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Article

Global Research Trends on Coastal Dunes: Implications for a Semi-Arid Coast in Northeastern Brazil

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Abstract

This study aimed to evaluate and quantify the environmental impacts generated by anthropogenic actions on coastal dunes globally using bibliometric data, while concurrently identifying human impacts in a local context on the Brazilian semi-arid coast. A systematic review identified 897 relevant publications from a final sample of 1838 works, revealing an increasing trend in global research, peaking in 2018. Geographically, the United States (141), Italy (95), and Spain (79) lead the field, with Brazil contributing 46 publications. The global overview highlights urbanization (217 studies) and tourism (193 studies) as the most frequent impact factors, contrasting with common mitigation measures like dune stabilization with vegetation (112 studies) and beach nourishment (74 studies). Critically, 11 studies reported that management actions, particularly stabilization without considering native flora, led to problems with invasive plants. A significant research gap was identified due to the absence of literature on wind farms, typically located in transgressive dune systems. The local case study in Ceará state confirms dynamics consistent with global trends, where intense exploitation results in management failures; quantitative temporal analysis (2015–2023) demonstrated a dramatic 86.76% loss of dune area in Fortim and a 4.24 km^2 loss in Jijoca de Jericoacoara. Findings suggest that, in the Ceará case study, restricting access, promoting community participation, and relocating infrastructure to more appropriate areas may help mitigate human impacts. In addition to identifying potential research gaps, this integration of global and local analysis approaches can contribute to evidence-based coastal dune management adapted to local conditions.

Keywords: systematic bibliometric review; coastal dunes; anthropogenic impacts; coastal management; Brazilian semi-arid coast

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1. Introduction

Coastal dunes, present in the transition ecosystems between the continent and the sea, can be considered a primary natural defense barrier against the impact of climate change on coastal/inland communities [1–3]. They are fundamental for the environmental balance

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of coastal areas. Furthermore, dunes provide services to society due to the economic and touristic potential that these environments offer [4,5].

The dynamics of coastal dunes are complex and can be influenced by several natural factors, such as (i) wind intensity and direction [6]; (ii) storms [7]; (iii) sediment characteristics [8]; (iv) vegetation [1]; (v) oceanographic factors [9]; (vi) climate change [10]; and (vii) sediment supply, among others. Many of these factors generate direct impacts on the beaches and indirectly affect the dunes.

In addition to natural processes, anthropogenic factors also influence dune dynamics, potentially causing morphological and vegetative cover alterations [11–13]. Examples of human activities cited in the literature as generating impacts on coastal dunes include the use of heavy machinery for cleaning beaches and dunes [14], trampling, vegetation removal for urban infrastructure development [15], urbanization, vehicular traffic [16], and sand mining [13], among others.

Although it is acknowledged that anthropogenic activities have the potential to impact dune dynamics, few global-scale studies attempt to quantify which activities generate the greatest impact and whether these activities vary over time. For instance, Ref. [17], through a global meta-analysis, assessed the impacts of one specific type of anthropogenic action, the use of off-road vehicles (ORVs) on dune vegetation. Their results revealed severe damage to dunes, with recovery responses exhibiting significant variations across different locations. Conversely, Ref. [18] evaluated the transformations that occurred in urbanized beaches across seven Latin American countries following the COVID-19 pandemic lockdown. Their research observed that the decrease in tourist presence in coastal areas permitted the recovery of dune vegetation and the formation of new dunes. The cited works suggest that reducing anthropogenic activities is essential for the recovery of dune systems.

Countries like Brazil exemplify the dilemma between exploitation and preservation, with dunes being utilized by sectors such as tourism, real estate, and industry [5]. Local studies are crucial for understanding the specific reality of each dune system, whereas a global perspective allows for the visualization of human behavior on a large scale. Although the exploitation of coastal areas is intense [19], the frequency and type of human activities on coastal dunes vary across different regions of the world.

Acknowledging the limitations of global-scale studies, which stem from the vast volume of existing research and the inherent differences among dune systems, bibliometrics enables a large-scale survey of the actions that impact dunes and the mitigation strategies applied to reduce their effects.

Bibliometric analysis is a methodology frequently employed to examine large volumes of scientific articles, thereby identifying global trends in a specific research area [20]. By establishing well-defined search criteria, it is possible to obtain a cohesive dataset [21] and, consequently, to infer and quantify the influence of human actions on coastal dunes.

Thus, this study aims to integrate a global assessment of anthropogenic impacts on coastal dune systems with a local-scale analysis conducted along the semi-arid coast of Ceará, northeastern Brazil. Specifically, the study seeks to: (i) characterize global research patterns concerning anthropogenic impacts on coastal dunes, including the main types of impacts and management measures reported in the scientific literature; (ii) quantify changes in dune area between 2015 and 2023 in two municipalities along the semi-arid coast of Ceará; (iii) identify the main anthropogenic drivers associated with the observed dune degradation in the study areas; and (iv) compare the locally observed patterns of anthropogenic impact with those identified in the global literature, highlighting convergences, particularities, and implications for coastal dune management. Integrating global and local analyses is necessary because of the limited information available on dune management along the semi-arid coast and may also reduce the risk of errors in applying management strategies reported in the literature that could intensify coastal dune degradation.

2. Materials and Methods

The systematic review was carried out using a package in R: A Language and Environment for Statistical Computing, developed by [22], called bibliometrix. This is a widely used tool in scientific mapping due to its ability to extract quantitative data from a database of scientific articles, in little processing time. The methodology involves several key steps, including the definition of eligibility criteria and search terms used to find the manuscripts. The methodology also included a local analysis through a case study in an area of the Brazilian semi-arid coast.

2.1. Materials

Data Base

In order to conduct a thorough search for sources for the articles, two databasesfrequently addressed in Systematic Literature Review (SLR) research studies were used [23,24], these being the Web of Science and Scopus, both accessed through the CAPES periodicals platform [25]. An important factor for the SLR is that any researcher who uses the same search criteria, including the research period, can find the same results found by other groups [26], covering all articles published. All studies retrieved by the search up to 26 June 2025 were considered, with no initial date limit applied.

2.2. Methods

2.2.1. Criteria

The eligibility criteria were defined following some items from the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol [21], which consists of a series of items that guide the systematic review and avoid bias in other stages of the research [27,28]. Only studies in English were considered; regarding the type of document, only articles from journals were accepted. The search terms were the same for the two databases, adapting only the Boolean operators according to the needs of each database.

To search for studies that address the environmental impact of anthropogenic actions on coastal dunes, the following combinations of words were used:

1. For Web of Science: (dune* OR foredune*) AND (influen* OR effect* OR activ* OR induc* OR impact* OR management) AND (huma* OR anthropogenic OR management OR urban* OR trampl* OR vehicle) (Title) OR (dune* OR foredune*) AND (influen* OR effect* OR activ* OR induc* OR impact* OR management) AND (huma* OR anthropogenic OR management OR urban* OR trampl* OR vehicle) (Abstract) OR (dune* OR foredune*) AND (influen* OR effect* OR activ* OR induc* OR impact* OR management) AND (huma* OR anthropogenic OR management OR urban* OR trampl* OR vehicle) (Author Keywords) NOT (health* OR holocen* OR medicin* OR arts* OR biolo* OR pharmaceutic*) (Title) NOT (health* OR holocen* OR medicin* OR arts* OR biolo* OR pharmaceutic*) (Abstract) NOT (health* OR holocen* OR medicin* OR arts* OR biolo* OR pharmaceutic*) (Author Keywords) and Article (Document Types) and English (Languages).
2. For Scopus: (TITLE-ABS-KEY ((dune* OR foredune*)) AND TITLE-ABS-KEY ((influen* OR effect* OR activ* OR induc* OR impact* OR management)) AND TITLE-ABS-KEY ((huma* OR anthropogenic OR management OR urban* OR trampl* OR vehicle)) AND NOT TITLE-ABS-KEY ((health* OR holocen* OR medicin* OR arts* OR biolo* OR pharmaceutic*))) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar")) AND (LIMIT-TO (SRCTYPE, "j")).

Each database (Section Data Base) returned a set of articles; these two sets were grouped into a new database and the duplicates were then deleted. These operations were performed using the bibliometrix tool. To validate the integrity of the obtained data, a preliminary check of the database was performed. An initial list containing 36 publications considered relevant in the dune research area was utilized, and 80% of these works were successfully retrieved in the final dataset of this research (thereby validating the query presented in Section Data Base).

2.2.2. Extraction

After grouping the articles into a single set, the extraction stage began. This consisted of two parts: the first being reading the abstracts of the studies and checking whether they addressed the topic of anthropogenic influence on coastal dunes—if the article was not within the theme of interest, it was excluded. The second part refers to the actual extraction of data from each study.

From the selected references, two sets of information were extracted: (i) year of publication, keywords, and area of study (country); (ii) human-induced impacts encountered and management measures adopted. Set (i) was extracted using the bibliometrix tool, and (ii) was carried out by reading the articles.

