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Research article

The effectiveness of elevated boardwalks in restoring coastal dunes

Óscar Ferreira

University of Algarve, CIMA/ARNET, Campus de Gambelas, 8005-139, Faro, Portugal

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ABSTRACT

Coastal dunes are important habitats that also play an important role in coastal protection. In areas of high tourist activity, they have often been degraded by trampling and intensive use, resulting in a loss of ecological, aesthetic and protective values. As a result, several management actions have been taken to minimise dune degradation and enhance their recovery. One of these measures is the installation of elevated boardwalks and dune crossovers to regulate human access to the beaches. This paper quantifies and analyses the impact of the installation of boardwalks and dune crossovers on dune recovery in a highly touristic area in southern Portugal. This was done using aerial photographs taken before and 5–10 years after the implementation of the measures, and an effectiveness index was applied. The recovery observed was high to very high, ranging from 51% to 98% of the previously degraded dune. The areas with the oldest interventions showed an average recovery of 86% of the degraded area, while the most recently managed areas showed an average recovery of 69%. The high rate of recovery is mainly explained by the new habits developed by the population and tourists to access the beaches. Nevertheless, in some specific cases (i.e. where the use of the boardwalks requires a detour or where they end far from the beach) new degraded areas were observed, indicating the high relevance of the design of the boardwalks to the final recovery result. This work can serve as a basis for assessing the effectiveness of coastal management measures in any other coastal dune area with similar interventions.

1. Introduction

Coastal dunes are ecosystems of high ecological importance that provide several services, including the protection of human settlements from shoreline retreat, overwash or inundation (Fernández-Montblan et al., 2020; Conery et al., 2020) and the recreational and therapeutic opportunities associated with their aesthetic values (Garcia-Lozano et al., 2018). However, they are often threatened, particularly in places where there is high tourist pressure, and they serve as direct access to beaches. In such areas, these ecosystems are degraded by direct trampling of the dune, construction, raking and by the passage of vehicles used for beach services (e.g. lifeguards, beach cleaning) or recreation. Several studies point to a drastic reduction in dune habitats and an increasing trend of the degradation of coastal dune ecosystems, especially after the 1960s, as a result of increased human pressure associated with massive tourism development (e.g. Gómez-Pina et al., 2002; Muñoz-Vallés and Cambrollé, 2014; Garcia-Lozano et al., 2018). These disturbances, mostly trampling, reduce plant survival and diversity (Hesp et al., 2010) and led to habitat fragmentation and areas of bare sand which, in turn, led to increased vulnerability and erosion (Johnston and Ellison, 2014).

Due to the severe dune degradation observed after large-scale tourism development and increasing coastal occupation, dune restoration projects have been put in place. These include fencing, planting, dune reconstruction and reducing human trampling by installing boardwalks or restricting access to dunes (e.g. Psuty, 1989; Gómez-Pina et al., 2002; Conway and Nordstrom, 2003; Matias et al., 2005; Johnston and Ellison, 2014; Teixeira, 2022). These dune management and restoration approaches protect existing systems from development and reduce human impacts on dune vegetation, allowing the revegetation of bare areas (Delgado-Fernandez et al., 2019).

Sand fencing and planting in combination with beach nourishment and/or dune building are known to be effective methods for creating, restoring and maintaining coastal dune systems (e.g. Mendelssohn et al., 1991; Nordstrom et al., 2000; Matias et al., 2004; Muñoz-Vallés and Cambrollé, 2014; Jackson and Nordstrom, 2018; Itzkin et al., 2021; Teixeira, 2022), which can then act as an effective disaster mitigation solution under current and future sea level rise scenarios (Fernández-Montblanc et al., 2020). The channelling of pedestrian access to boardwalks or dune crossovers to minimise dune destabilisation is also a common coastal management practice (Bernd-Cohen and Gordon, 1998). However, the effects of this restriction alone are not well

E-mail address: oferreir@ualg.pt.

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understood (Prisco et al., 2021) and in particular the consequences for the reconstruction and revegetation of dune systems.

The main objective of this study was to evaluate the extent of dune recovery following the installation of boardwalks and dune crossovers. To this end, an operator-based analysis of the vegetation cover before and after the interventions was carried out, and a new index was used to define the effectiveness of dune recovery. The index was tested in the dunes of Alvor (southern Portugal), an area with high tourist pressure that has caused severe disturbance to the coastal dune system.

2. Study area

Praia de Alvor is located in southern Portugal, on the eastern side of Lagos Bay (Fig. 1), and corresponds to a 3.5 km long sandy barrier peninsula that forms part of the Ria de Alvor barrier system. This consists of two barrier peninsulas separated by an inlet, which has been stabilised by breakwaters since 1990. The inner lagoon is a RAMSAR protected wetland since 1996 and is part of the European Ecological Network, Natura 2000, with high ecological and economic importance (Mateus et al., 2016). The dune system includes embryo dunes and a foredune (or primary dune), forming a relatively coherent and linear ridge that is either stable on its position or, in some of the areas studied, is shifting seaward due to the availability of sand after beach nourishment (Teixeira, 2022). On the landward side, there are secondary dunes, stabilised by the vegetation, which are not active. This grey dune system is not maintained by dune formation processes.

