MIHAELA TUDOR, ANA RAMOS-PEREIRA, AND JOANA GASPAR DE FREITAS

# The Encroaching Dunes of the Portuguese Coast

## *A Geohistorical Perspective*

▼ **ABSTRACT** Late Holocene dunes migration is intricately linked to climate change and anthropogenic actions. Along the Portuguese coast, large-scale sand drifts occurred between the sixteenth and nineteenth centuries, sometimes associated with the Little Ice Age (LIA) period, characterised by long-term cooling across the north Atlantic region. Primary historical sources, coupled with scientific data about paleoenvironmental conditions and OSL ages were used to analyse the spatial and temporal extent of the sand drift occurrences and explore their impact on coastal communities. Covering the period of the past millennium, the study describes the main drivers for drift events in Portugal. The results show the intensification of sand drift episodes after 1500 AD, which can be attributed to both natural forcing factors and human activities (e.g., agriculture and intensive deforestation). It is also clear that human pressure on dunes was dominant after 1800, when dunes fixing strategies through afforestation programmes were seen as the best solution to control sand encroachment. The negative impact of the drift-sands was an important trigger for the management of coastal areas and determinant for the

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implementation of a set of environmental policies in Portugal. Through a geohistorical perspective, the paper discloses the human-nature interactions over time, and the long-term efforts of governments to control natural processes, contributing to large-scale landscape transformation of the Portuguese coastal dunes.

▼ **KEYWORDS** sand drifts, LIA, land uses, afforestation, dunes stabilization

## Introduction

Coastal areas are highly dynamic systems exposed to pressures and hazards from both land and sea (Ramesh et al., 2015). As frontier territories, dunes reflect well the interaction between human, physical and biotic, marine and terrestrial processes (Santana-Cordero, Monteiro-Quintana and Hernández-Calvento, 2014; Santana-Cordero et al., 2017).

Extensive dune fields formation is globally associated with sea-level oscillation, shaped by the influence of tides, local meteorological-oceanic conditions and sediment supply (Jackson, Costas and Guisado-Pintado, 2019). From the Middle Ages to the twentieth century, most European coastal dunes underwent notable transformation. During this period, global climate change and the alternation of mild and cold weather conditions were responsible for the accumulation of large aeolian deposits, separated by periods of relative dune stability. In the literature, the most recent pulses of intense aeolian activity are often related to the Little Ice Age (LIA), since colder temperatures and increased storminess are identified as the main triggers for dunes development, directly affecting wind intensity, sediment budget and vegetation cover (Klijn, 1990; van der Meulen, Witter and Ritchie, 1991; Clemmensen et al., 1996, 2001a, 2001b; Wilson et al., 2001; Clemmensen and Murray, 2006; Aagaard, Orford and Murray, 2007; Jackson, Costas and Guisado-Pintado, 2019). Following this reasoning, LIA would have had a profound impact on dunes dynamics, leading to the formation of large-scale transgressive dune fields (also called sand drifts). The deflation of the sands affected mainly the low-elevation sandy coasts and the embayment in the rocky coasts from France, Belgium, the Netherlands, Denmark and Portugal (Clarke and Rendell, 2011). The sands moved inland over agricultural fields, silting rivers and estuaries, sometimes destroying villages and forcing the inhabitants to move elsewhere (Clark and Rendell, 2015). Many studies described the impact of sand invasion in different times and places, like the Culbin Estate (1694), in Scotland (Bain, 1900), Soulac (1744), in France (Buffault, 1897), Tvorup (1680-1750) in Denmark (Knudsen and Greer, 2008), Cape Cod in the USA (1700s) (Freeman, 1862) and the Manawatu-Whanganui region in New Zealand (Smith, 1879: 514-516). Other qualitative studies mainly explore the strategies adopted by coastal populations to face sand hazards (e.g., Freitas, 2004). More recent studies, however, link sand invasion to both climatic and human factors (Clarke and Rendell, 2006, 2011, 2015; Tudor, Ramos-Pereira and Freitas, 2021). The enhancement of dune mobility by human interference, less studied, is connected to the clearing of woodlands for agriculture, the use of forest resources, overgrazing, the uprooting of marram grass, the introduction of rabbits and trampling (Huddart, Roberts and Gonzales, 1999; Provoost, Jones and Edmondson, 2011; Stewart, 2015).

Interdisciplinary research is increasingly used to understand past dunes' environments, involving cross-referencing approaches, integrating natural and social sciences (climatic, geological, archaeological, cultural transformation and age estimation findings) (Keyzer, 2016; Keyzer and Bateman, 2018; Pierik et al., 2017, 2018). New works in coastal studies and critical physical geography highlight the role of historical approaches in interdisciplinary research to better understand human-environment interactions (Greer et al., 2018; Freitas, 2020, 2021). This perspective allows us to map socioecological transformation over time, identify natural and human drivers, detect impacts on ecosystems evolution and perceive people's coping strategies to deal with specific problems (Clark and Rendell, 2011, 2015; Sampath, Beattie and Freitas, in press). Coastal sand dunes have much potential to be studied through an interdisciplinary lens.

This article explores climatic and human factors (agriculture, pasture, deforestation) on largescale drifts expansion along the Portuguese coast, highlighting the role of natural and human-induced forcing mechanisms in coastal management strategies and forest policies. It focusses on late-Holocene dunes, complementing the existing knowledge about dune drifting in Portugal with new data. It answers these questions: Do historical sources have information on dunes' mobility? What were the consequences of dune drifting for populations? What were the dominant factors responsible for dunes' landscape transformation during the last millennium? Why did Portuguese governments put so much effort in fixing moving dunes? Did these measures leave legacies, such as specific management or environmental policies related to the coast? Using a geo-historical approach, this paper provides a long-term comprehensive study on dunes and their management.

