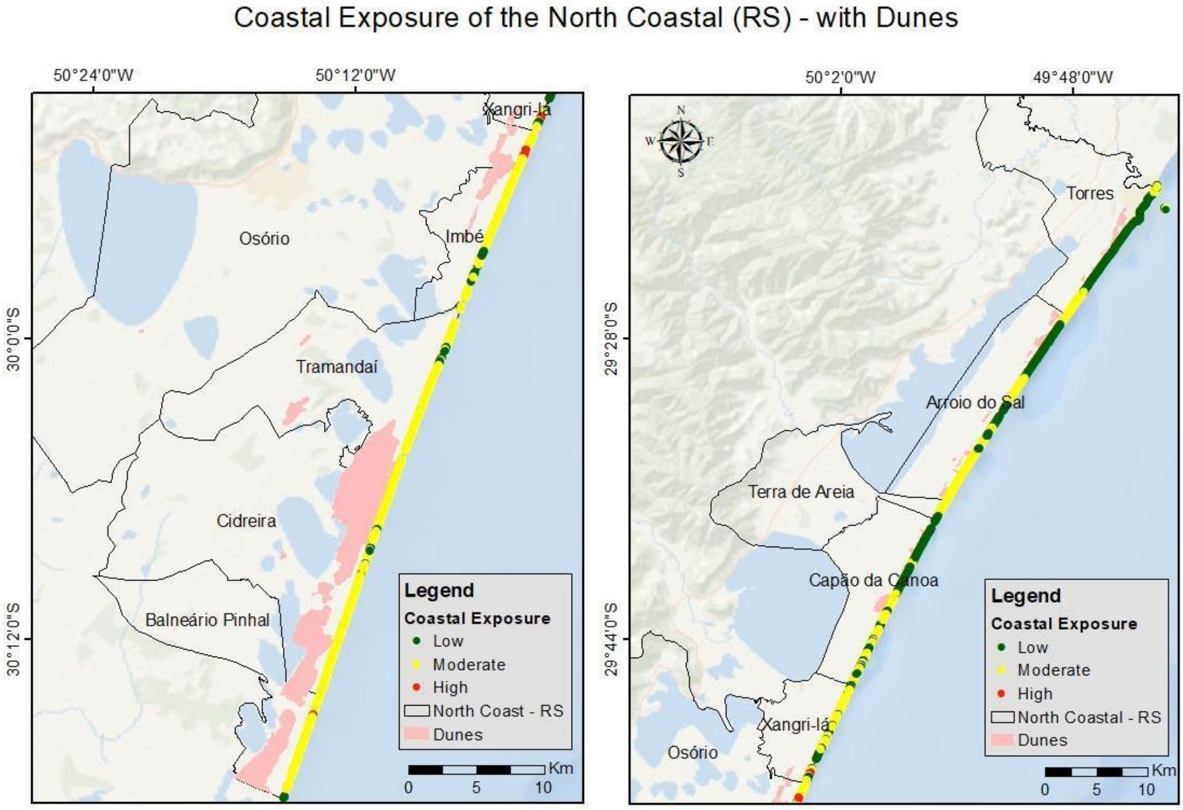
Using the Coastal Vulnerability model, 3736 points were plotted, 30 meters apart, along the coastline of the northern coast of RS. The results of the risk values for coastal exposure to erosion and flooding, considering the presence of dunes as an input variable, are illustrated below (Table 3, Figure 2, Figure 3 and Figure 4).

Table 3 - Percentage of the shoreline length ranked as showing low, moderate and high relative levels of exposure to erosion and flooding per coastal municipality, considering the presence of dunes.