The Bay of Lagos is exposed to the dominant W-SW waves (71% of the time) and E-SE conditions (23% of the time, Costa et al., 2001), which have low to moderate energy for most of the year, but occasionally promote episodic dune retreat during storm events (Teixeira, 2022). The area is mesotidal, with maximum tidal ranges reaching about 3.5 m. The dominant (and higher intensity) wind in the region is from the W-SW, although winds from the E can also have high velocity (but lower frequency) (Costas et al., 2023). The sand in the coastal system is predominantly quartz, ranging from fine to medium sand (Teixeira, 2009).

In the 1960s and 1970s, the rise of tourism led to major changes in coastal development (Proença et al., 2023). This was the case at Praia de Alvor, where the first tourist settlements were built over the dunes in the 1960s, with increasing occupation until the 1980s. This included large buildings, such as the Torralta project (Fig. 1), houses, roads, commercial areas, swimming pools, etc. In addition to direct dune destruction, tourism also resulted in heavy trampling and vehicle use over the dunes, with subsequent degradation of the dune system. Duarte et al. (1999) considered this dune system to be highly degraded and the most vulnerable of all coastal dune systems in the Algarve (southern Portugal) in the 1990s due to the human pressures and a clear negative balance between existing pressures and management/protection actions. A series of management actions were initiated in the 1990s to restore the coastal dunes, starting with beach nourishment in 1992 (Pinto et al., 2018), followed by dune reconstruction and dune demarcation by stakes and ropes (mostly near the embryo dune) (see Duarte et al., 1999; Mateus et al., 2016; Teixeira, 2022), and a major beach and dune nourishment in 2009 (275,000 m^3, Pinto et al., 2018). More recently, a series of elevated boardwalks and dune crossovers have been installed to allow direct and controlled pedestrian access to the beach. The first part of this management intervention, in the western sectors of the study area, took place in the first half of 2011, while the boardwalks located in the eastern sectors were installed in 2016. During this last part of the intervention, a roundabout and a car park were relocated 60 m inland, while several other car parks were redesigned. Finally, in 2019, a dune and beach replenishment of 250,000 m^3 was carried out in the eastern part of the study area. The dune nourishment consisted of placing several mounds of sand at places where embryo dunes should exist (see Teixeira, 2022), but not over the grey dunes, pathways or other bare sand areas caused by human stress.

3. Methods

The analysis of dune recovery following the installation of elevated boardwalks and dune crossovers was carried out by examining aerial imagery using an operator-based classification method. The study area was divided into eight sectors (BS1 to BS8, from west to east), according to the type of intervention (i.e. cross-shore boardwalks, cross-shore and longshore boardwalks), their geographical relationship and the area of intervention (e.g. bounded by a car park or by a beach restaurant) and the time of the intervention (i.e., 2011 or 2016) (Fig. 1 and Supplementary Table 1). Two control sectors located on either side of the Ria de Alvor inlet (CS1 and CS2, Fig. 1 and Supplementary Table 1), which were not subject to the installation of boardwalks, were also studied in order to compare their evolution with that of the intervened sectors. The images used were obtained from Google Earth Pro and analysed at the highest resolution available. The dates chosen for the analysis, based on the quality and availability of the images, were June 2007 (degradation before interventions, for the western sectors BS1 to BS5 and the control sectors), May 2015 (degradation before interventions, for the eastern sectors BS6 to BS8) and May 2021 (recovery after interventions, for all sectors considered). Bare sand areas and paths were mapped for all

Fig. 1. Location of the study area, including the acronyms of the sectors analysed (CS – control sectors; BS – sectors with boardwalks). Image from Google Earth, May 2021, 37°18′15 N 8°38′21 W, eye alt 5.25 km.

sectors, including the control sectors, representing conditions before and some years after the installation of boardwalks (10 years for the eastern and control sectors and 5 years for the western sectors). Bare sand was considered where there was no evidence of vegetation or where vegetation was extremely limited. Only bare sand areas associated with human activities were mapped, including dune degradation by trampling, use of vehicles or parking over dunes, etc. (Fig. 2). Natural bare areas, especially near embryo dunes or foredunes or caused by overwash, were not mapped (Fig. 2C and D). Pathways and bare areas were considered recovered and therefore not mapped if vegetation cover confirmed that there had been no consistent trampling for a period sufficient to provide consistent vegetation cover (Fig. 3). Sometimes parts of trampled paths were considered recovered while others showed continuity of bare sand and were still marked as degraded dune (Fig. 3D). All non-vegetated areas with a width of 2 m or more were considered as “bare areas” and a polygon was mapped for each of them with a corresponding measured area (m^2). Trampled paths were less than 2 m wide and were marked as lines with an associated length, which was then converted to an area. To convert paths into areas, the widths of 61 path cross-sections were measured, ranging from 0.4 m to 1.9 m, with an average of 1.03 m. The overall average was similar for control sectors (1.00 m) and managed sectors (1.05 m), with a slight difference being observed between cross-shore trampled paths (average of 1.2 m) and alongshore trampled paths (average of 0.8 m). A final rounded value of 1.0 m was used to convert path length (m) into bare area ($X\ m * 1\ m = X\ m^2$).