2.2.3. Case Study

Figure 1a presents the Brazilian Semi-Arid Coast (BSAC), which corresponds to a distinct sector of the northern Brazilian coastline, extending across parts of the states of Maranhão, Piauí, Ceará, and Rio Grande do Norte. This regionalization is based primarily on climatic and environmental characteristics rather than administrative boundaries. The sector is distinguished by the influence of a semi-arid tropical climate, marked rainfall seasonality, persistent trade winds, and high mobility of aeolian sediments, factors that favor the development of extensive coastal dune systems [29]. Therefore, only the coastal sectors directly influenced by these semi-arid conditions are included in the BSAC, which explains why its regional boundaries do not encompass the entire coastline of the four states.

Within this broader regional context, the coast of Ceará was selected as the case study area because it contains extensive and highly dynamic dune systems that are representative of the environmental conditions found along the Brazilian Semi-Arid Coast. Reference [30] highlights the region's high climatic vulnerability resulting from low rainfall and an intense wind regime, making it an area that requires particular attention in terms of integrated coastal management.

Figure 1b shows the area of this research study, highlighting the state of Ceará, with a coastal strip of approximately 573 km in length [31]. The Ceará coast is characterized by diverse and striking landscapes that attract visitors from around the world, and its beaches are increasingly subject to tourism-related pressures. Maia et al. [32] defined the total area of dune fields existing in the state of Ceará as representing 331 km^2, presenting intense wind dynamics due to the semi-arid climate characteristics of the coastal region of the state [33].

Figure 1c shows the selected dune areas along the Ceará coast. These are areas that are protected by law with the aim of preserving natural ecosystems and ensuring their sustainable use. Point 1 is located in the Jericoacoara National Park, which has fixed and mobile dunes of the barchan, barchanoid and longitudinal types. Despite the difficult access to the Park, this is an important tourist center in Ceará.

The Paracuru Dunes Environmental Preservation Area (EPA), at point 5, covers 2820.07 ha, where dunes cover 51.78% of the EPA. Unlike point 1, access to the Paracuru dunes is easy, having roads that cross over the dunes, although they are precarious due to the movement of the dunes. The Sabiaguaba Dunes Municipal Natural Park (point 8) covers an area of 467.60 ha, where mobile and fixed/semi-fixed dunes comprise 51% of this area, and their use is only permitted for ecological tourism and scientific research. The park is easily accessible, given that it is located in the capital of Ceará and is bordered by a state highway.

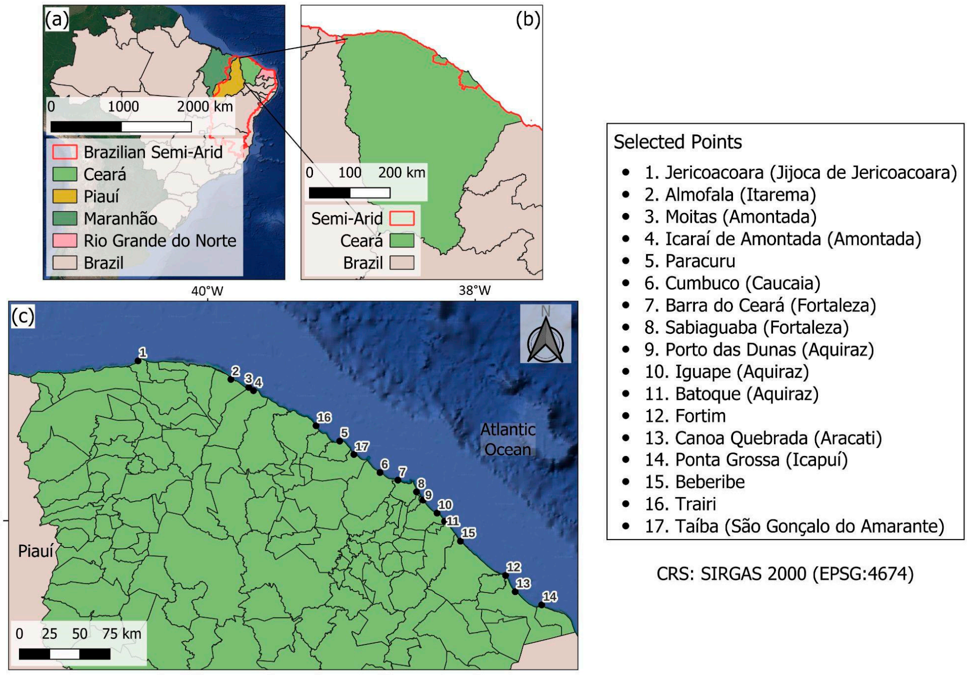

Figure 1. Map of the study area: (**a**) Location of the Brazilian Semi-Arid Region. (**b**) Indication of the state of Ceará and its coastline belonging to the Semi-Arid Coast. (**c**) Location of dune areas visited along the state's coastline.

The Canoa Quebrada EPA (point 13) is also an easily accessible area and is made up of diverse landscapes such as cliffs, dunes, mangroves, and others. As this is a region with well-developed tourism, it presents a high level of real estate speculation and poor monitoring of irregular activities in the preservation areas. In contrast to the previously mentioned EPAs, the EPA of Ponta Grossa Beach (point 14), in the municipality of Icapuí, is well preserved and has little hotel infrastructure. The dunes in this EPA have restricted access.

The Batoque Extractive Reserve (Reserva Extrativista—RESEX) (point 11) supports the subsistence of the local population and is characterized by limited urban development, while also facing management challenges related to dune migration over existing infrastructure. The other points that were not mentioned (Almofala, Moitas, Icaraí de Amontada, Cumbuco, Barra do Ceará, Porto das Dunas, Iguape, Fortim) present particularities such as wind farms installed on the dunes, sealed dunes, modification of native vegetation to fix dunes, and real estate speculation, among others, but such areas are not protected or have their uses regulated through Conservation Units (Unidades de Conservação—UCs).

2.2.4. In Situ Dune Surveys

The field visits aimed to identify the anthropogenic interferences with dune dynamics of the dune and their morphological consequences in each location, as well as to analyze the effectiveness of the management measures used to mitigate possible damage. Roads and houses were observed to be partially buried by migrating sand. To mitigate the advance of the dunes, the use of dry straw on them was recorded. The trips were carried out after the rainy season in Ceará, over the months of July and August 2022 [30].

2.2.5. Image Processing

Temporal satellite imagery from the Planet mission, from the years 2015 and 2023, was used and processed in the following steps: generation of mosaics according to the areas identified in Figure 1c; classification of the images using the Dzetsaka plugin (version 5.0.9) [34] in QGIS version 3.40.10 [35] to perform a supervised classification. The plugin was selected because it allows the definition of training samples and the standardized application of the same classification procedure to the different mosaics analyzed. In the classification stage, 4 classes were used (Vegetation, Water Bodies, Exposed Soil or Urbanized Area, and Sand), where in each mosaic 40 samples were identified for each class. The classification quality was evaluated using a confusion matrix. The identification of the change in the areas was performed qualitatively and quantitatively regarding the variation in the vectors obtained in the classification.

3. Results

The results obtained in this study can be divided into three sections: (a) bibliometric data from the review, presenting statistics about the publications found; (b) global overview of the anthropogenic actions that have generated the most impacts on coastal dunes and which management measures are being applied worldwide to reduce their effects; and (c) local view of the problems faced in Ceará through the temporal analyses of the spatial changes found.

3.1. Bibliometric Analysis

Figure 2 shows the flowchart of the PRISMA protocol applied. Through the systematic review, using the databases indicated in Section Data Base and the specifications in Section 2.2.1, the initial search returned 6670 articles, the sum of which was 3511 studies obtained from Scopus and 3159 from Web of Science (Figure 2).