## Methodological approach

An integrative approach was applied crossing reconstructed paleoenvironmental conditions during the last millennium, chronological data of aeolian deposits, historical documents on sand drift occurrences and societal responses to such hazards. For Portugal, abundant data on climate reconstruction is available, based on non-instrumental evidence and early systematic observation of weather extremes, including devastating storms, heavy rainfall and severe droughts with strong impacts on the natural environment and society. For this study, the regional overview of climate conditions during the first millennium was compiled from literature, including the North Atlantic Oscillation (NAO) index, using the winter NAO reconstruction data between AD 1300 and 1995, based on Trouet at al. (2009), downloaded from the paleo directory of National Centres for Environmental Information (NCEI) from National Oceanic and Atmospheric Administration (NOAA). Next, sand drift events were identified in historical documents (e.g., chronicles, official decrees, technical reports, newspapers and cartography), found in archives and libraries, such as Arquivo Nacional Torre do Tombo, Biblioteca Nacional de Portugal, Arquivo Histórico Ultramarino, Biblioteca e Arquivo da Economia and Arquivo do Instituto da Conservação da Natureza e das Florestas. The temporal distribution of the documented drift events was complemented with previously published OSL ages from Portuguese late-Holocene dunes (e.g. Clark and Rendell, 2006; Costas et al., 2012; Jackson, Costas and Guisado-Pintado, 2019). Historical sources were also checked for land uses and practices that contributed to the enhancement of sediment dynamics and to get information on the strategies used to prevent dune migration, which led to the implementation of specific forest policies for the coast.

To provide the spatial distribution of the sand-drifts, a map was drawn up using ASTER Digital Elevation Model for Portugal (30 km spatial resolution, DatumWGS_1984). Then, each location cited in the text related with afforestation actions on dunes was added to a previously georeferenced historical map from 1868 in GIS environment (*ArcGis Pro 10.7 software*), using the projected coordinate reference system ETRS89/Portugal TM06 and elevations referenced to mean sea-level (MSL): Cascais vertical datum.

## Climate as a trigger for sand drift?

Climate oscillations have been considered as the main driver for coastal dunes formation and sand drift episodes along the European coast (Arbogast, Hansen and Oort, 2002; Clemmensen and Murray, 2006). Several studies identified distinct environmental conditions over the first millennium (Fig. 1): i) the Medieval climate anomaly (MCA: circa 900-1300), which corresponds to a mild climate in many parts of the world (Lamb, 1965); ii) the Little Ice Age (LIA: spanning the period between circa 1300 and 1900), initially considered the coldest epoch since the Last Glacial Maximum (LGM: 18000 BP) (Mann, 2002); and iii) the Current Warm Period-CWP, starting after circa 1850 to present (Sejrup et al., 2010), culminating in the present climate warming, mainly attributed to human action, due to an increase in greenhouse gases in the atmosphere (IPCC, 2014). There is, however, no agreement within the scientific community about the exact timing of these changes. Long-term cooling during LIA and the warm phases of MCA and CWP were highly variable from region to region, with a general trend across the Atlantic region (Mann, 2002). The end of the Medieval warm period was marked by the first important climate cooling event around the beginning of the fourteenth century (the Wolf Minimum), linked to suppressed sunspot activity (Usoskin, et al., 2021). The fourteenth century is often seen as a transition period between MCA and LIA (Trouet et al., 2009).

Numerous publications demonstrate a transition period in Portugal after 1300, pointing to significant alluvial sediment budget on the coast synchronous to tidal marshes development, due to the enhancement of the runoff of rivers, suggesting a climatic change from dry to wetter conditions and a further increase of storm frequency (Moreno et al., 2019).

From the fifteenth century onwards, past climate reconstruction points to significant degradation (Fig. 1), which reach its culminating stages between 1550 and 1700 (Lamb, 1965). The period was marked by the cold phase of the Spörer event (1410-1540), followed by two other exceptional episodes of cooling, the Maunder Minimum (1645-1715), known as the coldest and dryer phase of LIA (Pfister et al., 1998) and the Dalton Minimum (1790-1820). These climatic fluctuations have been related to forces external to the climate system, i.e. low solar activity and volcanic eruptions (Vaquero and Trigo, 2018) and internal forces, involving changes in the ocean-atmospheric circulation system (Scourse et al., 2010), which dictate the spatial pattern of the North Atlantic Oscillation (NAO) across the north Atlantic region. From the climatic point of view, the NAO teleconnections produce significant changes in wind direction and speed over the North Atlantic, but also in heat and moisture transport and in the intensity and frequencies of storms (Hurrel, 1997). NAO index is a measure of the variability of the zonal flow (i.e. surface westerly winds) over the Atlantic basin and may be used to explain phases of enhanced and reduced storminess (Matulla et al., 2007). Typically, positive NAO phase (NAO+) reflects strong zonal flow and cyclone enhancement in north and western Europe related to northward displacement of storm activity, while negative NAO phase (NAO-) reflects storm tracks migration southward (Blöschl et al., 2019), bringing moist air and storminess increases into

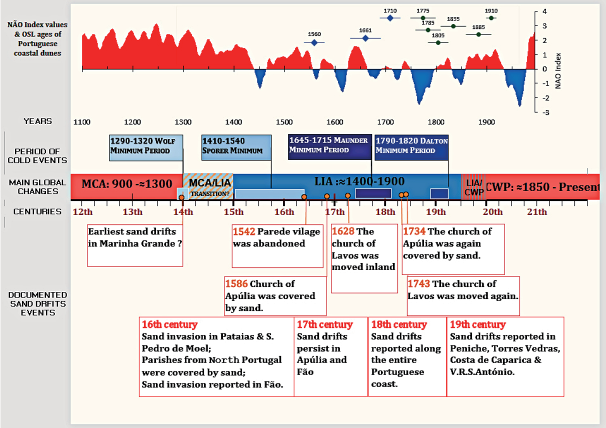


**Figure 1**: Timeline with the most important sand drift records available in the documentary sources (referenced in the text) and climate variability over the last millennium.
*Sources*: The main global climate changes and distinct periods of cooling are based on: Lamb, 1965; Mann, 2002; Usoskin, et al., 2021; Moreno et al., 2019. MCA is the Medieval Climate Anomaly; LIA the Little Ice Age and CWP the Current Warmer Period. The NAO Index values are based on the winter reconstructed data (original period between 1049 – 1995 AD) from Trouet et al. (2009). The upper dots (including the error bars) indicate the ages of the aeolian sand deposits found in the literature, the blue dots are the dated samples from Costa de Caparica (Costas et al., 2012), and the green dots are the samples dated from the Central Portuguese coast (Clark and Rendell, 2006).

the Mediterranean basin and Western Iberia (Tudor, Ramos-Pereira and Freitas, 2021). The NAO reconstruction values in winter, based on Trouet et al. (2009) show higher variability during LIA, with predominant NAO-mode between AD 1550 and 1850, suggesting intensification of storm activity over Iberia, although interposed by anticyclone conditions (Fig. 1). In fact, starting from the sixteenth century, all of Europe experienced both rainy and dryer conditions, with heavy rainfall and strong onshore winds, followed by persistent droughts (extreme heats) at large temporal and spatial scales (Pfister et al., 2015; Tudor, Ramos-Pereira and Freitas, 2021). At the global scale, the coldest century of the millennium was the seventeenth, with a temperature average of about 0.5-0.8 C below the 1961-1990 average (Jones et al., 1999).