A simple index (Ie) was used to define the effectiveness of the dune recovery after the installation of the boardwalk:

$$Ie = 100\ \%\ x\ \frac{(initial\ bare\ area - final\ bare\ area)}{initial\ bare\ area} \quad (1)$$

A value of 100% represents a full recovery of the analysed sector and 0% represents no recovery at all. Negative values represent an increase in bare areas during the period analysed. It should be noted that an X% recovery does not mean that X% of the pre-existing bare areas and paths have recovered. For example, it can mean 100% of recovery of pre-existing dune disturbance and the creation of new bare areas, as the use of the boardwalks can also create new habits that lead to new paths or bare sand areas. Therefore, the analysis was not performed pathway by pathway or area by area, but by mapping the entire sector. To assess and minimise errors, the georeferencing error of the images was analysed using 17 fixed points (see Supplementary Table 2). For 2007–2021, six points from BS4, BS5 and CS1 were used. For 2015–2021, eleven points from BS6, BS7 and BS8 were used. The images of 2021 were used as a reference to calculate the differences. The average root mean square errors were 0.23 m and 5.08 m, for the periods 2015–2021 and 2007–2021 respectively. The error observed between 2007 and 2021 mainly represents a west-to-east shift (average of about 4.5 m), which was taken into account in the delineation of the areas to ensure that the same areas were analysed for different years.

As dune recovery means the dominance of vegetated areas and not 100% of vegetation cover, the percentage of dune cover in recovered areas was also calculated. This was done by randomly marking seven polygons, all located in former bare areas (0% of vegetation by 2007 or 2015, depending on the sector). The percentage of dune vegetation coverage was calculated by mapping the dune vegetation patches within the polygon in 2021, calculating their area and comparing it with the total area of the polygon. The polygons were placed on foredunes (two) and grey dunes (five) (Fig. 4), including two in the control sectors, but in places where there had been no visible human activity in recent years.

In order to compare the vegetation of the recovered areas (former bare sand areas/trampled paths) with the surrounding natural (control) areas, seven areas were selected to observe and catalogue the existing vegetation. These seven areas were located in sectors BS7 (four), BS6 (two) and BS4 (one), including the foredune, the lee side of the foredune and the secondary dunes (see Supplementary Table 3 and Supplementary Fig. 1).

In the absence of high quality topographic surveys carried out before the management actions, analogues were used to analyse potential topographic changes between recovered and degraded dune areas, namely pathways. To this end, eight topographic profiles at existing paths and nine profiles at nearby recovered areas were surveyed using a GNSS-RTK system, with a vertical and horizontal resolution in the order of 2 cm. The profiles were located on the foredune, on the lee side of the foredune or on the secondary dunes (up to about 100 m inland) (see Supplementary Table 4 and Supplementary Fig. 2). The trampled area was marked in all profiles. For recovered profiles, it was necessary to interpret (in the field) what was the position of the trampled area prior to the recovery. The trampled width and height (vertical difference between the lowest trampled point and the elevation of the trampling start) were calculated for all profiles (see Supplementary Fig. 3), as well as their average values.

4. Results

The comparison of bare sand areas and paths before and after the

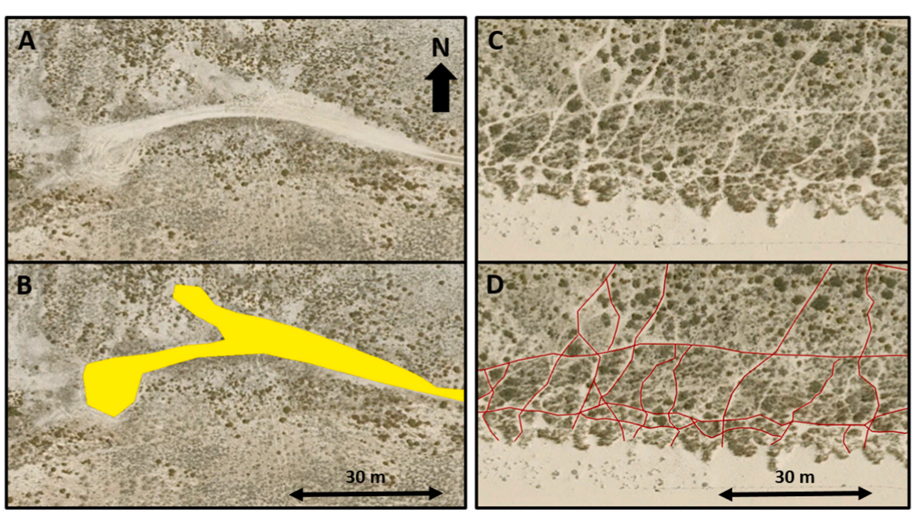

Fig. 2. Examples of (A) bare sand areas degraded by vehicles and (B) corresponding mapped areas, and (C) trampled paths and (D) corresponding mapped lines. C and D also include natural bare sand areas (with embryo dune formation), which are not marked as they do not result from direct human impact. Red lines represent tracks/paths and bare sand areas are mapped as yellow polygons. Google Earth images June 22, 2007.

Fig. 3. A sector with a high density of trampling paths, the bare sand area surrounding a beach bar in 2007 (A) and full recovery in 2021 (B). A sector with a lower density of trampling paths and a large bare sand area associated with a car park in 2015 (C) with recovery of the bare sand area in 2021 (D) and partial recovery of the trampling paths. The red lines represent the pathways mapped in 2021, which have been retained in the 2015 image to allow a better comparison of the evolution. Google Earth images June 2007, May 2015 and May 2021.