Municipality	Low (%)	Moderate (%)	High (%)	Total number of points
Balneário Pinhal	3.81	94.07	2.12	236
Cidreira	4.84	95.16	---	537
Tramandaí	8.62	91.38	---	406
Imbé	11.76	88.24	---	289
Osório	---	84.09	15.91	88
Xangri-lá	29.03	67.10	3.87	310
Capão da Canoa	53.46	46.54	---	578
Terra de Areia	21.05	78.95	---	76
Arroio do Sal	44.38	55.62	---	685
Torres	78.91	21.09	---	531
Total	33.24	65.93	0.83	3736

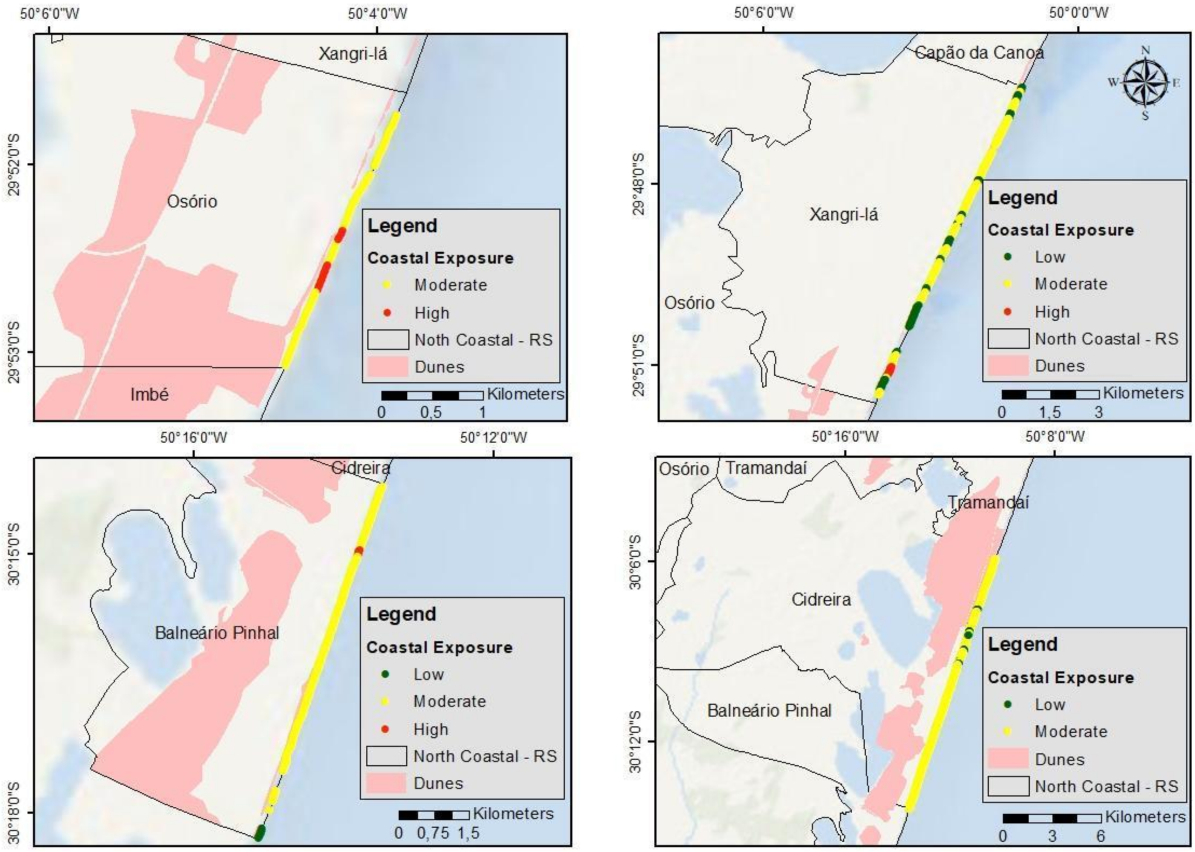
Source: The authors (2023).

Figure 2 - Spatial distribution of coastal erosion and flooding exposure levels along the southern (left) and northern (right) sectors of the North Coast of RS, considering the presence of dunes.