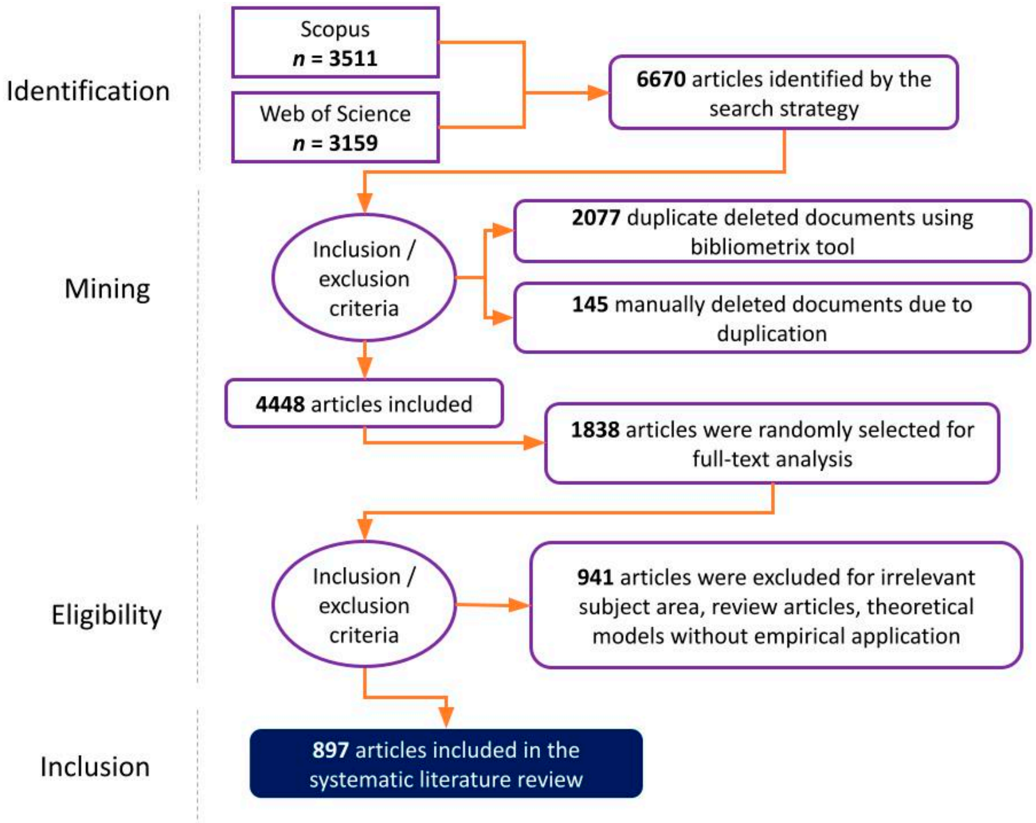

Figure 2. The flow diagram for article selection.

By using the Bibliometrix tool version 3.2.1, it was possible to combine the data from Scopus and Web of Science, and thus exclude 2077 duplicate studies. To validate the data, a manual verification was performed to confirm that there were no more duplicate studies, and hence 145 more documents not identified by the Bibliometrix were excluded due to the difference in the writing of the titles of the studies in the two databases.

From the 4448 articles included after the data mining phase, a full-text analysis of the entire dataset was unfeasible due to the sheer volume of papers and time constraints. Therefore, random sampling was adopted, and several tests were performed until a set representing approximately 40% of the database was reached. Although a smaller sample would have been statistically sufficient, this sub-sample of 1838 publications was utilized to reduce the margin of error and, critically, to minimize the likelihood of under-representation of sub-themes (e.g., specific geographic areas) that might not follow the general trend of the overall sample. This approach ensured that the analysis was conducted in a rigorous and representative manner, allowing for the extraction of data relevant to the research objectives.

After applying the eligibility criteria, 941 articles were excluded that did not address coastal dunes and the influence of anthropogenic actions or did not meet the criterion. In the end, of the 1838 papers in the sample, only 897 were included in the SLR.

The distribution of published works by year is shown in Figure 3. The bibliometric survey makes it possible to identify when the topic 'anthropogenic influence on coastal dunes' began to receive greater attention in the scientific literature, revealing that the number of publications per year has an increasing trend over time, with more pronounced growth in recent decades (Figure 3).

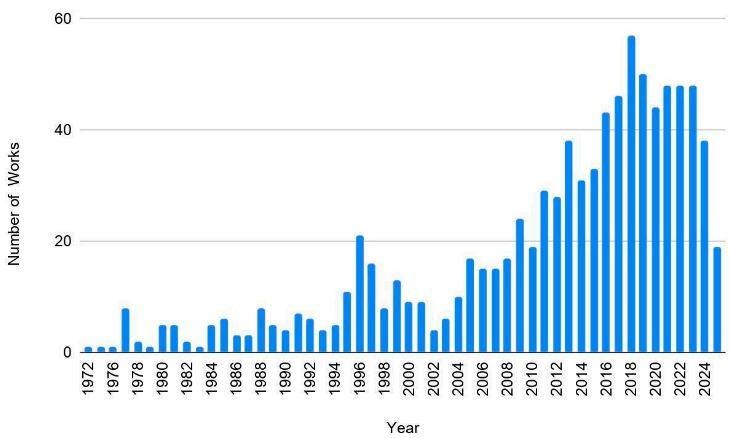

Figure 3. Temporal distribution of the number of publications related to anthropogenic influence on coastal dunes.

The first article on this topic was published in 1972, followed by an increase in publications in 1977, with another increase in 1996. From 2005 onward, a more consistent increase in the number of publications can be observed, becoming more pronounced after 2009 and reaching its highest value in 2018. The low number of occurrences for the year 2025 is due to the period in which the search was performed.

Figure 4 presents the choropleth map of the arrangement of these studies in relation to the areas studied, where 77 countries have shown interest in understanding the relationship between coastal dunes and human interference on their coastlines. The countries that lead the research in terms of numbers, as areas of study, are the United States (141), Italy (95), Spain (79), the Netherlands (67), United Kingdom (54), Brazil (46), Australia (45), and France (40). Other countries are identified in fewer than 30 articles.

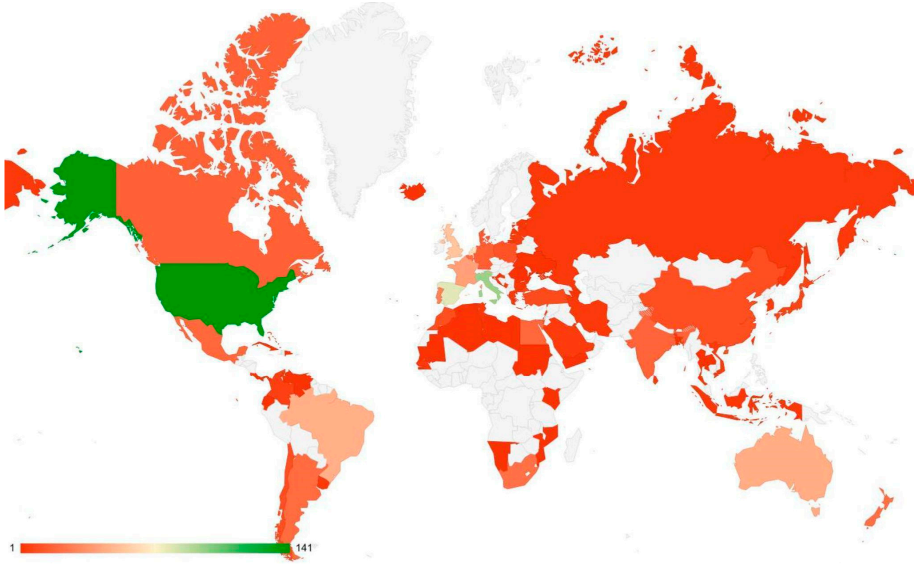

Figure 4. Geographical distribution of studies found in the review, according to area of study.

3.2. Global Overview

After a quantitative analysis of the results obtained in the systematic review (Section 3.1), this section presents the qualitative data from the 897 articles used. Figure 5 presents a summary of the anthropogenic activities indicated as responsible for the changes suffered in the coastal environments. Among the most cited are "Urbanization", cited in 217 studies; "Tourism Pressure" (193); "Tourism Infrastructure" (83); "Invasive Exotic Species" (76); and "Agricultural Activities" (73). It is worth noting that, in most articles, many of these activities are related to one another. "Tourism Infrastructure" is directly related to tourism; however, they are cited as two distinct problems.

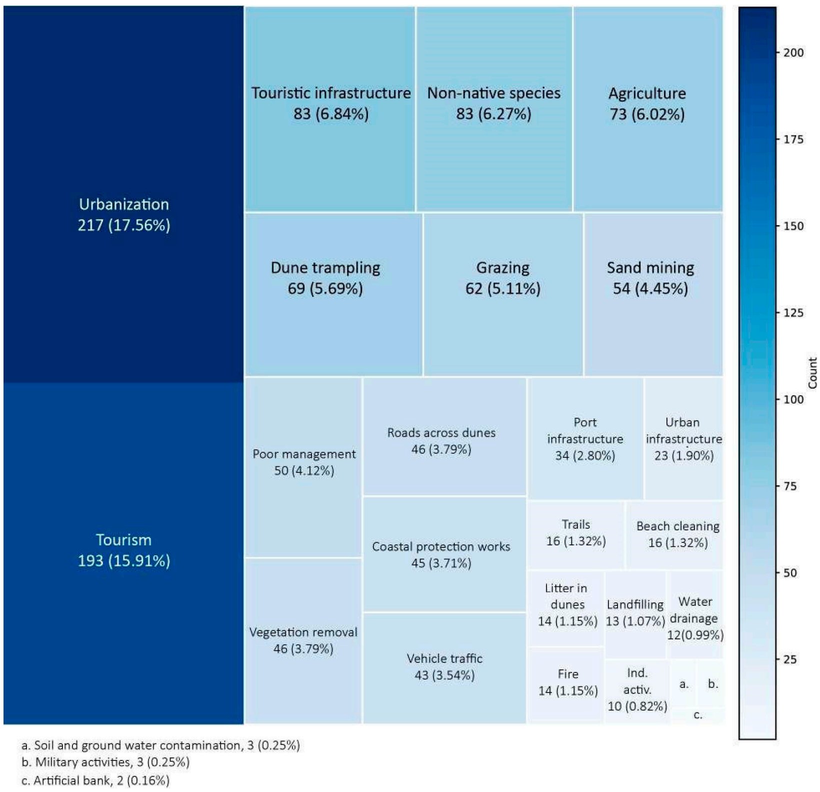

Figure 5. Impact factors represented in a graph, indicating the main anthropogenic pressures on the coastal dune environment.