Past weather reconstructions for Portugal report a remarkable cooling in the late seventeenth and in the beginning of the eighteenth century, particularly in winter and spring (Alcoforado et al., 2000). Very dry years alternating with ones with excessive rainfall, severe winters with snowfall events in Lisbon (unusual today) and intense storms were felt during this period, related to persistent NAO negative mode (NAO-) (Alcoforado et al., 2000; Luterbacher et al., 2006; Taborda, 2006; Pfister et al., 2010; Fragoso et al., 2015). By the late nineteenth century there was an improvement of the weather conditions corresponding to the onset of the Current Warmer Period (CWP), characterised by a return to calm conditions (i.e. predominance of anticyclone conditions) and reduced storminess (Luterbacher et al., 2002; Tudor, Ramos-Pereira and Freitas, 2021).

In terms of coastal processes, LIA period was marked by intense sediment accretion, resulting in the formation of several tombolos connected to islands and the enclosing of many coastal lagoons (Dias et al., 2000). This pattern supports the suggested dune growth in Portugal, related to the increase of storm activity in the Atlantic region during NAO- phase in winter (Clark and Rendell, 2006), although it may be linked to both NAO modes (Tudor, Ramos-Pereira and Freitas, 2021). Under prolonged NAO- phase in winter, heavy rainfall during storms promoted soil erosion on exposed slopes and large sediment discharges from the rivers into the littoral drift. On the other hand, notable drifts episodes would have occurred under subsequent cool and dryer conditions during NAO+ mode, as large beaches remained under a subaerial environment, facilitating sand deflation and landward dune migration. Anticyclone conditions in winter also amplified coastal upwelling (Abrantes et al., 2005), providing stronger onshore winds and subsequent increase in sand drift intensity. Also, the rise in both wind frequency and velocity can have implications for vegetation growth, by affecting the evapotranspiration, promoting water stress and cooling effects on exposed plants (Gardiner, Berry and Moulia, 2016).

In Portugal, vegetation growth depends on the wintertime rainfall regime, since dryness is a characteristic of the Mediterranean summer. If a winter drought continues into spring, its negative impact on vegetation is quite significant (Alcoforado et al., 2000), resulting in the depletion of dune vegetation and, consequently, in the intensification of aeolian processes. Contrarily, when the dunes have a thick vegetation cover it is extremely hard for the wind to blow sand, as plants act as protection against aeolian erosion (Tsoar, 2005; Tsoar et al., 2009; Roskin et al., 2011).

Sand drift events are well documented in the Portuguese archives from the sixteenth century onwards. Before that, there is so far no known accurate data on sand invasions. They existed for sure, scientific data shows that different episodes of dune drifting occurred over the last millenium, but they may have left no written records or these have not been identified yet. There is, however, a story, connected to an area (Marinha Grande) that later had serious problems with the dunes, that might suggest the occurrence of a sand drift episode in the late thirteenth or early fourteeth centuries (Pinto, 1938). It is said that King D. Dinis (1279-1325) ordered the planting of the Leiria Pine Forest to fix the sandy soils of the region (Borges et al., 1897, Granja and Soares de Carvalho, 1992). The forest still exists, yet there is no historical evidence that D. Dinis was responsible for its creation nor that the planting was directly connected to sand drifting control (Freitas, 2004). This event can tentatively be linked to the first cold outbreak – the Wolf Minimum period, however, it is not related to any storm conditions (Fig. 1). The most likely reason is that these drifts resulted from the reworking of existing dunes rather than from a new source of sediment supply, since none of the dated samples from that area is consistent with this timeframe period (Clark and Rendell, 2006).

In the following centuries, there are many descriptions about the damages caused by dunes to villages and agricultural lands. For instance, around 1500 the hamlet of Paredes (Fig. 2) was menaced by the sands and abandoned in 1542 (Brandão, 1650: 120; Anonymous, 1868: 155, 156; Morais, 1939: 16, 17). The same sources also report sand incursions near Paredes, Pataias and S. Pedro de Muel (Fig. 2). The case of the nearby Costa de Lavos (Fig. 2) is also interesting; the sand invasions forced its inhabitants to move away, and the church was transferred twice. According to ecclesiastic sources, in 1628 the building was relocated to a higher place, at about 3.5 kilometres North-East from the coast (Anonymous, 1868). Later, in 1743, the dunes again threatened and the inhabitants built another temple "a quarter of a league" inland (circa 1.25 kilometres), where the village of Lavos presently stands (Guerra, 1950: 44) (Fig. 2).

Up north, in the Minho region (North-West Portugal, Fig. 2), part of the lands of the parishes of S. João de Ester and Santa Maria das Areias were covered by the sands in the sixteenth century. The village of Fão had the same problem. A similar situation was described in 1586 in Apúlia (Fig. 2), where the sands destroyed many rural settlements, forcing its inhabitants to request the protection of the king (Neiva, 1991; Granja 2002). In 1693, S. Miguel church (in Apúlia) was repaired, but it was again flooded by sand in 1734 (Lopes, 2019). The church of Fão was also in ruins for the same reason. Many properties were lost in that area during the seventeenth and eighteenth centuries, overwhelmed by the sand dunes. To the south, sand drifting was described mainly in the nineteenth century in Costa de Caparica and the surrounding area, extending southward to Albufeira lagoon (Fig. 2). Also, sporadic events were documented on the southwest coast, in Carrapateira dunes near Alvor and Vila Real de Santo António on the southern coast (Fig. 2). In some places, the dunes continued to drift for a longer period, advancing eastward in the early twentieth century (Rei, 1940). Many of these dunes remained active until they were fixed through afforestation projects.

The OSL dated age of Portuguese coastal dunes confirm significant aeolian activity during LIA (Jackson, Costas and Guisado-Pintado, 2019).