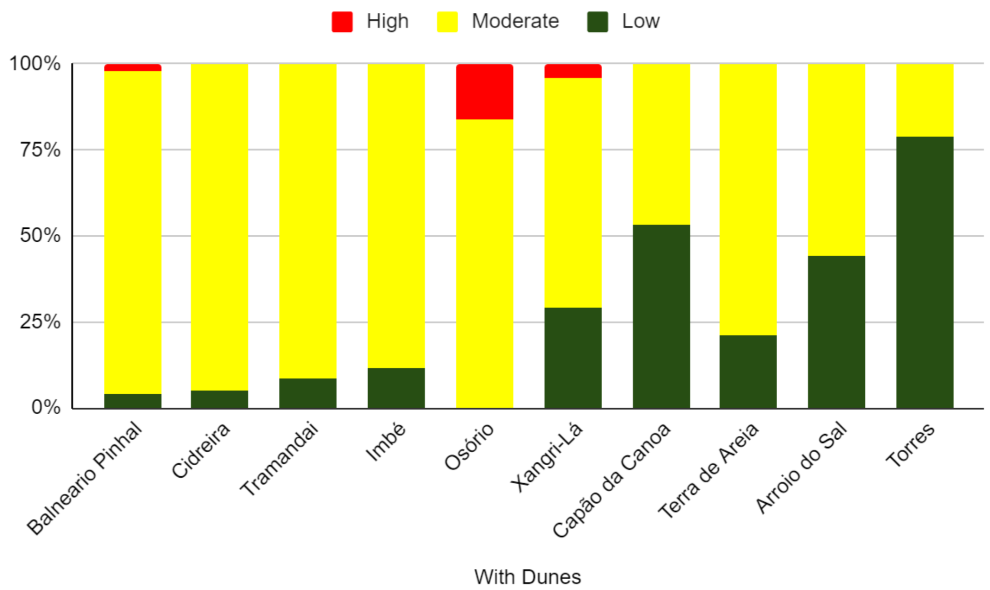
Source: The authors (2023).

Figure 3 - Spatial distribution of coastal erosion and flooding exposure levels along the coast of (a) Osório, (b) Xangri-lá, (c) Balneário Pinhal and (d) Cidreira, considering the presence of dunes.



Source: The authors (2023).

Figure 4 - Distribution of low, moderate and high relative exposure levels in the municipalities on the North Coast of RS (as a percentage of the shoreline length), considering the presence of dunes.



Source: The authors (2023).

Results from the simulation excluding the presence of dunes (Table 4, Figures 5, 6 and 7) show an increase in the relative exposure levels in most municipalities when compared with the simulation without dunes. The exceptions were Imbé and Osório, where no changes were observed. Across the study area, an additional 198 points were ranked as high exposure and 64 points were added to the moderate exposure ranking, representing an increase of 5.3% and