As illustrated in Figure 5, "Mismanagement" is identified as an anthropogenic factor. Furthermore, several studies have demonstrated that certain management practices, instead of providing protection, have contributed to the degradation of coastal environments. Regarding vegetation, two main factors are indicated: "Removal of Vegetation" and the introduction of "Alien Plants". The removal of native vegetation may be associated with urbanization or agricultural activities. Alien Plants, in turn, are non-native species introduced into the environment for dune stabilization or for ornamental purposes.

Figure 6 shows which of the management measures identified in the review are most widely applied worldwide. Five actions stand out, accounting for almost 50% of the results (Figure 6): "Dune Stabilization with Vegetation" was mentioned in 112 articles, "Beach Nourishment" (74), "Coastal Protection Works" (57), "Dune Reconstruction" (50), and "Sand Fences" (45).

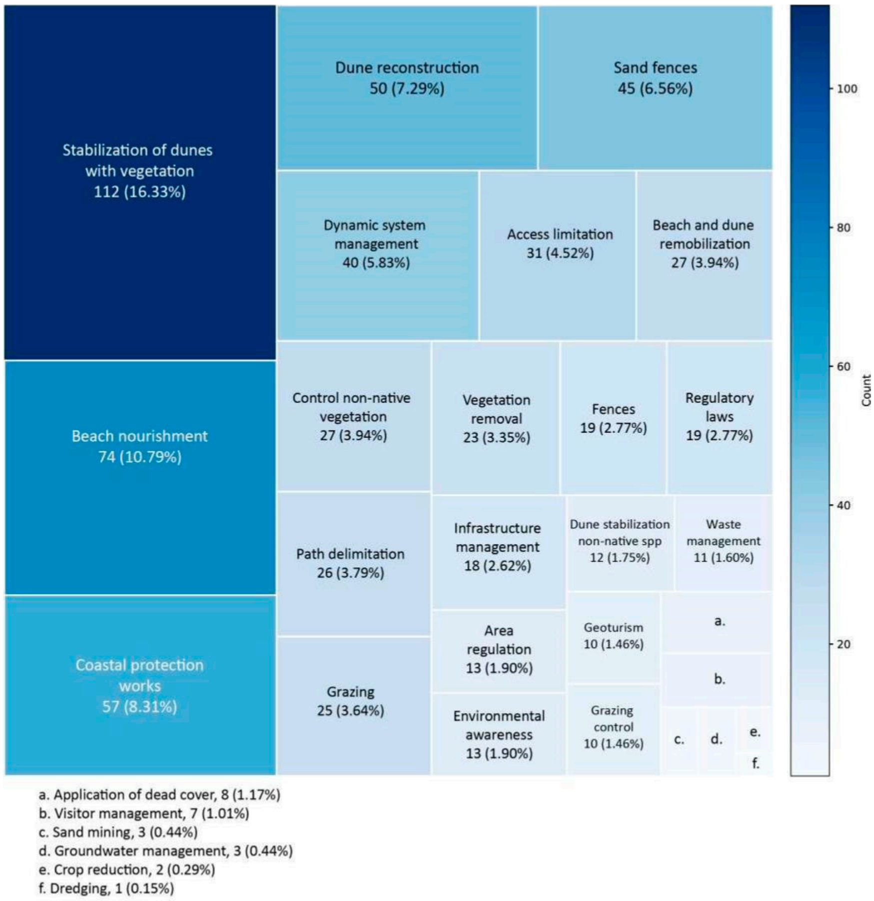

Figure 6. Illustration of the main conservation and environmental management strategies and practices implemented to mitigate human impacts and promote the sustainability of the coastal ecosystem.

Figure 5 illustrates the problems found, and Figure 6 outlines the management measures used. In this context, the bibliometric survey reveals an association between the themes of "Stabilization of dunes with vegetation" and "Removal of Vegetation". In 11 studies, dune stabilization without considering the native vegetation resulted in a problem with invasive plants, compromising the natural conditions of the environment.

3.3. Semi-Arid Coastal Dunes

Despite the Ceará coast having extensive coastal dune fields and being a popular tourist destination, there are few studies in the region on the dynamics of these fields and anthropogenic influence. In the land use classification for 2015 and 2023, bare sand was categorized as dune. Figure 7 shows the result of the classification of images, indicating the extent of the dunes for the localities of Beberibe and Trairi, both with the presence of wind farms. The segmentation of the dune areas in Beberibe (Figure 7a,b) is due to soil compaction or paving of the access roads to the wind farms in the areas, unlike the wind farm in Trairi (Figure 7c,d), where there is no segmentation of the dunes despite the presence of the wind farm, since in this area the road is not paved.

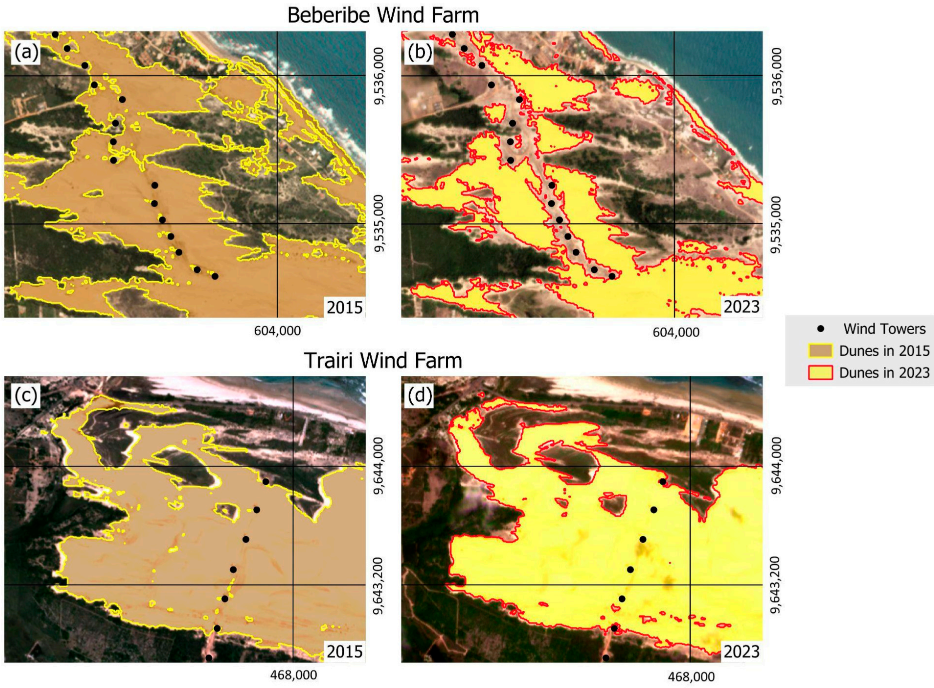

Figure 7. Identification of dune areas, with temporal variation between 2015 and 2023. Section of dune fields with wind farms, with wind towers identified with black markers, in (**a**) Beberibe in 2015, (**b**) Beberibe in 2023, (**c**) Trairi in 2015, and (**d**) Trairi in 2023.

As a result, in addition to the vectors of change in the dune fields for the years 2015 and 2023, the values of the areas for the points listed in Figure 1c were obtained. Table 1 presents values for 2015 and 2023, in square kilometers, for 8 areas with dune fields in Ceará. Through the difference column, it is possible to quantitatively identify a loss of area in Beberibe (Point 15), also identified in Figure 7b, with a negative difference close to 1.8 km^2, and in the Trairi area (Point 16), the difference is a positive gain of 0.2 km^2, confirming what Figure 7d indicates.

Table 1. Comparison of areas between 2015 and 2023.