For instance, in Costa de Caparica (south of Lisbon), the last phase of dunes development is within LIA, with pulses of aeolian activity dated between 0.44 and 0.30 ka. ago (AD 1560-1710), the late date from AD 1710 is synchronous with the end of the Maunder Minimum event (Costas et al., 2017). Up north, the majority of dated dunes have ages spanning between 95-230 years ago (AD 1770-1910), with a date of 220 ± 25 year for a transverse ridge formed parallel to the modern foredunes at São Pedro de Muel, while in Vagos and Furadouro elongated parabolic dunes and transverse ridges have ages of 230 ± 25 years and 170 ± 25 years, respectively (Clark and Rendel, 2006) (Fig. 1). Younger drifts were found in Quiaios, indicating ages from the late nineteenth century (120 ± 25 years) and Cantanhede with dated ages from the early twentieth century (95 ± 10 years ago) (Clark and Rendell, 2006).

The spatial distribution of these drifting events was unequal along the coast for two main reasons. First, cliffs are predominant on the southern Portuguese coast and, second, most settlements are concentrated to the north of the Tagus River. The few written documents about drifts events at the south of the Tagus River can be explained by lack of population in this region until the late nineteenth century, marked by the absence of large urban centres (with some exceptions), low accessibility and low population density (Bastos et al., 2012).

## The troubling dunes: human drivers and responses

From the early eleventh century onwards, many European countries underwent a set of transformations and population growth trends. In Portugal, a significant population increase occurred between the eleventh and thirteenth centuries (Galego and Daveau, 1996), requiring more agricultural land. The second half of the thirteenth century was marked by economic development, the extension of cultivated land and thriving urban life. The intensive use of wood products for domestic purposes coupled with the large use of forested areas for pastures and their conversion into agricultural fields led to the decline of medieval forests (Devy-Vareta, 1986). Previous studies, based on pollen assemblages, evidence a large forest on the western coast of Portugal, dominated by a mixed pine-oak composition, which was gradually replaced by a semi-natural heathland as a consequence of climate change and human activities, mainly pastoral practices and agriculture (Danielsen et al., 2011). Near the coast, in sheltered areas, like lagoons and estuaries, there was also an intensification of human activities, such as salt production in Aveiro's lagoon and cattle grazing in the nearby dunes (Bastos and Dias, 2012; Bastos et al., 2017). Historical evidence shows that the sediment influx on the coast increased due to a rise in riverine sediment transport linked, among other things, with deforestation and land cultivation in the watershed's basin areas (Dias et al., 2000). This large amount of sands on the coast also explains the significant geomorphological changes in the Portuguese shore from the eleventh century onwards, such as the development of the sandspit of Aveiro, that led to the creation of a lagoon, followed by the progressive silting and closing of many coastal lagoons and estuaries, like Pederneira, Alfeizerão, Óbidos and Atouguia (Fig. 2) (Dias et al., 2000). Human actions, coupled with the subsequent climate deterioration during LIA period, possibly triggered dunes destabilisation and their inland migration.

Documents from the fifteenth and sixteenth centuries prove the increase in land use in the regions of Aveiro, Mondego and Atouguia (near Peniche in Fig. 2), with woody areas, small lagoons and wetlands near the coast and the dunes being transformed into croplands (Baeta-Neves, Vol. IV: 204, 205; Vol. V, Fasc.1: 57, 58). In this period also, with the beginning of the Portuguese Discoveries, the increase in shipbuilding and the expansion of urban areas led to the overexploitation of forests, particularly oak and pine. The ones located near coastal areas were deeply affected, as they were more accessible than the forests in the mountainous regions (Rego, 2001).

The decline of the forests and the scarcity of wood storage increasingly worried the authorities, and some attempts were made by monarchs to encourage afforestation. For instance, the *Lei das Árvores*, "Law of the Trees", promulgated by King Filipe I in 1565 prohibited the removal or cutting of vegetation and encouraged landowners to plant trees, pine or chestnut trees, in wastelands. This law was not enough to restore the degraded forest, but it opened the way for one of the main objectives of the future forestry policy, the afforestation of all the lands considered unsuitable for agriculture (Devy-Vareta, 1986).

Until the mid-sixteenth century, deforestation continued and increased, due to the expansion of crops and the intensive use of wood for shipbuilding, but also for industrial purposes, like glass production and metallurgy, urban construction, grazing and wildfires (Devy-Vareta, 1986). This intensification of human activities and land use transformations, mainly in the river basins, was causing changes to coastal environments, particularly on the western façade, contributing to higher sediment supply on the coast (Freitas and Dias, 2017). Large volumes of sands arriving to the shore through rivers were released into the littoral drift and distributed along the beaches, feeding the dunes. Historical sources reveal a rise in sand encroachment episodes from the sixteenth century onwards. In the seventeenth and eighteenth centuries, there are many descriptions of problems with the windblown sand and the damage caused to villages and arable lands in Costa de Lavos, Apúlia and Fão (Fig. 2). The social and economic impacts of these hazards are not well known, except that in the worst cases lands and settlements were abandoned.


**Figure 2**: Location of documented sand drifts events referred to in the text. Red stars represent the sites with documented sand drifts events. Blue squares are the lagoon and wetlands. Black triangles are the ports and estuaries with silting problems: 1- Aveiro; 2- Esposende (Cávado River mouth); 3- Guadina River mouth; 4- Leixões; 5- Mondego River mouth; 6- Porto; 7- Sines; 8- Viana de Castelo; 9- Vila de Conde.
*Sources*: ESRI base map. The hill shade map was derived from Aster Digital Elevation Model for Portugal, 30 m spatial resolution (DatumWGS_1984) and elevation referenced to mean sea-level (MSL), Cascais vertical Datum.