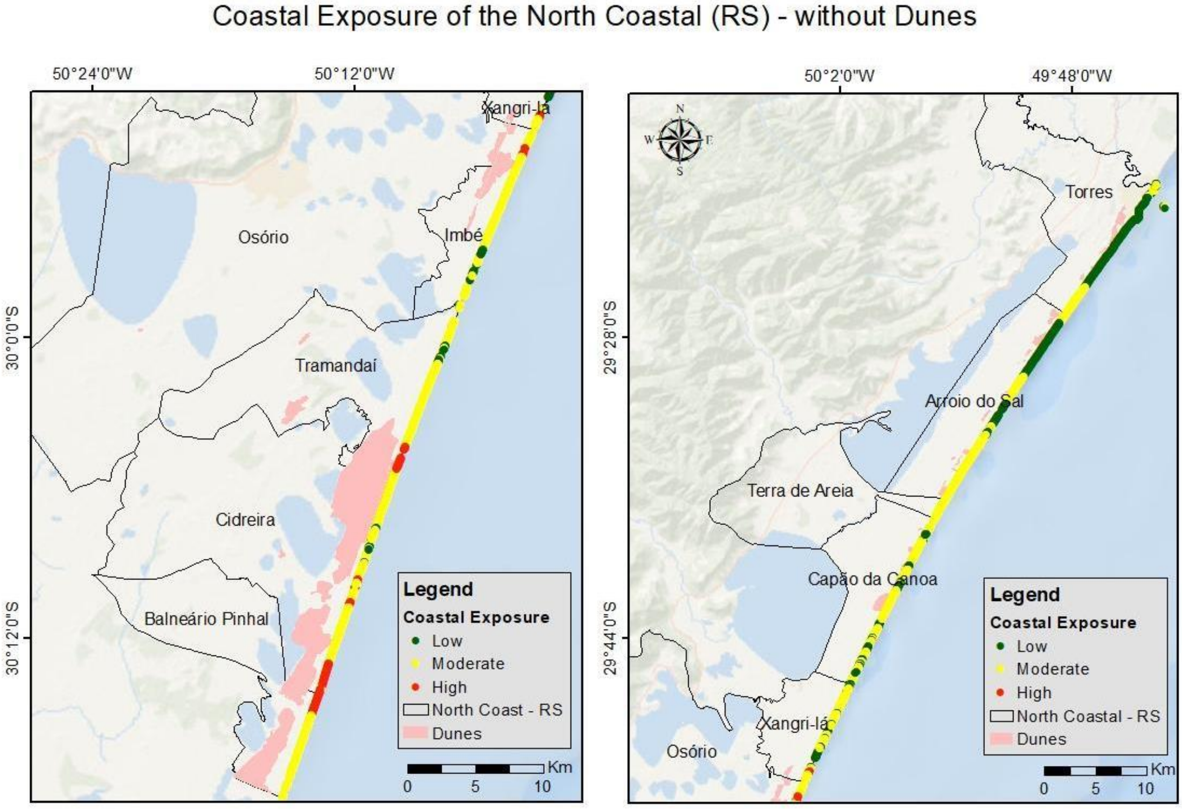
1.71%, respectively. Consequently, there was a proportional reduction in the number of points ranked as low exposure, as a total of 262 points (or 7.01%) had their index of exposure upgraded in the simulation without dunes.

Table 4 - Percentage of the shoreline length ranked as showing low, moderate and high relative level of exposure to erosion and flooding per coastal municipality, excluding the presence of dunes.

Municipality	Low (%)	Moderate (%)	High (%)	Total number of points
Balneário Pinhal	---	77.54	22.46	236
Cidreira	3.54	76.54	19.93	537
Tramandaí	8.37	81.03	10.59	406
Imbé	11.76	88.24	---	289
Osório	---	84.09	15.91	88
Xangri-lá	24.52	71.61	3.87	310
Capão da Canoa	21.11	78.89	---	578
Terra de Areia	---	100	---	76
Arroio do Sal	42.92	57.08	---	685
Torres	75.52	24.48	---	531
Total	26.23	67.64	6.13	3736