Area	Description	2015 (km^2)	2023 (km^2)	Difference
Point 13	Aracati	30.15	26.66	−3.49 (−11.58%)
Point 12	Fortim	0.68	0.09	−0.59 (−86.76%)
Point 15	Beberibe	4.33	2.53	−1.80 (−41.57%)
Point 16	Trairi	4.47	4.67	0.20 (4.47%)
Point 9	Aquiraz	0.10	0.06	−0.04 (−40.00%)
Point 17	São Gonçalo do Amarante	0.89	0.47	−0.42 (−47.19%)
Point 3	Amontada	1.12	0.99	−0.13 (−11.61%)
Point 1	Jijoca de Jericoacoara	17.17	12.93	−4.24 (−24.69%)

The anthropogenic advance of hotel infrastructure into dune areas can be identified in Fortim in Figure 8, where areas classified as dunes in 2015 were no longer classified as such in 2023. A satellite image reveals the change from a dune field to hotel infrastructure in Sector 1 (Figure 8a,d). Still in Figure 8, an increase in land development can be observed in Sector 3, as represented in Figure 8c, for 2015, and Figure 8f, for 2023. The observed variation in area in Sector 2, when comparing (b) and (e) in Figure 8, can also be interpreted as a process of erosion of the local beach and dunes, in addition to urbanization. In Table 1, Fortim presents a loss of 0.59 km^2 of dune area, which is approximately 87% of its area in 2015.

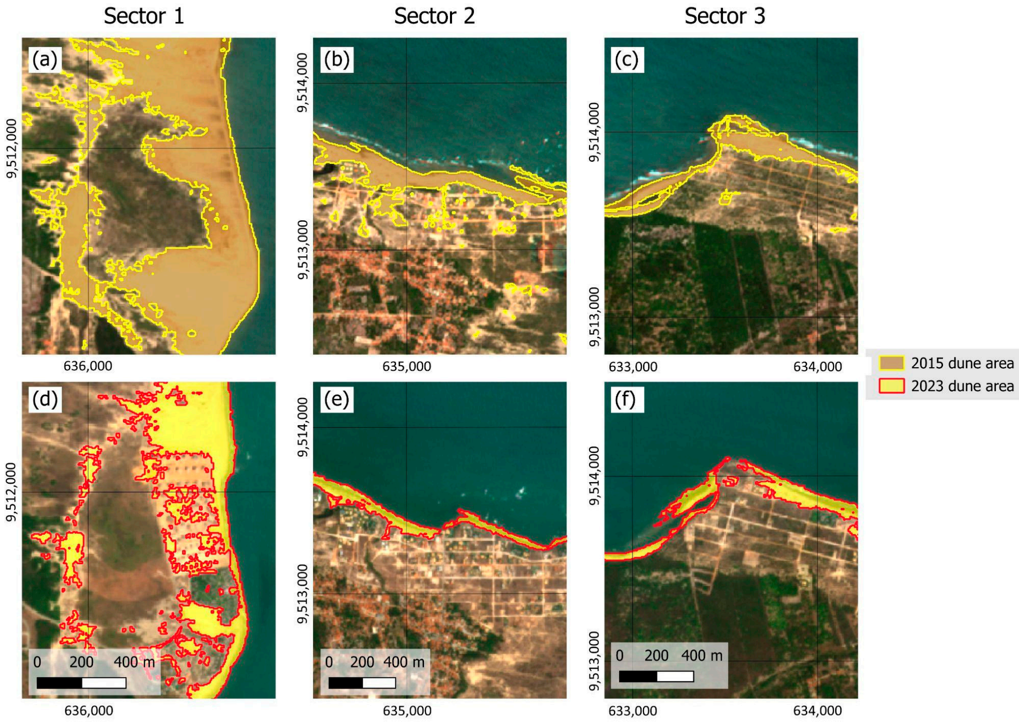

Figure 8. Classified dune areas in three coastal sectors of Fortim in 2015 (**a**–**c**) and 2023 (**d**–**f**): Sector 1 (**a**,**d**), Sector 2 (**b**,**e**), and Sector 3 (**c**,**f**). Each pair is presented using the same spatial extent and scale.

The differences observed in Sector 3 can be attributed to tidal changes between the dates the images were acquired. Additionally, the development of still-uninhabited areas suggests real estate speculation.

Figure 9 shows the temporal variation in the dune system of Jijoca de Jericoacoara, indicating dune migration toward the sea. The locally used dune names are included to facilitate their identification throughout the text. A marked reduction in the Pôr do Sol Dune was observed and was also reported by the local press in April 2023. The measurements presented in Table 2 show a substantial decrease in the width of this dune. In Figure 9a, d1 represents the dune width in 2015 (187.03 m), whereas d2 represents its width in 2023 (31.88 m), corresponding to a reduction of 155.15 m. The remaining measurements (d3–d7) represent dune displacement distances between 2015 and 2023. The greatest displacement was recorded for the unnamed dune (d7), which migrated 187.68 m during the analyzed period.

Table 2. Linear measurements of dune changes in Jijoca de Jericoacoara between 2015 and 2023.

Description	Distance (m)
d1—Pôr do Sol Dune (2015)	187.03
d2—Pôr do Sol Dune (2023)	31.88
d3—Meia Lua Dune	164.22
d4—Lagoa dos Homens Dune	103.71
d5—Lagoa dos Homens Dune	89.51
d6—João Pepite Dune	111.83
d7—Unnamed	187.68

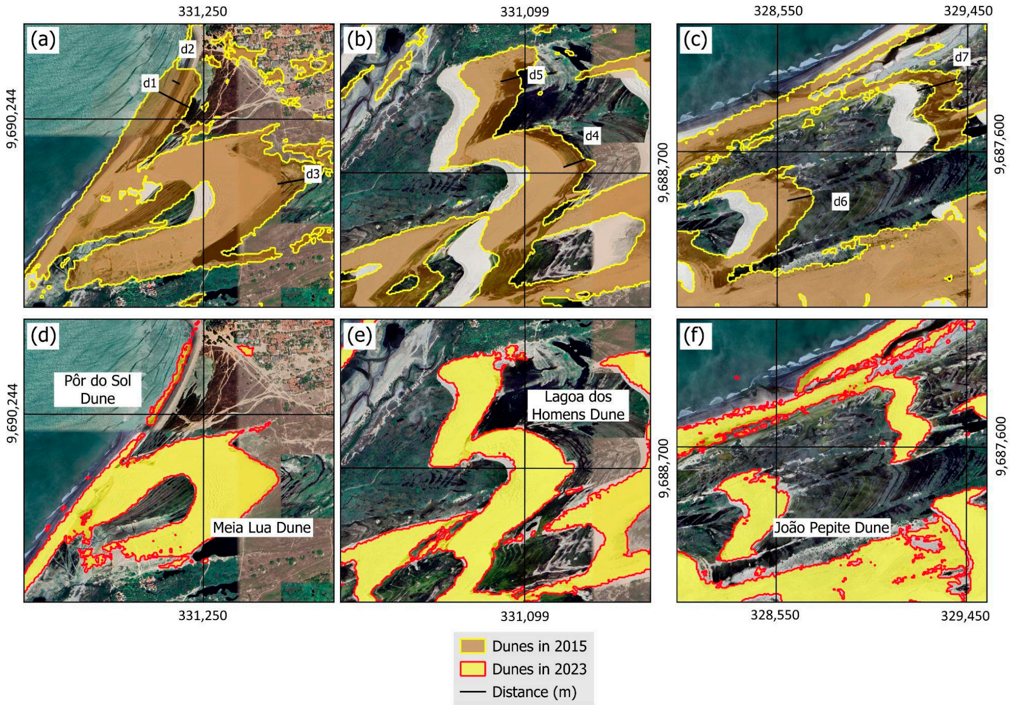

Figure 9. Classification of dune areas in Jijoca de Jericoacoara in 2015 and 2023, showing changes in dune width and position between the two dates. The labels d1 and d2 indicate the width of the Pôr do Sol Dune in 2015 and 2023, respectively, whereas d3–d7 represent dune displacement distances, as indicated by the black lines. Panels (**a**,**d**) show the Pôr do Sol and Meia Lua dunes; (**b**,**e**) show the Lagoa dos Homens dune; and (**c**,**f**) show the João Pepite dune and an unnamed dune.

Considering the quantitative results from Table 2, the dunes of Jijoca de Jericoacoara showed a large loss of area (4.24 km^2), and correlating with the result of the vectorization (Figure 9), it is clear that part of this lost area was in the section that presents the Pôr do Sol Dune and Meia Lua Dune, which are the closest to the urbanized area of Jericoacoara. All the other dunes indicated in Table 2 and Figure 9 show a displacement greater than 89 m, but visually they do not show significant area losses.

The state of Ceará has other areas where there are conflicts between the interaction of the dunes and aanthropogenic action; however, there are no scientific studies that address these areas because they are not as explored by tourism as Jericoacoara. Some of the problems found in these areas can be seen in Figure 10. Figure 10a shows a photograph of the implementation of vegetation on the dunes. This measure was used as a strategic action to prevent sediments from being moved by the wind towards the road. In Figure 10b, the road is covered by sediments where cars pass.

In Figure 10c, it is possible to observe a building surrounded by dunes on Batoque beach, located in the municipality of Aquiraz. This type of situation is repeated around other residences. On the field, we identified other building structures that have already been destroyed and their debris is accumulating at the dunes by the beach. The dunes of Canoa Quebrada (Aracati) also suffer from urban pressure that interferes with their movement and conservation. Field observations confirmed that soil sealing from constructions, a well-developed hotel infrastructure, and a high number of tourists in the region have resulted in impacts such as the alteration of sand transport flow in the dunes. The quantitative results presented in Table 1 highlight the evolution and dynamic context of the dunes, with emphasis on the Canoa Quebrada dune (Aracati), which in this comparison showed a loss of 3.5 km^2.