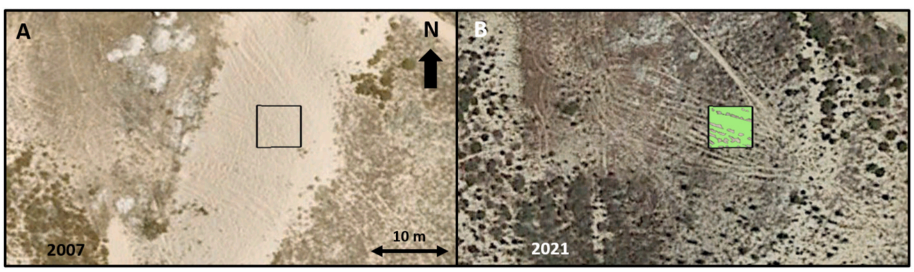

Fig. 4. Example of a polygon used to determine the percentage of dune vegetation cover, before (2007) and after (2021) dune recovery at a grey dune. Vegetated areas within the polygon are shown in light green. Google Earth images, June 2007 and May 2021.

installation of elevated boardwalks and dune crossovers shows a high recovery in all managed sectors, whereas the control sectors showed a variable behaviour with an average slight recovery. The control sectors showed 3303 m^2 of trampled paths and 6462 m^2 of bare sand areas, in 2007, resulting in 9765 m^2 of degraded dunes (Table 1, Fig. 5). In 2021, these values changed to 1986 m^2 of paths and 5519 m^2 of bare sand, giving 7505 m^2 of dunes without vegetation due to human pressure. The managed western sectors (BS1 to BS5) had 10,707 m^2 of bare dunes in 2007, divided into 6154 m^2 of paths and 4553 m^2 of bare areas. By 2021, the recovery was evident, with the total value of degraded dunes being reduced to less than one fifth (1794 m^2), split between 710 m^2 of paths and 1084 m^2 of bare sand areas (Table 1, Fig. 5). For the eastern sectors (BS6 to BS8), with boardwalks and crossovers built in 2016, the total degraded area decreased from 6392 m^2 in 2015 to 1777 m^2 in 2021 (Table 1, Fig. 5). This corresponds to a 75% reduction in bare sand areas (from 5572 m^2 to 1415 m^2) and a smaller reduction in pathways (from 820 m^2 to 362 m^2). The percentage of degraded dune areas in relation to the total area of the sector before interventions was higher in the sectors close to the tourist activity (BS4 to BS8, Fig. 5B), with a strong reduction in 2021 for all sectors except the control ones.

The recovery index values for the control sectors, where no boardwalks or trampling restrictions were implemented, were 29.2% and −22.9% (a negative value indicates an increase of the bare sand area) for the western and eastern sectors, respectively (Table 1, Fig. 5C). Although some of the initial bare areas recovered almost completely, new areas were formed, partially compensating for the observed recovery (CS1) or even increasing dune degradation (CS2) (Fig. 6A and B). Sectors BS1 to BS5, where access to the dunes was managed by installing boardwalks in 2011, showed Ie values ranging from 51.2% to 97.8% (Table 1, Fig. 5C), with a weighted average value of 86.4%. This

Table 1
Pathways and bare sand areas, per sector and as a percentage of the area considered for each sector, for 2007, 2015 and 2021. Ie values, per sector, for 2007/2021 and 2015/2021.

	2007 (CS1-BS5)/2015 (BS6-BS8)				2021				2007/2015- 2021
Sector	Pathways (m^2)	Bare Sand (m^2)	Total (m^2)	% of the sector	Pathways (m^2)	Bare Sand (m^2)	Total (m^2)	% of the sector	Ie (%)
CS1	3270	5363	8633	4,6	1654	4460	6114	3,2	29,2
CS2	33	1099	1132	1,5	332	1059	1391	1,8	−22,9
BS1	560	113	673	2,8	160	0	160	0,7	76,2
BS2	2229	0	2229	3,4	49	0	49	0,1	97,8
BS3	734	464	1198	4,2	148	65	213	0,7	82,2
BS4	2565	3224	5789	15,8	322	651	973	2,7	83,2
BS5	66	752	818	10,4	31	368	399	5,1	51,2
BS6	159	2703	2862	20,4	206	426	632	4,5	77,9
BS7	569	2453	3022	6,9	129	805	934	2,1	69,1
BS8	92	416	508	5,1	27	184	211	2,1	58,5