There is not much information about how local populations dealt with the blown sands: they were aware of the relevance of protecting the vegetation cover and, in some cases, fences were built to safeguard assets (Lopes, 2019). Most data in the archives is about the damage caused by the sands, not so much about the solutions to avoid them. One of the best strategies, though, also useful to avert coastal risks, was to not live on the beach or dunes. The open coasts of the Portuguese western facade, especially the low-sandy areas, were indeed sparsely populated until the end of the eighteenth century. The coast was a marginal utterly unattractive territory, due to lack of fresh water and proper soil for agriculture and its exposure to many dangers, such as strong winds, storms, tsunamis, coastal overwashes and piracy (Bastos et al., 2012; Freitas, 2016a). People rather lived in nearby inland areas, where they could explore both land and maritime resources, staying away from the perils of the shore. As in many other countries, dunes were the key between these two worlds, providing complementary areas for domestic incomes, being widely used for hunting and grazing (Huddart, Roberts and Gonzalez, 1999), and their vegetation was collected for roofing and winter fodder (Provoost, Jones and Edmondson, 2011). Population only settled on the beach and dunes during the summer months, more suitable for maritime fishing, during the rest of the year they were farmers or fished in sheltered waters, like rivers and lagoons. Because of their temporary residence along the shore, fishers did not build permanent houses near the sea. They developed, however, temporary homes able to endure in such a harsh and unstable environment. The typical construction of the Portuguese low sandy coasts was the *palheiros*, wooden houses on piles (Fig. 3), which allowed the movement of the sand and the passage of the waves. They were also easily raised to avoid being buried, or moved in response to coastline changes (Freitas, 2016b). The *palheiros* were entirely made of easy-to-get materials: wooden planks as walls and marram grass or other sand plant species roofing (Oliveira and Galhano, 1964). It is difficult to say when the *palheiros* started being used, Peixoto (1990) refers to the thirteenth century, but they only disappear from the coast at the beginning of the twentieth century. These constructions were as ephemeral as the dunes where they were installed and their substitution by masonry buildings brought significant changes to the pattern of coastal settlements and had negative impacts on this environment (Freitas and Dias, 2017).

## Fixing dunes: from barren land to productive forests

John McNeill (2001: xxii) says the twentieth century was different from all others due to the intensity of global change and the role of humans in that process: new social, political, economic and intellectual patterns evoked new ways of life, mass production and consumption. Significant, socio-environmental transformations occurred also at the littoral. The "lure of the sea", as Alain Corbin (1994) calls it, made western societies shift towards the coast, installing cities and services next to the ocean. Just

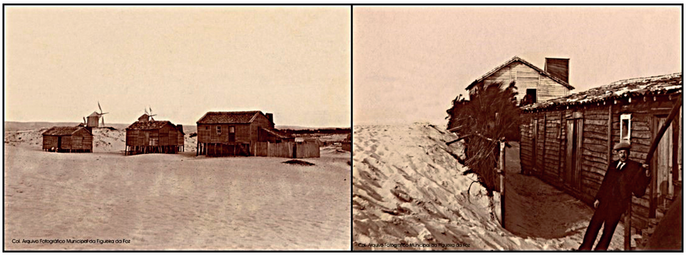

**Figure 3**: Photos with typical stilt houses [*palheiros*] from Costa de Lavos dunes.
*Source*: Arquivo Fotográfico da Câmara Municipal da Figueira da Foz.

before that, as nations turned to the exploration of their national and overseas territories and resources, the problem of the "pernicious movement of the sands" (Ribeiro and Delgado, 1868: 69) had to be solved. Experts and authorities considered then that the best solution was to trap dunes with vegetation and trees, thus converting them into forest areas with the double purpose of preventing the destruction of fertile land and increasing economic value (Annales de L´Agriculture Française, 1806: 11-14; Bremontier, 1833: 180-183; Bortier, 1874: 24; Mouls, 1866). Forests were thought to improve the climate and seasons, protect the streams and harbours from silting and provide timber, firewood, planks, resins and tar, precious resources that nations needed for their development (Silva, 1815: 19, 20). The work of converting the sterile white sands into green forests was regarded as an urgent need because of the benefits this could bring to local and national economies (Borges et al., 1897: 4, 35). Underlining the relevance of this work, the Portuguese forester C. Pimentel wrote: "where today there are only naked hills, later lush woods will be found. […] Which today only brings us misery and destruction, in the future will be a perennial source of wealth" (Pimentel, 1873: 64-65). At the time, there was a sense that nature had to be organised for human ends, it was a matter of "ordering chaotic nature, a wilderness, into a world of lightened culture" (Hughes, 2004: 29-30). Hard human work and technology were being used for building a landscape for the future (Rei, 1940: 40-42; *Repovoamento Florestal* [194-]: 16, 18; Freitas 2004).

At the beginning of the nineteenth century José Bonifácio Andrade e Silva, Portuguese General-Chief of Mines and Head-Inspector of Forests, made the first experiments to fix the sands of Lavos. He is considered responsible for the introduction of dune afforestation techniques in Portugal, based on French and German models (Vieira, 2007: 227). Sent abroad in 1790 by Queen Maria I to study the latest developments in chemistry, mineralogy, metallurgy and forestry, Andrade e Silva travelled through

Europe for 10 years, visiting France, England, Scotland, Germany, Sweden, Norway, Denmark and other countries. His work, about the relevance of tree planting published in 1815 is a kind of handbook on dune sowing, based on the theoretical knowledge learned in foreign lands and the practical experience acquired through his experiments on the Portuguese coast. Soromenho-Marques and Pereda-Garcia (2017: 51) considered his writings the genesis of public environmental policy in Portugal, even though the term had not been invented yet. At the time concerns about environmental issues were quite different from present ones, Andrade e Silva, nevertheless, believed afforestation to be highly beneficial, improving local climate, air and soil qualities. He also emphasised the public interest of forests, referring to a set of economic gains that justified the increase of green areas (known now as "forestry clusters"), highlighting the urgent need for developing what is called today "spatial planning tools".

In Portugal, the first half of the nineteenth century was marked by political, economic and social problems, due to the Napoleonic invasions, a civil war, several popular uprisings, an economic crisis and institutional instability (Melo, 2017). The transition from an Absolutist to a Liberal Regime brought many alterations to the established forest management paradigm. The 24 July 1824 law, decreeing the creation of the General Administration of Forests of the Kingdom [*Administração Geral de Matas de Reino-AGMR*], responsible "for the pine forests and coastal dunes of the Crown" (*AGMR* Regulation, 1824), was a milestone in the history of coastal dunes and forest policies. It promoted new management measures and protection programmes, leading to the development of specific legislation to solve the problems of land use and cover. In 1832, Mouzinho da Silveira's law reinforced local powers, allowing the municipalities to impose some resolutions to prevent sand invasion. For instance, in some locations the cutting or pulling of vegetation growing in the dunes was forbidden, as these actions destroyed protection against the wind (*Posturas do Couto de Lavos between 1840-1853, Código das posturas municipais do Concelho da Figueira da Foz, 1877 and 1882*). In other cases, more active measures were taken against drifts. The Municipality of Peniche, for example, decided to fix the surrounding wastelands, creating a forest buffer to prevent soil erosion. These were, however, scattered local interventions. Only after the 1860s did the major works coordinated by the General Administration of Forests start presenting the first practical results (Freitas, 2004).