Figure 10. Anthropogenic interventions in the dunes: Paracuru, (**a**) use of straw to fix sediments; (**b**) municipal road in the dune field; (**c**) residence surrounded by dunes in Batoque.

4. Discussion

Bibliometric analysis is an effective tool for understanding global research trends. The selection process for this systematic review began with 4448 works, but a smaller sample of 1838 works was selected for the application of eligibility criteria. From this group, 897 works were finally included in the review. This sharp reduction is consistent with the methodology of other reviews, such as [23], who analyzed 49 articles from a total of 631, and in [28], where 43 works were selected from 9964. The substantial volume of initial results was due to a comprehensive search strategy that considered all document types (including conference papers and book chapters), instead of being restricted to journal articles, as per the established criterion for the final sample.

The first publication (Figure 3) on human interventions in dune environments was a 1972 study in the United Kingdom that analyzed the impact of grazing, burning, and mowing on dune pastures. Although these measures compromised the development of the pastures, they were observed to be beneficial for the local floristic diversity [36]. Subsequently, Ref. [37] analyzed dune management on the east coast of the United States and concluded that, in some cases, human action disturbed the ecosystem, while in others, measures such as dune construction were necessary to preserve recreational infrastructure. The increase in publications after 2005 may be related to growing scientific attention to the effects of climate change and coastal erosion, as well as to the intensification of human occupation in coastal environments [1,19].

The geographical distribution of the studies showed a marked concentration in certain countries, particularly the United States and European countries. This uneven distribution may be associated with several factors, including the intensity of urban development in coastal zones, which increases the need to understand and manage anthropogenic impacts on dune systems [16,19], as well as the greater availability of data and stronger research capacity in these countries. Furthermore, the observed pattern may have been influenced by the methodological characteristics of the bibliographic survey itself [20].

Still on the subject of interventions in the dune ecosystem, it is worth highlighting the extraction of aggregates as one of the most aggressive [38], given that the systems are unable to recover due to the large volumes of sediment extracted. Among the studies obtained in the review, when it comes to aggregate extraction, the island of Tenerife stands out due to its historical exploitation and the respective consequences of these actions up to the present day [38–40]. Management measures such as the implementation of geotourism or even the construction of artificial dunes are adopted to minimize the damage caused by sand extraction, but they do not always bring benefits to the areas and can even generate more instability in the dune system [40].

In these cases, management measures need to be carefully assessed in terms of the inherent characteristics of the environment in order to preserve the natural conditions of the location [40]. Sampath et al. [41] discusses the problem experienced by New Zealand when, in order to stabilize coastal dunes that had been deforested years earlier for use in livestock farming, they adopted the management measure of reforesting the areas with a type of vegetation used by countries such as France and Germany (marram grass). This action had a negative impact on the region, reducing the abundance of native dune plant species. Other authors such as [42–44] also highlight the problem of the insertion of invasive plants that cause instability in dune environments.

In order to minimize the damage caused to ecosystems by human pressure, different management measures are adopted throughout the world. However, as noted in this review, indicated as "Mismanagement", there are many cases in which these measures become yet another action that harms the system or even intensifies the damage. Flor-Blanco et al. [45] highlights that, although all the dune systems in Canabria have suffered a natural retreat, the anthropized areas have shown accelerated erosion due to the impacts of human management. The study by [46] highlights that large-scale interventions in the coastal dunes of Truc Vert beach (France), such as the installation of fences and mechanical reshaping, resulted in lasting morphological changes in the region. The current landscape is a direct reflection of these modifications, which were implemented over a period of up to 150 years.

A study by [47] carried out in the Corrubedo Natural Park in the Iberian Peninsula identified that the use of wooden structures as a measure to minimize damage from tourism to dune fields had the opposite effect, altering the wind sediment dynamics and the movement of the dune field. The removal of structures on the Corrubedo dunes allowed the re-establishment of the area's natural dynamics and resulted in a decrease in tourist pressure on the more sensitive dune surface. Pinna et al. [2], on the other hand, recommends the use of light wooden structures on dunes to limit the effect of human trampling on sensitive areas of the dunes and to avoid the loss of native vegetation. It is important to maintain continuous monitoring of planned interventions to mitigate the impacts of anthropogenic actions on these coastal environments, and to identify the possible negative effects.

Case Study Discussion

Despite its extensive coastal dune fields, the coast of Ceará, located in the Brazilian Semi-arid Coast (Costa Semiárida), does not receive the necessary management attention to mitigate the impacts of increasing tourist exploitation. The bibliometric review reveals that few studies focusing on the state were found (3), given that the majority of research in Brazil concentrates on the southern region of the country. For example, in a study conducted in a dune field near Jericoacoara, Ref. [48] demonstrated that higher sand fences have a greater trapping efficiency. Furthermore, Ref. [49] highlights that the stabilization and construction upon dunes in the Metropolitan Region of Fortaleza threaten the sediment supply to the mangroves, emphasizing the negative impacts of human interventions. Meanwhile, Ref. [50] addresses the utilization of sediments from the state's beaches and dunes for use in coastal engineering, construction, and natural processes.

Beyond the publications identified in the bibliometric review, other literature sources provide important information regarding the study area. Meireles [51] highlights that even though there are limitations regarding anthropogenic activities in the Jericoacoara National

Park, such as the construction of access roads or the installation of urban equipment, the park has been undergoing other important impacts due to the flow vehicle traffic and consequent compaction of sediments over the dune body [51].

Still focusing on Jericoacoara, Ref. [52] emphasizes that the period of greatest acceleration in dune movement (between 2001 and 2005) is directly linked to the increased tourist flow in the region. In this context, restricting access to dune areas is an important management measure that has proven effective in regions such as Asturies, the Iberian Peninsula, and Mexico [45,47,53], and which could represent a viable solution for Jericoacoara. However, the same authors [47] warn that the implementation of boardwalks or other wooden structures over the dunes can generate negative impacts, such as the disturbance of sand mobilization.

Other dune fields in the region have been undergoing changes due to anthropogenic interference, but they are not highlighted in the publications. Brannstrom et al. [54] provides an overview of wind farms in the state of Ceará and the damage they have caused to dune areas, such as the case of the Xavier Wind Farm in the municipality of Camocim, where actions such as the removal of vegetation from stable dunes, destruction of fixed and mobile dunes and freshwater lagoons for land leveling, among other actions, are gradually destroying the region's dune ecosystem [55,56]. The theme of wind farms was not identified in this bibliometric review, which can be justified by their predominant location in transgressive dune systems. This absence, in turn, points to a gap in global studies addressing anthropogenic actions in these areas.

In the example presented in [38], the management measures adopted included the removal of buildings from dunes and surrounding areas and the relocation of residential areas to more appropriate locations. These measures could also be effective in the Batoque region. From another perspective, Ref. [39] emphasizes the importance of popular participation in creating tools to reduce the impacts of tourism on Tenerife (Spain). This participatory approach is applicable to Canoa Quebrada, where tourism is the main source of income for the local population.

Areas located in the metropolitan region of the study area, such as the region of Porto das Dunas, stand out due to the topographic modification, where are modified to make way for real estate development, compacting the soil and removing the native vegetation that previously fixed the dunes present in the area. Fernández and Bértola [57] warns about the advancement of construction in coastal dune areas aggravating erosion processes in Argentina, suggesting the implementation of sand fences to contain sediments. Based on the experiences obtained in the global overview (Section 3.2), several management measures can be adapted to local conditions in the dune areas of Ceará state to mitigate the consequences of anthropogenic actions. Such measures include restricting access to dune areas, popular participation as a preservation tool, and the relocation of residential areas and urban infrastructure (e.g., roads) to more appropriate locations.

5. Conclusions

This study aimed to evaluate the environmental impacts caused by anthropogenic interference on coastal dunes globally using bibliometric data, and to propose viable management solutions for similar challenges faced in countries with limited investment in environmental monitoring and recovery. This systematic approach yielded several key findings:

- Growing Research Trend: Publications focusing on anthropogenic influence on coastal dunes show an increasing trend over time, with more pronounced growth in recent decades, peaking in 2018. This highlights a growing global need for the recovery and preservation of these ecosystems.