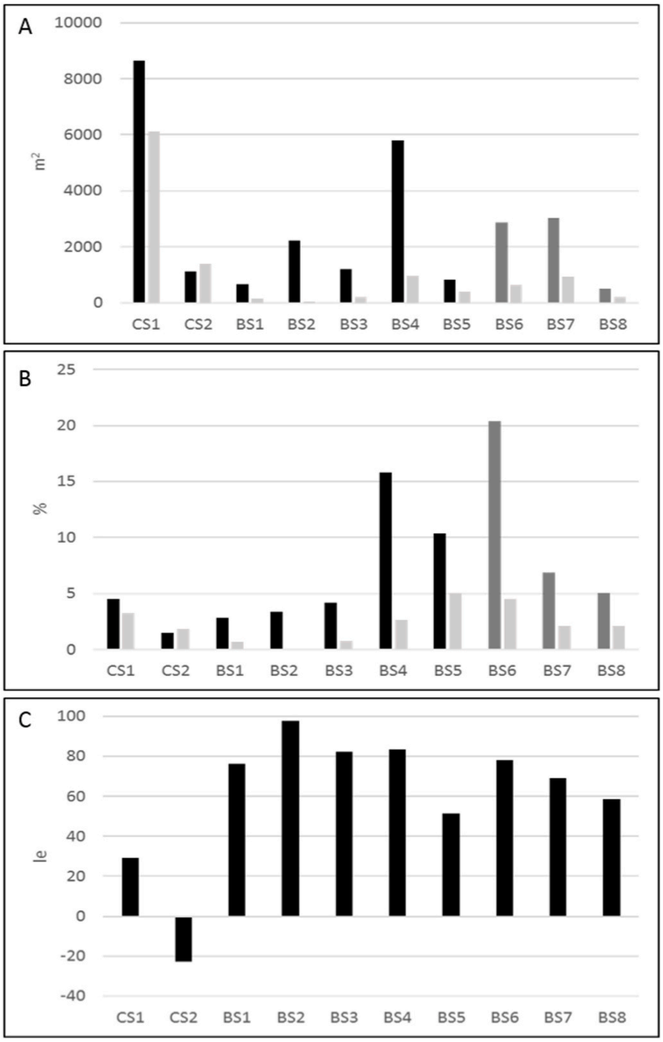

Fig. 5. Total (bare areas + pathways) degraded dune area (A) and percentage of degraded dunes (B) for 2007 (black; Cs1 to BS5), 2015 (dark grey, BS6 to BS8) and 2021 (light grey), and recovery index value (C), per sector.

indicates a high effectiveness of the management actions on dune revegetation (Fig. 6C and D). The low Ie value observed in BS5 (51.2%) is related to the presence of recovery prior to the analysis period, due to the crossovers installed at this location before 2007 and the maintenance of beach access for authorised vehicles (i.e. lifeguards, marine police). In a few cases, however, new footpaths were created as a direct response to the design of the boardwalks. This was the case where the boardwalk ended at a viewpoint a few tens of metres from the beach (BS2). As there is no direct connection from the viewpoint to the beach, the visitors created three new paths by trampling the dune (Fig. 6E and F and Supplementary Fig. 2d).

Sectors BS6 to BS8, where the boardwalks and crossovers were placed in 2016, had a recovery rate (from 2015 to 2021) between 58.5% and 77.9% (Table 1, Fig. 5C), with a weighted average Ie of 69.3%. These sectors are under greater pressure from tourism. In some specific locations, the old footpaths still exist, with tourists passing under the boardwalks, as their use would mean a detour from a car park or an existing access (Fig. 7). In this analysis, only the period after construction of the boardwalks was considered and only for dune areas that had not been restored by any other direct management interventions. It should be noted that for the western sectors, the analysed period of recovery after management actions was about ten years (from 2011 to 2021), while for the eastern sectors, the analysed period after interventions was only five years (2016–2021).

Vegetation cover in recovered areas ranged from 62.1% to 85.6%, with a weighted mean of 78.3% and a standard deviation of 7.1%. There was no clear difference in the final percentage of vegetation cover between grey dunes and foredunes, or between managed and control sectors. Any area with a grey tonality was considered vegetated and only clear white areas within the recovered area were considered non-vegetated. Thus, values may be slightly overestimated due to image resolution and visual pixel aggregation, as it is not possible to identify bare sand areas below (or similar to) the pixel resolution (25 cm in the May 2021 images). The ecological succession of the recovered areas was similar to that of the surrounding natural (control) areas, but with a lower cover density. On the foredune and its lee side, species such as *Ammophyla arenaria, Malcolmia littorea, Crucianella maritima* and *Medicago marina* were among the most abundant. The secondary dune is strongly dominated by *Pycnocomon rutifolium*, in all areas (see Supplementary Fig. 1 and Supplementary Table 3). Only one of the sites analysed showed a clear difference between the recovered and the control (natural) vegetation. This occurred in a recovered area that was formerly a car park (Fig. 7a), currently dominated in places by *Carpobrotus edulis* (see Supplementary Fig. 1c).

The analysed topographic profiles show no relevant differences in morphology between degraded (trampling) and recovered profiles, with an average width/height of 1.67/0.10 m for degraded areas and 1.69/0.11 m for recovered areas (see Supplementary Table 4 and Supplementary Figs. 2 and 3). This means that there was no morphological recovery of the trampled areas, neither on the dune lee side of the foredune nor on the secondary dunes. However, small foredunes or embryo dunes grew on some former areas of bare sand bordering the beach, as observed in the field (not measured as there was no way to define a former bare sand surface).