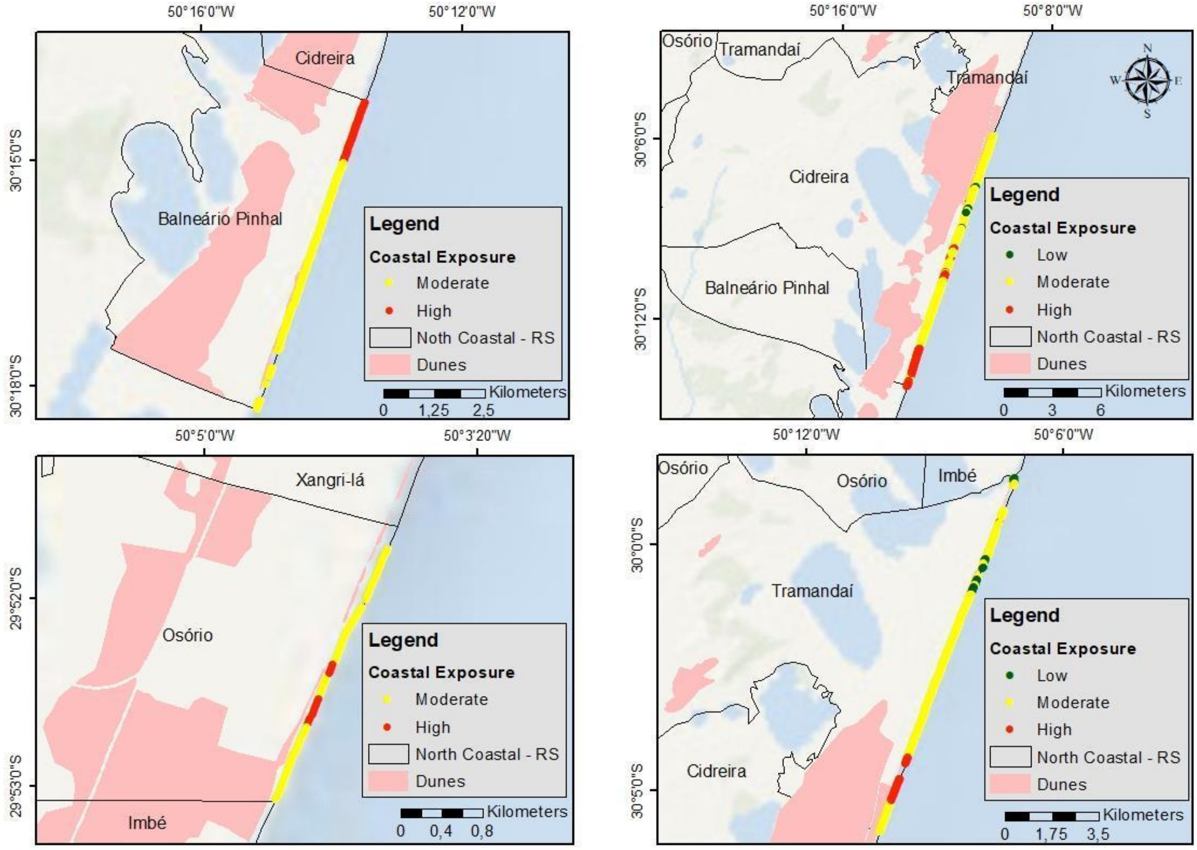
Source: The authors (2023).

Figure 5 - Spatial distribution of coastal erosion and flooding exposure levels along the southern (left) and northern (right) sectors of the North Coast of RS, excluding the presence of dunes.



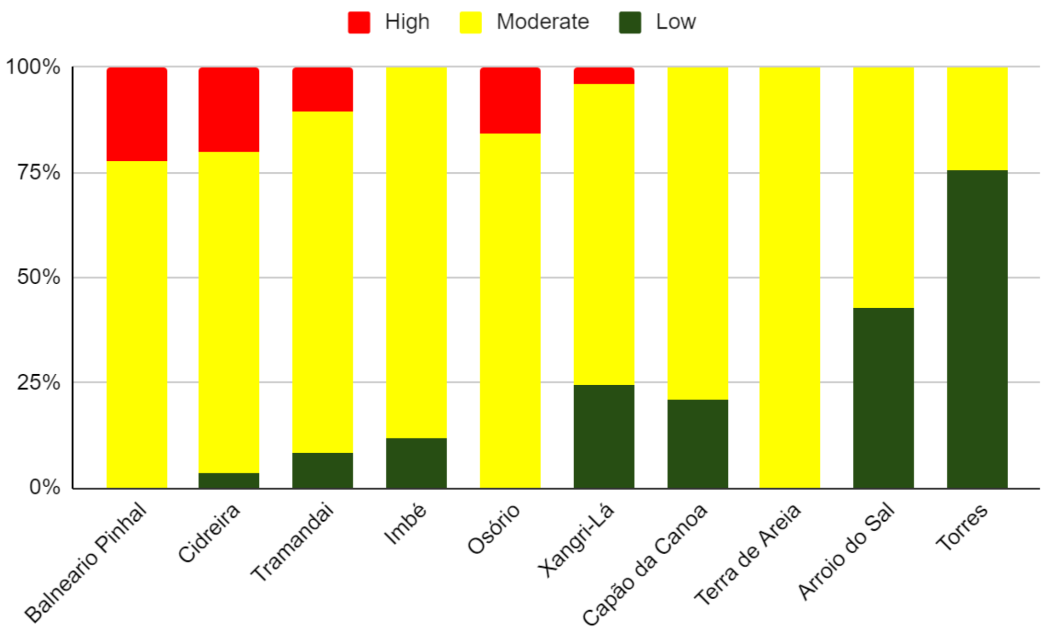
Source: The authors (2023).