- Geographical Focus: European countries such as Italy (95 publications), Spain (79), and France (40) are among the research leaders, along with the United States (141) and Brazil (46). Their high volume of publications indicates a significant global concern regarding the behavior and management of these environments.
- Management Malpractices: The global overview indicates that certain management actions—categorized as "Mismanagement" in the bibliometric analysis—are often responsible for the advancement of coastal dune degradation. Specifically, dune stabilization without considering native vegetation led to issues with invasive plants in 11 studies.
- Local-Global Consistency: The case study on the Brazilian Semi-arid Coast reveals dynamics consistent with the global review. The temporal analysis and field visits confirmed that areas of intense tourist and urban exploitation—such as Fortim, which showed an 86.76% loss of dune area, and Jijoca de Jericoacoara, with a 4.24 km^2 loss—require urgent intervention to mitigate anthropogenic impacts.
- Identified Gaps: The absence of wind farms in the global review is notable and suggests a research gap in studies addressing anthropogenic actions in transgressive dune systems, where these infrastructures are predominantly located.

The experiences and mitigation measures developed in other regions can be highly valuable as references for coastal dune areas facing conservation challenges, particularly in the semi-arid coast of Ceará. However, their application should be preceded by an assessment of local environmental and socioeconomic conditions, such as wind regime, sediment availability, dune morphology and vegetation cover, and the intensity of anthropogenic pressures. Proposed solutions include: restricting access to dune areas, promoting popular participation as a preservation tool, and the relocation of infrastructure to more appropriate locations.

While this systematic review provides valuable guidance, it does not preclude the need for more robust, site-specific studies on coastal dune areas and the factors driving their degradation. The combination of temporal analysis and field surveys successfully identified degraded areas in Ceará that have not been addressed in the prior scientific literature, and these findings can inform targeted actions for environmental preservation. The main contribution of this study is the integration of global bibliometric results with local quantitative findings. This approach also made it possible to identify issues overlooked in the global literature, such as the impacts of wind farms on transgressive dune systems. Future research should monitor these impacts over the long term and evaluate management measures applicable to local conditions.

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References

1. Jackson, D.W.; Costas, S.; González-Villanueva, R.; Cooper, A. A global 'greening' of coastal dunes: An integrated consequence of climate change? *Glob. Planet. Change* **2019**, *182*, 103026. [CrossRef]
2. Pinna, M.; Bacchetta, G.; Cogoni, D.; Fenu, G. Is vegetation an indicator for evaluating the impact of tourism on the conservation status of mediterranean coastal dunes? *Sci. Total Environ.* **2019**, *674*, 255–263. [CrossRef] [PubMed]
3. Šimanauskienė, R.; Linkevičienė, R.; Povilanskas, R.; Satkūnas, J.; Veteikis, D.; Baubinienė, A.; Taminskas, J. Curonian spit coastal dunes landscape: Climate driven change calls for the management optimization. *Land* **2022**, *11*, 877. [CrossRef]
4. George, E.; Lunardi, B.; Smith, A.; Lehner, J.; Wernette, P.; Houser, C. Storm impact and recovery of a beach-dune system in prince edward island. *Geomorphology* **2021**, *384*, 107721. [CrossRef]
5. Soares, M.O.; Barros, E.L.; Guerra, R.G.P. Not just sand: The folly of dismantling the environmental protection of dunes in Brazil. *Land Use Policy* **2022**, *112*, 105803. [CrossRef]
6. Manzolli, R.P.; Portz, L.C.; Fontán-Bouzas, A.; Bitencourt, V.J.B.; Alcántara-Carrió, J. Contribution of reverse dune migration to stabilization of a transgressive coastal dune field at lagoa do peixe national park dune field (south of Brazil). *Remote Sens.* **2023**, *15*, 3470. [CrossRef]
7. Burvingt, O.; Castelle, B. Storm response and multi-annual recovery of eight coastal dunes spread along the Atlantic coast of Europe. *Geomorphology* **2023**, *435*, 108735. [CrossRef]
8. Costas, S.; de Sousa, L.B.; Kombiadou, K.; Ferreira, Ó.; Plomaritis, T.A. Exploring foredune growth capacity in a coarse sandy beach. *Geomorphology* **2020**, *371*, 107435. [CrossRef]
9. D'Alessandro, F.; Tomasicchio, G.R.; Frega, F.; Leone, E.; Francone, A.; Pantusa, D.; Barbaro, G.; Foti, G. Beach–dune system morphodynamics. *J. Mar. Sci. Eng.* **2022**, *10*, 627. [CrossRef]
10. Keijsers, J.; De Groot, A.; Riksen, M. Modeling the biogeomorphic evolution of coastal dunes in response to climate change. *J. Geophys. Res. Earth Surf.* **2016**, *121*, 1161–1181. [CrossRef]
11. Delgado-Fernandez, I.; O'Keeffe, N.; Davidson-Arnott, R.G. Natural and human controls on dune vegetation cover and disturbance. *Sci. Total Environ.* **2019**, *672*, 643–656. [CrossRef] [PubMed]
12. Han, S.; Hogue, W. Assessing human influence and vegetative dune dynamics on barrier islands via satellite raster classification. *Environ. Manag.* **2025**, *75*, 524–537. [CrossRef] [PubMed]
13. Doyle, T.B.; Woodroffe, C.D. Modified foredune ecomorphology in southeast australia. *Ocean Coast. Manag.* **2023**, *240*, 106640. [CrossRef]
14. Bozzeda, F.; Fanini, L.; Costantini, F.; Mikac, B.; Colangelo, M.A. Disentangling the effects of sandy beach management on intertidal macrobenthic fauna: A path analysis approach. *Estuar. Coast. Shelf Sci.* **2025**, *319*, 109254. [CrossRef]
15. Andriolo, U.; Gonçalves, G. Impacts of a massive beach music festival on a coastal ecosystem—A showcase in portugal. *Sci. Total Environ.* **2023**, *861*, 160733. [CrossRef] [PubMed]
16. Aguilera, M.A.; Pacheco, S.; Manzur, T. Human-derived effects and failure in management drive coastal urban foredune degradation and novel vegetation structure. *J. Environ. Manag.* **2022**, *311*, 114843. [CrossRef] [PubMed]
17. Schlacher, T.A.; Weston, M.A.; Orchard, S.; Kelaher, B.P.; Maslo, B.; Dugan, J.E.; Hubbard, D.M.; Costa, L.; Bishop, M.J.; Kostoglu, K.N.; et al. Adverse impacts of off-road vehicles on coastal dune vegetation are widespread, substantial, and long-lasting: Evidence from a global meta-analysis of sandy beach-dune systems. *Estuar. Coast. Shelf Sci.* **2025**, *312*, 109038. [CrossRef]
18. Soto, E.H.; Botero, C.; Milanés, C.; Rodríguez-Santiago, A.; Palacios-Moreno, M.; Díaz-Ferguson, E.; Velázquez, Y.; Abbehusen, A.; Guerra-Castro, E.; Simoes, N.; et al. How does the beach ecosystem change without tourists during COVID-19 lockdown? *Biol. Conserv.* **2021**, *255*, 108972. [CrossRef] [PubMed]
19. Ranasinghe, R. On the need for a new generation of coastal change models for the 21st century. *Sci. Rep.* **2020**, *10*, 2010. [CrossRef] [PubMed]
20. Donthu, N.; Kumar, S.; Mukherjee, D.; Pandey, N.; Lim, W.M. How to conduct a bibliometric analysis: An overview and guidelines. *J. Bus. Res.* **2021**, *133*, 285–296. [CrossRef]
21. Moher, D.; Shamseer, L.; Clarke, M.; Ghersi, D.; Liberati, A.; Petticrew, M.; Shekelle, P.; Stewart, L.A. Preferred reporting items for systematic review and meta-analysis protocols (prisma-p) 2015 statement. *Syst. Rev.* **2015**, *4*, 1. [CrossRef] [PubMed]