The late nineteenth century was a turning point for dune stabilisation for two main reasons: i) the onset of the Current Warmer Period, with better weather conditions after 1860 (Sejrup et al., 2010), contributing to the growth of vegetation of the dunes (including new sowing); and ii) a bigger interest from national and local authorities to support – with human and financial resources and legal tools – dune afforestation (Tudor, Ramos-Pereira and Freitas, 2021). The passage of the General Administration of

Forests [AGMR] to the new Ministry of Public Works, Commerce and Industry in 1852 was the beginning of the implementation of a systematic scheme of works on the dunes (Rego, 2001). Such investment was also justified by the worsening of the problem, with sands affecting maritime and river traffic and trade, and therefore local and national economies. Reports abound about the blocking of river channels and the silting of estuaries and coastal lagoons. The Mondego River was one of the most troubled areas. A similar situation was described in the Cávado River (Fig. 2), where the local municipality forbade the cutting of shrubs and required the cleaning of roads to avoid the dispersion of sands (Lopes, 2019). The silting of rivers also resulted from increasing precipitation, responsible for the accumulation of large amounts of sediments at their mouths and along the banks during periods of floods. Many engineering works and dredging were then done to improve river navigation and access to maritime ports.

In 1866, with the extension of liberal laws, many of the Old Regime assets and rights – ecclesiastical, aristocratic and common – became public property under state administration. The lack of knowledge about some of the afforested areas – size and situation – was emphasised in the parliamentary debates and concerns were raised about the challenge of their public management. Hence, to proceed to the recognition of the "lands whose afforestation is necessary and useful", Andrade Corvo (Minister of Labour) requested a technical report that included an inventory of the dunes and lands that needed intervention (Corvo, 1875: 19). The instructions for the preparation of the report stated that it should incorporate "dunes and adjacent lands with a maximum width of 5 kilometres, defining as boundaries the orographic accidents, the limits of forests and the confining cultures" (Corvo, 1875: 19). In 1868, in response to the Minister's request, the engineers Carlos Ribeiro and Nery Delgado presented the General Report on the Country's Afforestation [*Relatório Acerca da Arborização Geral do Paiz*], which described the wastelands that should be converted into forests, which were mainly coastal and mountainous areas (Ribeiro and Delgado, 1868: 21). The map made for this report (Fig. 4) presents the barren lands of Portugal [*Mapa de Incultos*], including a rigorous delimitation of coastal dunes from Guadiana River (on the southern border with Spain) to the Minho River in the north (see location in Fig. 2), with a precision never reached before (Melo, 2017: 65).

Almost 5 million hectares of sterile lands were identified, equivalent to about 60% of the mainland territory, with an estimated area of 72,000 hectares of mobile coastal dunes to forest. For instance, from Pedrogão beach (Fig. 4) to the Mondego, the transgressive dunes were almost 18 kilometres in length and on average 5 kilometres in width, sometimes reaching up to 8 kilometres inland. Despite the existence of some well-developed forests, such as Urso and Leiria (FU and FL respectively in

Fig. 4), the sands invaded the Ervedeira lagoon and Coimbrão village and were silting the mouth of River Lis (all toponyms in Fig. 2 and Fig. 4). This report reflects the extraordinary dimension of sand drift events and denotes the government's interest in forest and dune management. The initial stabilisation works followed Andrade e Silva's instructions, based on the methods of Burgsdorff[1] and Bremontiér.[2] Later, with the creation of the Portuguese School of Forestry in 1865 (Baeta-Neves, 1984: 153-174), and the development of a corps of graduated foresters, those methods were progressively adapted to the local social and environmental conditions.

Typically, fences and plants were used to stabilise dunes. Grasses (*Ammophila arenaria* and *Leymus arenarius*), pine (*Pinea marítima*) and a wide range of autochthone species, such as *Artemisia crithmifolia, Triticum junceum, Arundo arenaria, Spartium album, Spartium grandiflorum* and *Ulex europaeus* were recommended by Andrade e Silva, according to his learnings abroad and his experiences in Lavos (Silva, 1815). The afforestation works, like in France, were based on the sowing of maritime pine trees, but first, to stabilise the sandy soils so that the pines could thrive fences were installed and grasses planted in the dunes closer to the sea, to break the winds. When foredunes were stabilised, they offered protection to those behind, creating favourable conditions for the trees to grow and a forest to develop. The French and German techniques provided instructions for the different stages and the sequence of the works, as well as the materials and vegetation species to be used. Several technical reports written by Portuguese foresters describe the efforts to fix the dunes from the north and central coast of Portugal (Fig. 4). The task of preventing the hazardous sand drifts was full of difficulties and setbacks: the chronic lack of financial resources and labour, the frequent loss of plants due to heat, sand burying and sea flooding all turned dune afforestation into a harsh slow procedure (Mendia, 1881; Mesquita, 1885; Pimentel, 1882; Freitas, 2004). There were, nevertheless, clear signs that the authorities were decided to keep up with the stabilisation of the dunes. In 1886, the government promulgated a law that laid the foundations of the Forestry Services in Portugal. Further legislation to prevent sand drift followed in the next decade. In 1897, the Forestry Services presented a National Afforestation Plan for the dunes, to implement between 1897 and 1916, consisting of interventions in specific perimeters (Borges et al., 1897). The plan included an inventory of all

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1 Freidrich Ludwig von Burgsdorff (1747-1802) was responsible for the Forests in Brandenburg (Prussia).

2 Nicolas Thomas Brémontier (1738-1809), engineer of Ponts and Chaussées, was nominated in 1784 to work in Bordeaux, France. His famous report – Mémoire sur les dunes et particulièrement sur celles qui se trouvent entre Bayonne et la Pointe de Grave, à l'embouchure de la Garonne – set the method for dunes fixing, explaining the techniques applied and the advantages of such works.