Figure 6 - Spatial distribution of coastal erosion and flooding exposure levels along the coast of (a) Osório, (b) Xangri-lá, (c) Balneário Pinhal and (d) Cidreira, excluding the presence of dunes.



Source: The authors (2023).

Figure 7 - Distribution of low, moderate and high relative exposure levels in the municipalities on the North Coast of RS (as a percentage of the shoreline length), excluding the presence of dunes



Source: The authors (2023).

DISCUSSION

The simulations with and without the presence of dunes showed that dunes play an important role in reducing exposure to coastal erosion and flooding, especially in the southern portion, between Imbé and Balneário Pinhal, on the northern coast of RS.

The mapping of the dunes highlighted discontinuities in the dune systems along the study area's coastline. Analysis of historical records (mainly aerial photography) indicated that this coast was characterised by extensive and connected transgressive dune fields (Martinho *et al*., 2010; Tomazelli *et al*., 2008). The continuity of the dune system is better preserved in the municipalities of Terra de Areia and Arroio do Sal. The urbanisation process undergoing in the area is evident in the IBGE/2022 urban land cover data (IBGE, 2023). This is one of the factors affecting the integrity of the dune fields, by interrupting or reducing the sediment supply that contributed to the formation and maintenance of the beach-dune systems along this coast (Martinho *et al*., 2010; Tomazelli *et al*., 2008). Urbanisation has also interfered with the natural drainage system, resulting in higher water tables (Calliari *et al*., 2010; Vianna *et al*., 2015), which increases the risk of flooding.

Osório is a clear example of urban sprawl visible in the urban mesh data (IBGE, 2023). No differences were observed between the results of the model simulations with and without the presence of dunes along the coast of Osório. Urbanisation led to the loss or discontinuity of the dune system to the point where they have no or limited role in coastal protection. Osório is one of the most populous municipalities on the North Coast of RS (Rio Grande do Sul, 2021) and real estate speculation has increased in the region since 2021 (Rodrigues, 2020).

In Xangri-lá the situation is similar. Intensification of coastal development (IBGE 2023), including luxurious condominiums, has led to the degradation of local dunes that were abundant in the past (Martinho *et al*., 2010; Tomazelli *et al*., 2008). Here, the remaining dunes are still able to reduce exposure (from moderate to low) along a modest 4% of the shoreline. Urban sprawl also threatens the integrity of dunes in other municipalities in the region.

Two municipalities still show dune fields near the shoreline albeit of different characteristics. Transgressive dune fields occur in Cidreira and reversing dunes occur in Torres, and their contribution to coastal protection differs, as indicated in the results presented here.

The transgressive dune fields are wide and elongated in the direction of the dominant NE-SW winds highly dependent on the preservation of connected feeding corridors that can be cut out due to urban sprawl (Tomazelli *et al*., 2008). This effect has been observed in Cidreira (Esteves, 2004). Here, the loss of dunes can increase exposure from moderate to high along almost 20% of the coast, mostly in the southern section.