22. Aria, M.; Cuccurullo, C. Bibliometrix: An r-tool for comprehensive science mapping analysis. *J. Informetr.* **2017**, *11*, 959–975. [CrossRef]
23. Ansari, M.; Farzadkia, M. Beach debris quantity and composition around the world: A bibliometric and systematic review. *Mar. Pollut. Bull.* **2022**, *178*, 113637. [CrossRef] [PubMed]
24. Papadimitriu, M.; Allinson, G. Microplastics in the mediterranean marine environment: A combined bibliometric and systematic analysis to identify current trends and challenges. *Microplast. Nanoplast.* **2022**, *2*, 8. [CrossRef]
25. Portal de Periódicos da CAPES. Available online: https://www-periodicos-capes-gov-br.ez11.periodicos.capes.gov.br/ (accessed on 26 June 2025).
26. Shahbaz, M.; Bashir, M.F.; Bashir, M.A.; Shahzad, L. A bibliometric analysis and systematic literature review of tourism environmental degradation nexus. *Environ. Sci. Pollut. Res.* **2021**, *28*, 58241–58257. [CrossRef] [PubMed]
27. O'Dea, R.E.; Lagisz, M.; Jennions, M.D.; Koricheva, J.; Noble, D.W.; Parker, T.H.; Gurevitch, J.; Page, M.J.; Stewart, G.; Moher, D.; et al. Preferred reporting items for systematic reviews and metaanalyses in ecology and evolutionary biology: A prisma extension. *Biol. Rev.* **2021**, *96*, 1695–1722. [CrossRef]
28. Chumky, T.; Basu, M.; Onitsuka, K.; Hoshino, S. The current research landscape of disaster-induced migration: A systematic review and bibliometric analysis. *Int. J. Disaster Risk Reduct.* **2022**, *74*, 102931. [CrossRef]
29. Short, A.D.; Klein, A.H.d.F. Brazilian Beach Systems: Review and Overview. In *Brazilian Beach Systems*; Short, A., Klein, A., Eds.; Coastal Research Library; Springer: Cham, Switzerland, 2016; Volume 17, pp. 24–25.
30. Soares, M.d.O.; Campos, C.C.; Carneiro, P.; Barroso, H.; Marins, R.V.; Teixeira, C.E.P.; Menezes, M.O.B.; Pinheiro, L.d.S.; Viana, M.B.; Feitosa, C.V.; et al. Challenges and perspectives for the brazilian semi-arid coast under global environmental changes. *Perspect. Ecol. Conserv.* **2021**, *19*, 267–278. [CrossRef]
31. Lima, L.C.; de Morais, J.O.; de Souza, M.J.N. *Compartimentação Territorial e a Gestão Regional do Ceará*; Funece: Fortaleza, Brazil, 2020.
32. Maia, L.P.; Leal, J.R.L.V.; de Souza Pinheiro, L.; Cunha, E.M.S.; Raventós, J.S. Gestão de dunas costeiras e conflitos de usos nos estados do Ceará e Rio Grande do Norte-Nordeste do Brasil. In *La gestión Integrada de Playas y Dunas: Experiencias en Lationoamérica y Europa*; Societat d'Història Natural de Balears: Palma, Spain, 2013; pp. 257–270. ISBN 978-84-616-2240-5.
33. Guerra, R.G.P.; Moreira, A.d.S.; Silva, J.R.M.; Nascimento, H.H.O.; Barros, E.L. Migração de dunas e o processo de soterramento no litoral de barroquinha, ceará, brasil. *Arq. Ciên. Mar.* **2020**, *53*, 100–109. [CrossRef]
34. Karasiak, N. *Dzetsaka: Classification Tool*, Version 5.0.9; GitHub Repository: San Francisco, CA, USA, 2026. Available online: https://github.com/nkarasiak/dzetsaka/ (accessed on 11 August 2026).
35. QGIS Development Team. *QGIS Geographic Information System*, Version 3.40.10; Open Source Geospatial Foundation Project: Beaverton, OR, USA, 2025. Available online: https://www.qgis.org/ (accessed on 11 August 2026).
36. Green, B.H. The relevance of seral eutrophication and plant competition to the management of successional communities. *Biol. Conserv.* **1972**, *4*, 378–384. [CrossRef]
37. Godfrey, P.; Godfrey, M.M. An ecological approach to dune management in the national recreation areas of the united states east coast. *Int. J. Biometeorol.* **1974**, *18*, 101–110. [CrossRef]
38. Marrero-Rodríguez, N.; García-Romero, L.; Peña-Alonso, C.; Hernández-Cordero, A.I. Biogeomorphological responses of nebkhas to historical long-term land uses in an arid coastal aeolian sedimentary system. *Geomorphology* **2020**, *368*, 107348. [CrossRef]
39. Marrero-Rodríguez, N.; Dóniz-Páez, J. Coastal dunes geomorphosites to develop the geotourism in a volcanic subtropical oceanic island, tenerife, spain. *Land* **2022**, *11*, 426. [CrossRef]
40. Sanromualdo-Collado, A.; Marrero-Rodríguez, N.; García-Romero, L.; Delgado-Fernández, I.; Viera-Pérez, M.; Domínguez-Brito, A.C.; Cabrera-Gámez, J. Foredune responses to the impact of aggregate extraction in an arid aeolian sedimentary system. *Earth Surf. Process. Landf.* **2022**, *47*, 2709–2725. [CrossRef]
41. Sampath, D.M.R.; Freitas, J.G.d.; Dias, J.A. Extending the dpsir framework to analyse driver-pressure-state-impact-response of sand dune management in manawatu-whanganui (new zealand) since the 19th century. *Ocean Coast. Manag.* **2022**, *230*, 106348. [CrossRef]
42. Marignani, M.; Lussu, M.; Murru, V.; Bacaro, G.; Cogoni, A. Effect of invasive alien species on the co-occurrence patterns of bryophytes and vascular plant species—The case of a mediterranean disturbed sandy coast. *Diversity* **2020**, *12*, 160. [CrossRef]
43. Buffa, G.; Gaetan, C.; Piccoli, S.; Del Vecchio, S.; Fantinato, E. Using fine-scale field data modelling for planning the management of invasions of oenothera stucchii in coastal dune systems. *Ecol. Indic.* **2021**, *125*, 107564. [CrossRef]
44. de Francesco, M.C.; Tozzi, F.P.; Buffa, G.; Fantinato, E.; Innangi, M.; Stanisci, A. Identifying critical thresholds in the impacts of invasive alien plants and dune paths on native coastal dune vegetation. *Land* **2022**, *12*, 135. [CrossRef]
45. Flor-Blanco, G.; Alcántara-Carrió, J.; Jackson, D.; Flor, G.; Flores-Soriano, C. Coastal erosion in nw spain: Recent patterns under extreme storm wave events. *Geomorphology* **2021**, *387*, 107767. [CrossRef]
46. Robin, N.; Billy, J.; Castelle, B.; Hesp, P.; Lerma, A.N.; Laporte-Fauret, Q.; Marieu, V.; Rosebery, D.; Bujan, S.; Destribats, B.; et al. 150 years of foredune initiation and evolution driven by human and natural processes. *Geomorphology* **2021**, *374*, 107516. [CrossRef]

47. Pérez-Alberti, A.; Gómez-Pazo, A.; Otero, X. Natural and anthropogenic variations in the large shifting dune in the corrubedo natural park, nw iberian peninsula (1956–2017). *Appl. Sci.* **2021**, *11*, 34. [CrossRef]
48. Ning, Q.; Li, B.; Ellis, J.T. Fence height control on sand trapping. *Aeolian Res.* **2020**, *46*, 100617. [CrossRef]
49. Ward, R.D.; de Lacerda, L.D.; da Silva Cerqueira, A.; Silva, V.H.M.C.; Hernandez, O.C. Vertical accretion rates of mangroves in northeast brazil: Implications for future responses and management. *Estuar. Coast. Shelf Sci.* **2023**, *289*, 108382. [CrossRef]
50. de Souza Pinheiro, L.; de Morais, J.O.; Maia, L.P. The Beaches of Ceará. In *Brazilian Beach Systems*; Coastal Research Library; Springer: Cham, Switzerland, 2016; Volume 17, pp. 175–199. [CrossRef]
51. Meireles, A.J.A. Geodinâmica dos campos de dunas móveis de jericoacoara/ce-br. *Mercat.-Rev. Geogr. UFC* **2011**, *10*, 169–190. Available online: https://www.redalyc.org/articulo.oa?id=273619427012 (accessed on 5 August 2026). [CrossRef]
52. Meireles, A.J.; Gorayeb, A. Campos de dunas em jericoacoara: Intervenções humanas como possível indicador de mudança na dinâmica morfológica. *Confins. Rev. Fr.-Brés. Géographie/Rev. Fr.-Bras. Geogr.* **2018**, *34*. [CrossRef]
53. Silva, R.; Martínez, M.L.; van Tussenbroek, B.I.; Guzmán-Rodríguez, L.O.; Mendoza, E.; López-Portillo, J. A framework to manage coastal squeeze. *Sustainability* **2020**, *12*, 10610. [CrossRef]
54. Brannstrom, C.; Gorayeb, A.; de Sousa Mendes, J.; Loureiro, C.; de Andrade Meireles, A.J.; da Silva, E.V.; de Freitas, A.L.R.; de Oliveira, R.F. Is brazilian wind power development sustainable? Insights from a review of conflicts in ceará state. *Renew. Sustain. Energy Rev.* **2017**, *67*, 62–71. [CrossRef]
55. Meireles, A.J.d.A. Danos socioambientais originados pelas usinas eólicas nos campos de dunas do nordeste brasileiro e critérios para definição de alternativas locacionais. *Confins. Rev. Fr.-Brés. Géographie/Rev. Fr.-Bras. Geogr.* **2011**, *11*. [CrossRef]
56. Loureiro, C.V.; Gorayeb, A.; Brannstrom, C. Implantação de energia eólica e estimativa das perdas ambientais em um setor do litoral oeste do ceará, brasil. *Geosaberes Rev. Estud. Geoeducacionais* **2015**, *6*, 24–38.
57. Fernández, J.M.; Bértola, G.R. Shoreline evolution of an urbanized coastal dune: Médanos private neighborhood, necochea, argentina. *J. South Am. Earth Sci.* **2023**, *124*, 104258. [CrossRef]