5. Discussion

5.1. The Ie index application and limitations

Indicators of dune vulnerability are widely used and have been implemented for several decades (e.g. Williams and Bennett, 1996; Duarte et al., 1999; Garcia-Lozano et al., 2020; García-Mora et al., 2001; Williams et al., 2001; Judge et al., 2003; Sancho et al., 2012; Muñoz-Vallés and Cambrollé, 2014). Recently, a new set of indices has been proposed to assess the potential for future dune restoration in coastal areas (Garcia-Lozano et al., 2020). However, the use of indices to categorise dune recovery is not so common and the few existing ones are mostly related to the ability to retain sand within fences (see Matias et al., 2004), which requires intensive and long-term monitoring programmes. Such indices are not easily applicable to the recovery associated with other coastal management actions, such as elevating boardwalks or the regulation of pedestrian access. The index (Ie) presented here is easy to apply, replicable for all other coastal dunes, and can use existing and accessible imagery (for instance from Google Earth or other open data sources). Due to its ease of use, it also has limitations. It does not include a vertical (volumetric) assessment of the dune recovery, using vegetation growth as the most relevant indicator of dune recovery capacity. In systems such as the one studied, vegetation is expected to promote habitat diversity compared to the previously degraded dunes (Prisco et al., 2021; Talavera et al., 2022). In turn, the increase in dune vegetation is also responsible for a reduction in dune mobility, thereby increasing stabilisation (Arens and Geelen, 2006), which is likely to have occurred in the Alvor dunes. Ie alone cannot identify these morphodynamic feedbacks and, due to its simplicity, will not inform about such aspects of dune evolution. The Ie index does not provide direct information on plant diversity and a comparison of ecological status between natural and recovered areas, but simply represents the ability of dune vegetation to recover after dune disturbance ceases. The complementary dune vegetation survey carried out as part of

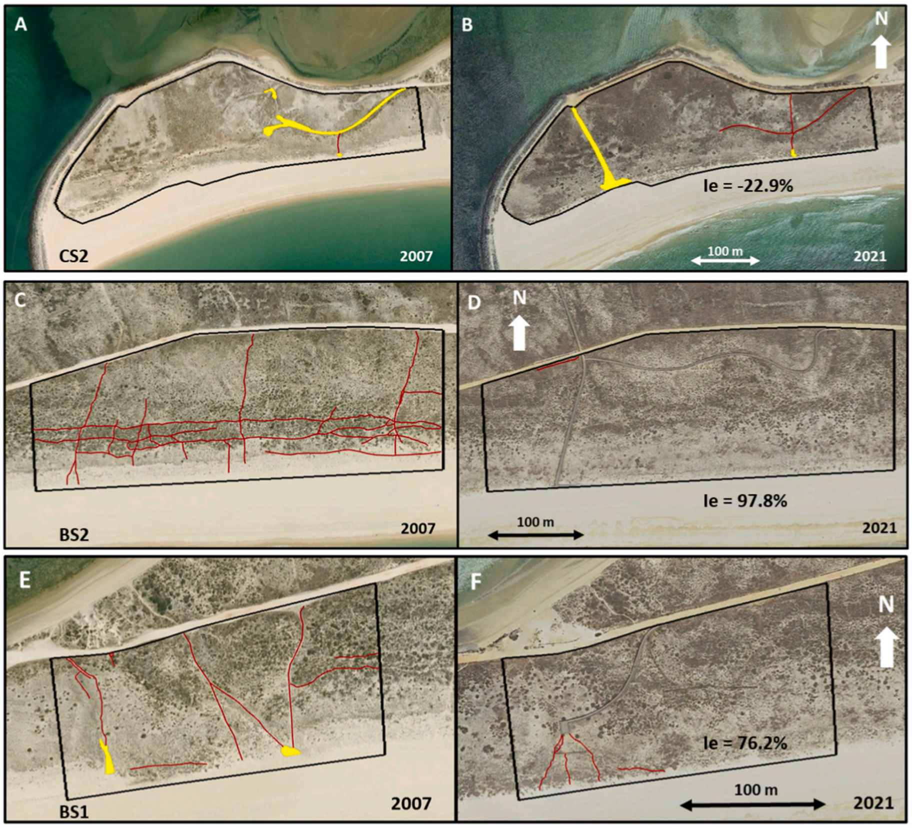

Fig. 6. Comparison of degraded dune areas in control sector CS2 between 2007 (A) and 2021 (B), with partial recovery of formerly degraded areas (e.g. from bare sand in A to pathway in B) and creation of new areas (new road over the dune in B), with a negative recovery index (Ie). Example of full recovery of footpaths in sector BS2, between 2007 (C) and 2021 (D), with the only marked trampling path in 2021 being a new one created near the access to the boardwalks (Ie close to 100%). Full recovery of footpaths in BS1, from 2007 (E) to 2021 (F), and the presence of new ones in front of the boardwalk viewpoint (Ie = 76.2%). Red lines represent paths and bare sand areas are shown as yellow polygons. Google Earth images, June 2007 and May 2021.

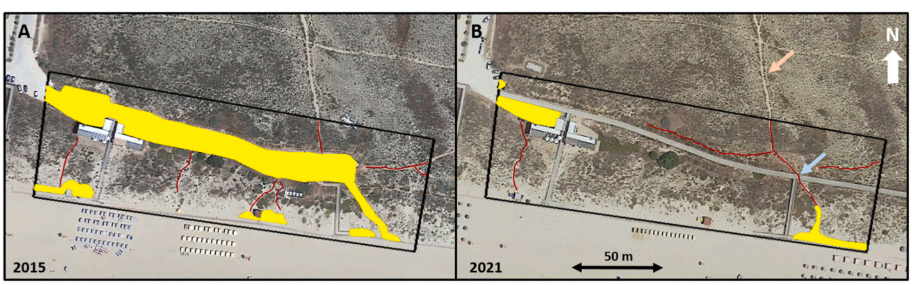

Fig. 7. Example of recovery between 2015 (A) and 2021 (B) for sector BS6, following the installation of a new elevated boardwalk over a former car park on the dunes. Note the continuity of trampling from the still existing car park to the beach (immediately to the west of the beach restaurant), and the continuity of trampling along the northern beach access (light orange arrow) with the new path passing under the boardwalk (light blue arrow). Red lines represent paths and bare sand areas are shown as yellow polygons. Google Earth images, May 2015 and May 2021.

this study confirmed that the vegetation in the recovered areas was generally similar to that in the surrounding natural areas (see Supplementary Table 3 and Supplementary Figs. 1 and 2).