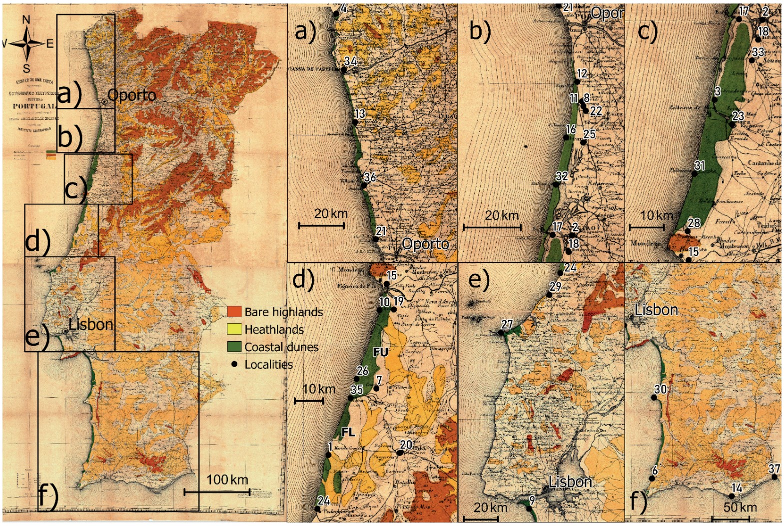


**Figure 4**: Map with the barren lands of Portugal, retrieved from Ribeiro and Delgado (1868), scale 1/50,000 – left image. The dunes are represented in a green colour and zoomed in six images. The main cities and the toponyms cited in the text are also represented in alphabetical order: 1- Águas de Medeiros; 2- Aveiro; 3- Barrinha; 4-Camarido; 5- Cantanhede; 6- Carrapaterira; 7- Coimbrão; 8- Cortegaça; 9- Costa de Caparica; 10- Costa de Lavos; 11- Esmoriz; 12- Espinho; 13- Esposende; 14- Faro; 15- Figueira da Foz; 16- Furradouro; 17- Gafanha; 18- Ílhavo; 19- Lavos; 20- Leiria; 21- Leixões; 22- Maceda; 23- Mira; 24- Nazaré; 25- Ovar; 26- Pedrogão Beach; 27- Peniche; 28- Quiaios; 29- São Martinho do Porto; 30- Sines; 31- Tocha; 32- Torreira; 33- Vagos; 34- Viana de Castelo; 35- Vieira Beach; 36- Vila de Conde; 37- Vila Real de Santo António. FU and FL are the large forests of Urso and Leiria, respectively.
*Sources*: original map: *Biblioteca Nacional de Portugal*. The original map was georeferenced with *ArcGis Pro 10.7 software.*

active dunes, identifying the sites with an urgent need for afforestation, the costs and their situation. The study estimated an approximate area of 37,000 hectares to be fixed, almost half of what had been reported in 1868 (Borges et al., 1897: Chapter 1, Art. 10), which can be explained by the fact that many coastal dunes were already sown in 1896 and some were completely stabilised (Freitas, 2004).

In the beginning of the twentieth century new legislation established the Forest Regime in Portugal, regulated by two decrees from 1901 and 1903 (Germano, 2000). According to these acts, coastal "forest perimeters" corresponded to vacant lots, both state and private, in a 500 metre wide area from the coastline, totally or partially submitted to the forest regime. For example, according to the 1903 Law, the dunes of Costa de Lavos, being publicly owned, were submitted to a total forest regime. In Mira, the loose sands not only caused the loss of "magnificent agricultural land", but also drastically reduced the area of the three existing lagoons, which had great relevance for the people of the region (Rei, 1924). Their afforestation was seen as a necessary improvement. For the same reason, in the following years, many municipalities requested the Forestry Services' intervention for several sites in western Portugal: Ilhavo, Gafanha, Pataias, Águas de Medeiros, Mina de Azeche, Alvor, Cortegaça Esmoriz, Maceda, Ovar, Furadouro, Mira and Barrinha (toponyms in Fig. 4). The afforestation works were also considered beneficial to control unhealthy conditions caused by stagnant waters (Melo, 2017). Wind-blown sands blocked the drainage of the fresh waters and/or its renewal inside the lagoons, causing the degradation of water quality and the proliferation of mosquitoes, carriers of malaria. In addition to wetland drainage, lagoons' margins were also afforested to avoid inland sand invasion and for embellishment (Rei, 1914). In the 1930s, during the new political regime called *Estado Novo*, dune control was included in land use propaganda. The sands, still regarded as wastelands, were part of a national campaign for resource exploitation and soil improvement. Further legislation was created with the purpose of increasing the economic potential of these uncultivated areas. In 1938, the Forest Settlement Plan, a large-scale project designed for the following 30 years, determined that the wastelands to the north of the Tagus River and in coastal areas all over the country would be forested (Lei 1:971).[3]Thus, the year 1939 began with a sequence of projects to achieve the afforestation of the dunes (DGSFA, 1939-1942).[4] The *Estado Novo* had more financial and human resources (Fig. 5) to carry out these works than the previous regimes (the Monarchy until 1911 and the Republic from 1911 to 1926). It also had more political (and repressive) power to impose its decisions on local populations and authorities, if these did not comply with the afforestation plans (Rego and Skulska, 2019).

After one hundred years of interventions in the mid-twentieth century, sand drifting problems seemed to have been solved, with almost all dunes fixed in 1947 (Baeta-Neves, 1972: 10). Some sporadic works were still performed in 1959, to the south of Tagus River, on Alentejo coast (Fig. 4), to fix the moving sands north of the Sines port (DGSFA, 1959) and from the Carrapateira dunes. These represented the last phase of the dunes'

3 The Law no. 1971 was proposed by the Corporative Chamber, it was published in 1938 in the *Diário do Governo* and put into practice in 1939.

4 Between 1939-1942, the Direcção Geral dos Serviços Florestais e Aquícolas (DGSFA) published several projects concerning the afforestation of dunes. [*Projecto de Arborização do Perímetro Florestal*…]. Complete reference included in the final list.


**Figure 5**: Sowings in the dunes of Quiaios, 1930s.
*Source*: Arquivo Fotográfico da Câmara Municipal da Figueira da Foz.

afforestation process (*Diário do Governo,* 32 de 2 de Agosto de 1965). The general account of the public afforestation programmes between 1939 and 1965 points to a planted area of about 8255 hectares of coastal dunes (Mendes, 1998).

## Paradigm shifting: dunes as valuable ecosystems

Stabilisation was not the last chapter of dunes and forest management. In the final decades of the twentieth century, a different problem emerged, related with coastal dunes degradation. Since the end of the 1800s, the use of beaches for seaside bathing started, attracting people to the coast. Over the years, the small fishing camps of *palheiros* were transformed into seaside villages, as beaches became recreational and leisure places.