As a result, the greatest threat in this region is the process of urban expansion (Martinho *et al*., 2010; Tomazelli *et al*., 2008), coupled with an increase in the urban network (IBGE, 2023), and growing real estate speculation (Rodrigues, 2020) the natural coastal protection barrier, in this case the dunes, in this municipality, there was no increase in high values of coastal exposure, as observed in the results of the simulation without dunes in the municipality, there was an increase of almost 4% in the moderate values of coastal exposure in Torres.

It can be seen that the high exposure values in the simulation without the presence of dunes are more concentrated in the southern part of the North Coast of RS, from Imbé to Balneário Pinhal. This region suffers greater influence from the winds, and without the dynamic protection of the Serra escarpments (Martinho *et al*., 2010; Tomazelli *et al*., 2008).

Despite this, the municipalities of Capão da Canoa and Terra de Areia have their coastal exposure values increased in the simulation results without the presence of dunes. With observed data on the urban fabric (IBGE, 2023), and the real estate speculation that occurs in this municipality, in Capão da Canoa (Rodrigues, 2020). In Terra de Areia, these processes do not occur (IBGE, 2023; Rodrigues, 2020).

In the municipality of Arroio do Sal there is a 2% increase in moderate coastal exposure values. In previous studies, these three municipalities showed an increase in their coastline: 29.1% - Arroio do Sal, 56.6% - Terra de Areia and 86.5% - Capão da Canoa (Esteves, 2004).

As can be seen from the results of the simulation without dunes, the north coast of RS has two different dynamics. One in the north, between Torres and north of Imbé, whose local topography, proximity to the Serra escarpment, and influence on the dynamics of the decrease in winds, mean that the simulation results do not have high coastal exposure values. And another, in the southern portion, from Imbé to Balneário Pinhal, where there is no influence from the local topography, due to there being no proximity to the Serra escarpment, which causes wind speeds to increase, consequently the simulation results have increased the high values of coastal exposure.

This southern portion of the northern coast of RS, from Imbé to Balneário Pinhal, is directly influenced by the natural protective barrier, in this case, dunes, as shown in the comparison of results between the two simulations with and without dunes. Its high coastal exposure values increased by 13.49%, while in the northern portion, coastal exposure increased by moderate values of 10.80%.

Factors such as the increase in the urban fabric (IBGE, 2023), and real estate speculation (Rodrigues, 2020) in coastal areas cause serious impacts on ecosystem services, such as coastal protection, damaging natural coastal protection barriers such as dunes (Ruheili; Boluwade, 2023).

Studies using simulations with and without natural barriers in the InVEST Coastal Vulnerability model have shown an increase in coastal exposure on the coastline (Ballesteros; Esteves, 2021; Ruheili; Boluwade, 2023). This simulation contributes to verifying future global threats to coastal ecosystem services and assists in the search for actions that predict or mitigate these threats (Ruheili; Boluwade, 2023).

FINAL CONSIDERATIONS

This study assessed the importance of dunes on the North Coast of RS for the provision of the ecosystem service of coastal protection. The presence of dunes acts as a natural barrier against erosion and flooding, reducing exposure to coastal hazards. Model simulations indicated that coastal exposure values increase in the absence of dune fields.

However, dunes are not the only factor that influences the ecosystem service of coastal protection. This was evident in the northern part of the study area, particularly in the municipality of Torres, where local topography and wind dynamics play a role in reducing exposure to erosion and flooding. Here, the expansion of urban areas is a primary threat, which is aggravated by real estate speculation.

In the southern sector of the study area, dunes have a more important role in providing natural coastal protection as model results indicate that their presence effectively reduces exposure to coastal hazards, particularly in the municipality of Cidreira.

Future studies should incorporate a wider range of coastal habitats, in addition to dunes, to obtain a more comprehensive mapping and understanding of the provision of the ecosystem service of coastal protection.

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AUTHOR CONTRIBUTION

Daniela Forgiarini da Silva conceived the study, collected, analyzed the data and wrote the text. Tatiana Silva da Silva and Luciana Slomp Esteves conceived the study and corrected the text. Giuliana Andréia Sfreddo corrected the text.