To date, the effectiveness of boardwalks and pedestrian access restrictions on coastal dunes recovery has mostly been evaluated in qualitative terms (e.g. Gómez-Pina et al., 2002; Kinnan, 2004; Johnston and Ellison, 2014; Muñoz-Valles and Cambrollé, 2014; Conery et al., 2020; Prisco et al., 2021). The use of Ie serves as a basis for understanding the effectiveness of dune management actions, allowing quantification and comparison between different sectors of the same coastal area and between different coastal areas. For the calculation of Ie, this work used an operator-based analysis of the dune vegetation. This can be replaced by vegetation indices, such as NDVI (Normalised Difference Vegetation Index) or DUVES (see Talavera et al., 2022). These indices can be particularly useful when comparing larger areas or when using higher resolution imagery. However, they require calibration and a direct application to compare images with different light exposures or subject to seasonality (e.g. different vegetation colour and size) is not straightforward (Talavera et al., 2022).

5.2. New habits and dune recovery

The use of wooden boardwalks, on the ground or raised, and the control of pedestrian access have been shown to be effective in avoiding human impacts on coastal dunes, with direct benefits for dune recovery in different coastal dune environments (Gómez-Pina et al., 2002; Kinnan, 2004; Johnston and Ellison, 2014; Muñoz-Valles and Cambrollé, 2014; Conery et al., 2020; Prisco et al., 2021). For the analysed coastal area (Alvor dunes), the effectiveness of dune recovery was higher than 50% for all managed sectors, with average values of 69.3% and 86.4% for the sectors where management actions were implemented in 2016 and 2011, respectively. In almost all areas analysed, the recovered vegetation is similar to the natural vegetation in the surrounding areas, but with lower vegetation cover densities. The recovered area was colonised by a non-native invasive species (*Carpobrotus edulis*) only in one specific area, a former car park on the secondary dunes. The rapid recovery of dune vegetation has been accompanied by a change in the habits of visitors and beach users, who prefer to access the beach in controlled ways rather than encouraging continuous dune trampling. This is mainly due to an improvement in the comfort and quality of walking, including the possibility of easily carrying trolleys (e.g. for children). It is also beneficial for and the elderly and people with walking difficulties. The vast majority of the sectors do not have ropes and stakes to restrict access to the dunes, allowing visitors to take the shorter route or walk over the dune if they wish. The boardwalks and crossovers have changed the way people reach the beach, creating a new and environmentally positive habit.

The rapid recovery of the dune vegetation and the absence of evolution from bare sand areas to blowouts or sand sheets are associated with relatively mild wind velocities, indicating that when the disturbance ceases, the dune rapidly recovers its vegetation instead of developing mobility. This was confirmed by the comparison of recovered and degraded profiles, both showing similar characteristics. There was no evidence of sand transport, with the exception of the former bare dunes facing the beach, which now have embryo dunes or small foredunes. On the leeward side of the foredune and the secondary dunes there is no evidence of wind driven sand transport. This is consistent with observations from other studies (Arens and Geelen, 2006; Castelle et al., 2019) in coastal areas with higher wind intensity, where dune disturbance was deliberately induced to improve dune mobility. In such cases, it was observed that after the end of the perturbation (months to years), sand transport and dune mobility were low or null, indicating the dominance of biotic over abiotic processes.

The percentage of dune vegetation coverage within the recovered areas (average of 78.3%) is within the vegetation density values observed for a nearby coastal area (Ancão Peninsula, southern Portugal), which has natural vegetation coverages above 50% and maximum values of 85% (Costas et al., 2023). These authors considered that a value below 50% would be classified as a low vegetation cover. This means that when the disturbance is removed, not only is there the possibility of recovery, but also that recovery can rapidly reach values of dune cover that are representative of the natural behaviour of dunes in southern Portugal.

5.3. New and old bad habits

Although the vast majority of the degraded areas showed significant recovery, some of these areas were maintained as footpaths over the dune. This happened when using the new boardwalks would require a detour to reach the beach. Thus, in some cases, direct trampling over the dune continued to provide an easy access to the beach from a car park or tourist resort (see Fig. 7B). In these cases, the "old habits" were still maintained and the vegetation did not recover. Other examples are the existence of footpaths that connect the main road or a car park to areas of the beach that are far away (about 200 m) from the end of the boardwalk (Fig. 8A), in order to reach a less crowded beach zone in summer. In this case, the motivation is to not only save time or walk less, but also to find a quieter spot on the beach.

Some new habits have also led to dune degradation in areas not previously affected. At the very end of the boardwalks, direct trampling often degraded embryo dunes and foredunes, creating small areas of bare sand (Fig. 8B). In one particular location, where the boardwalk did not reach the beach but ended at a lookout point (about 40 m from the beach), a number of new trampling tracks have been created by people descending from the lookout point and accessing the beach by crossing the dune (Fig. 6F).