From the 1960s onwards, the progressive migration of population and economic activities towards the littoral as well as the development of seaside mass tourism converted coastal forests, dunes and beaches into most-sought-after areas, increasing the value of these lands. Pressure rose in these spaces and many coastal dunes were excluded from the forest regime upon request of certain municipalities (*Diário de Governo,* 131, 6-1-1968: 854; Freitas, 2004). This was the case with Mira beach and the adjacent dunes as well as two plots near the actual Vila de Paredes beach (previously Paredes) and Mina de Azeche to the south, with the aim of urban expansion and tourism development.

Moreover, other triggering factors, such as hard engineering coastal defences, dredging, sand mining, global mean sea level rise, the decrease of sediment supply to the coast and intense urbanisation contributed to the destruction of existing dunes (Cunha, Pinto and Dinis, 1997). In the meantime, the development of international and national scientific knowledge on coastal systems revealed the role of dunes as unique ecosystems and the last line of defence against sea flooding. In a scenario of climate change and of exponential increase of human vulnerability on the coast, the protection and rehabilitation of dunes became a major concern worldwide.

In Portugal, the democratic regime in 1974 and entrance into the European Union in 1986 were crucial steps for the promotion of nature conservation and the development of a national environmental policy. In following years, coastal dunes were included in the National Ecological Reserve (REN) and in Natura 2000. At an operational level, the first set restrictions to public use of the coast, delimitating coastal protected areas, which include active, inactive and fossil dunes, while the European network Natura 2000 adopted in Portuguese legislation established guidelines to protect coastal systems and their habitats, maintaining the dunes as flexible sea flood defences. In spite of existing legal measures, there have been many conflicts between public and private interests and entities regarding coastal uses and conservation.

## Discussion and conclusion

The Portuguese coastal landscape is characterised by an extensive sand cover area, deposited in its last stage during the Little Ice Age. Historical sources and scientific data show that for more than four centuries, sand encroachment affected many Portuguese settlements. The wind-blown sand heavily affected some communities, especially between the sixteenth and eighteenth centuries. An important factor that triggered the rise of drifting-sand activity after AD 1500 were obviously the weather conditions during LIA. Nevertheless, drifting-sand activity seems to be more related to the pronounced climatic variability and interspersed NAO modes, rather than only the NAO- phase. This reflects the complexity and uncertainty of considering the NAO- related storms as the main trigger for sand drifting. As pointed out by Jackson et al. (2019) the climatic conditions of LIA cannot be attributed to only a single parameter (e.g. increase in storminess), and most likely, the LIA would have involved a set of environmental variables. Storms were responsible for sediment supply to the coast, but not necessarily for the deflation of the sands. As suggested in other studies (e.g. Ramos-Pereira, 1987; Tudor, Ramos-Pereira and Freitas, 2021), anticyclonic dry conditions could be more favourable for sand mobilisation, since during abundant rains water creates a film that aggregates the sand grains and does not provide good conditions to deflation. The above suggests that many drifts retrieved from archives and supported by OSL ages performed on the Portuguese dunes, are correlated with post-storm periods associated with positive NAO mode. However, the continuous NAO+ mode, as occurred during the MCA period, would not have contributed to the increase in dune mobility, since the sediment budget on the coast was probably limited and the optimal climatic conditions allowed the normal growth of plant species of dunes. Once the dunes were vegetated, as referred to in several works (e.g. Danielsen et al., 2011), it was more difficult for sand to be blown by the wind. Moreover, the transition between MCA, LIA and the CWP periods was a gradual process, with irregular climatic fluctuations on European coasts, which mean different timeframes for sand drifts, depending on their location (Clark and Rendell, 2006). Although we can point to the LIA as the major climatic event that significantly altered the dune landscape, the drift processes were much more complex, involving a set of environmental and human factors.

This long-term overview also shows a strong correlation between sand invasion and human pressure on the coast. Historical records worldwide revealed that agriculture and deforestation led to the decline of the medieval forests, promoting soil degradation and an increase in sediment supply (van Mourik, Vera and Wallinga, 2013). Likewise, colder temperatures during LIA must have raised the need for wood for heating and the expansion of agricultural lands to assure crop production. Population subsistence put more pressure on marginal lands, closer to the dunes, exposing communities to the drifting sands. The coastal population in Portugal lived mostly in adjacent inland areas, exploiting in a complementary way both sea and land resources. They often preferred to avoid danger rather than face it. The abandonment of farms and hamlets and the resettlement of relevant buildings, like churches, suggests that populations, being small communities, had some degree of mobility, and there were other lands where they could move. As pointed out by Soens (2018), natural hazards were part of these people's everyday lives. Sand drifts were certainly a significant coastal risk, but not a disaster, a reflection of the resilience of these populations to the climate changes and their ability to cope with harsh environmental conditions (Keyzer, 2016; Bampton et al., 2017; Bampton, Kelley and Kelley, 2018). It was only at the end of the eighteenth century that sand drifting emerged as a national scale problem that had to be solved, due to more proactive governments (and experts) seeking to survey, explore and increase revenue from coastal territories and resources. As Warde (2018: 7-8) explains, this spirit turned "the state of that natural world into a *political* issue", nurtured by public responsibility and resource management, justified as improvement, with the aim of increasing economic earnings. Therefore, for more than one hundred years, the political decision was to fix the sands with vegetation and re-establish a forested area. This task, supported by legislation, specialised services and staff occurred between 1850 and 1965, being at the origin of a great coastal dunes landscape transformation.

This combination of long-term conditioning factors shows that the drifts' origin could be more complex, suggesting that the climate played an important role but was not the only trigger for sand mobilisation. It is likely that prior to 1800, there was a combination of human and climatic drivers, resulting in the extension of drifting landscapes. This is in line with Pierik et al. (2018), who pointed out that the cold conditions during LIA possibly accelerated the expansion of dune fields, although these conditions were initially facilitated by population pressure and overexploitation. From the early nineteenth century onwards, human pressure became a dominant forcing factor, contributing to the stability of the dunes, shaping these environments. Dune fixing strategies in Portugal represented a huge effort to control natural processes, setting the stage for the development of coastal management and specific forest policies, which had significant implications for spatial planning during the next century.

Ideas about dunes and their relevance changed in the twenty-first century. The current issue of coastal management is that it focusses on the present and future, hardly ever considering the past and the long-term human-nature interactions that shaped the dunes' landscapes. New integrated strategies should consider, in addition to adequate legislation and planning instruments, the values of cultural heritage and attend to the environmental history of these areas, because, as this paper shows, dunes and beaches have been deeply human-made. The complexity of the entanglement of human reasons and natural processes is at the root of the problems that coastal management has to deal with now and in the years to come.

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