The above old and new habits confirm that elevated boardwalks and controlled beach access are only used and respected when people make direct use of them. The subsequent recovery of the dune is most likely not a result of increased awareness of the need for dune protection but rather an indirect consequence of the ease of beach access facilitated by the boardwalks and crossovers. This is in line with the findings of Charbonneau et al. (2019), who mentioned a lack of background education on beach users regarding dune function and the rationale for dune management. It was also evident that the area of bare sand is still relatively higher in the sectors with higher tourist activity, namely around beach bars and in specific locations where it is necessary to maintain unvegetated beach accesses for garbage collection or lifeguard and marine police vehicles (as in sector BS5). In such cases, the dune will never recover 100% or to values similar to those observed in the western (less touristic) sectors.

5.4. Management recommendations

Intensively developed coastal areas with less management tend to have less developed dunes (Garcia-Lozano et al., 2020). However, such areas can retain natural dune characteristics if ecological boundaries are allowed to replace cultural boundaries (Conway and Nordstrom, 2003) and management activities are intensified (Garcia-Lozano et al., 2020). Furthermore, the resilience and adaptability of dune systems derive from their biophysical properties (Singhvi et al., 2022), so it is fundamental to have appropriate management measures that respect dune formation and evolution. One appropriate management measure that promotes the development of natural dune characteristics is the construction of elevated boardwalks that facilitate beach access, but also sediment transfer and biodiversity recovery. To improve the effectiveness of such structures, particular attention should be paid to the design phase. For example, the boardwalks should be placed so that they cover the main beach accesses already in use, reducing the possibility of trampling or the creation of new trampling paths. Ending the boardwalks before reaching the beach (as in the case of the viewpoint, see 5.3) is likely to lead to new trampling, since the main purpose of tourism in most coastal areas is to use the beach and not simply to benefit from the aesthetic value of the coast.

Restricting or controlling dune access and trampling should be coupled with a range of other measures that will enhance the dune recovery outcome. These include.

a) Promoting awareness of the values of coastal dunes, including ecology, biodiversity and ecosystem services such as nature-based tourism and protection from flooding and erosion.
b) Avoiding beach raking, especially in areas where the dune can develop seaward. The cessation of raking allows the dune to build

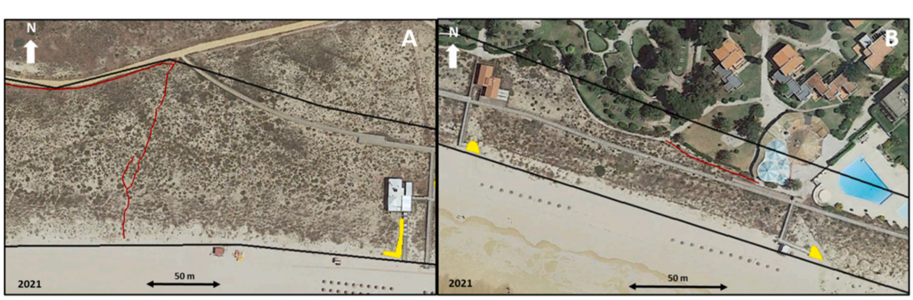

Fig. 8. A) Trampling path created after construction of the boardwalk to reach a more isolated part of the beach (BS4). B) Bare sand areas at the tipping point of the dune crossovers (BS7). Red lines represent paths and bare sand areas are shown as yellow polygons. Google Earth images, May 2021.

seaward while creating a greater diversity of habitats (Nordstrom et al., 2012).

c) Create seaward accommodation space (e.g. by promoting beach nourishment), which will result in embryonic dune formation and a revival of aeolian processes, with positive effects on biodiversity, and allow dunes to grow as sea level rises (Arens et al., 2013; Ruessink et al., 2018; Itzkin et al., 2021; Costas et al., 2023).

d) Involving residents and visitors in dune management activities to increase their awareness and appreciation of dune beach systems (Charbonneau et al., 2019), including reporting initial observations of dune degradation, which can increase dune the integrity and resilience, as observed by Johnston and Ellison (2014).

To ensure the long-term effectiveness of the structures and measures, regular inspections, monitoring and repairs must be carried out, allowing people to access the beach safely and comfortably, while preserving the dunes.

6. Conclusions

An effectiveness index has been proposed to evaluate the recovery of dunes following the construction of elevated boardwalks and dune crossovers to access beaches. The index is based on the evaluation of the recovery of vegetation in previously degraded areas (trampled paths and bare sand) and was applied to the highly touristic coastal zone of Alvor, both in managed and unmanaged (control) areas. The effectiveness of the promoted dune management actions was, on average, 86.4% and 69.3% for the western (less touristic and managed in 2011) and eastern (highly touristic and managed in 2016) sectors, respectively. These values are notably higher than those observed in the control sectors where no intervention took place (maximum observed value of 29.2% of dune recovery). The results demonstrate how relatively simple management measures can effectively promote dune recovery after high levels of use and associated dune degradation.

The analysis provided, including the use of the recovery index, is easy to apply, requires information that is often available at no additional cost, and can be applied to a large number of coastal areas where similar dune management (i.e. boardwalks and/or access regulation) has been considered and implemented. It allows a comparative analysis of different areas subject to similar interventions and helps to better define complementary management actions where necessary.

Credit author statement

As sole author, OF developed all the work from data collection to final paper production.

Declaration of competing interest

The author declares that it has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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