Natural and human controls on dune vegetation cover and disturbance

Irene Delgado-Fernandez[1*], Nicholas O'Keeffe[1], Robin Davidson-Arnott[2]

[1]Geography Department, Edge Hill University, Ormskirk, Lancashire, UK

[2]Geography Department, University of Guelph, Ontario, Canada

*Corresponding author email: delgadoi@edgehill.ac.uk

Abstract

Beaches and dunes are one of the most heavily used environments on Earth, with tourism and residential uses leading to ecosystem loss and dune degradation. Many coastal dune fields also host a range of economic activities such as farming, mining, and animal grazing, which can affect their evolution. The second half of the 20th century has seen an increase of dune vegetation cover in many dunes around the world, with climatic forcing often cited as a driver for this. However, identification of the relative contributions to landscape change due to climate vs. natural and/or artificial disturbances remains unclear. This poses a problem for managers seeking to maintain some 'desirable' landscape characteristics, because understanding the reasons for dune field change is essential prior to implementing interventions, as is differentiating what is natural from what is not. This study proposes a systematic approach to identifying dune disturbances and isolating them from the effect of climate. The approach assumes that it is possible to measure dune disturbances by comparing observed vegetation cover with that expected due to climate. A semi-quantitative procedure is proposed to explore the existence of disturbance, its significance, and the causes for it. The procedure can also be used in reverse to explore the effect of variables driving disturbance and the likely landscape trajectory if the driver is removed. The approach is tested with a case study of the Sefton dunes in NW England, a large dune field subject to multiple interventions and degrees of human impact. The discussion focuses on the importance of disturbance location and the range of variables involved in changes to vegetation cover at this and other locations. In natural dune fields, it is recommended as best practice to managers that artificial stressors and human-led disturbances are minimized to allow coastal dune systems to evolve naturally.

Keywords

Coastal dune field evolution, climate change, human impact, dune management.

1 INTRODUCTION

Coastal dunes are depositional features that depend on sediment input from the beach, wind events capable of transporting sediment, and the growing capacity of vegetation (Psuty, 1988; Delgado-Fernandez and Davidson-Arnott, 2011; Carter *et al*., 2018). Dunes are geographically diverse, with climatic variables such as precipitation, temperature, and wind patterns dictating their relative degree of mobility (Lancaster and Helm, 2000). The lack of vegetation in arid to semi-arid locations leads to coastal dunes that have larger degrees of mobility; wet conditions in tropical and temperate latitudes favour vegetation colonization and dune stabilization (Hesp, 2013). The long-term state of dune fields based on climatic conditions can be generally predicted using relatively simple mobility indices based on wind power (Tsoar, 2005) or on some combination between wind strength, precipitation, and temperature (e.g., Lancaster and Helm, 2000).

Local to regional studies have reported rapid rates of dune stabilization at multiple sites including South Africa (e.g., Avis, 1989), Canada (e.g., Darke *et al.*, 2013), Brazil (e.g., Seelinger *et al.*, 2000), and several dune systems in West/Northwest Europe (Rhind *et al.*, 2001; Provoost *et al*., 2011). A mix of natural and anthropogenic processes have been cited as potential drivers for vegetation cover changes. These include alterations in the length of the growing season (Jackson and Cooper, 2011), fluctuations in Pacific Decadal Oscillations (PDO) and El Niño-like events (Miot da Silva *et al.*, 2013), management plans promoting dune stabilization such as planting and fencing (e.g., Arens *et al*., 2013; Pye *et al*., 2014), the spread of invasive species and/or eutrophication due to atmospheric nitrogen deposition (Provoost *et al*., 2011). However, the relative contribution of natural vs. human-induced disturbances has not been quantified, making it difficult to separate what is expected from climate variability and/or climate change from direct human impacts. Appropriate identification of artificial disturbances is important to detect whether the environment is in fact degraded or not (e.g., Nordstrom *et al*., 2000). If artificial disturbances are detected, then removing stressors and reasons for degradation can give the system an opportunity to recover autonomously, with some authors arguing that this is in fact the best management option for restoration (Elliot *et al.*, 2007). This is particularly important in dune systems with moderate to large degrees of human impact such as NW Europe, where "restoring natural dune characteristics" should involve understanding of vegetation responses to climate, natural and anthropogenic disturbances, and dune evolutionary cycles (Hesp, 2013).

This study proposes a systematic approach that allows: (1) calculating the mobility state and estimating the amount of vegetation cover that can be expected due to climate; (2) distinguishing between natural and human causes/controls on vegetation cover and dune disturbance; (3) predicting the likely trajectory of a dune system if human impacts on vegetation cover are reduced. This is important in order to identify any significant deviation of a dune system from its predicted mean state, as well as to assess management interventions designed to either reduce or increase vegetation disturbance. The paper first introduces the conceptual background for the approach (section 2) and describes its application (section 3). The approach is then tested using the Sefton dunes (NW England) as a case study. The Sefton coast benefits from rich data sets including changes in bare sand and climate variables over 70 years and anthropogenic activities leading to a range of disturbances. The discussion focuses on the role played by extent and location when assessing the significance of disturbances to coastal dunes, as well as the capacity of the landscape to recover following disturbances. Results presented in this article also provide insights into the potential reasons for observed large scale (planetary) trends in dune stabilization.

2 CONCEPTUAL BACKGROUND

2.1 Establishing the general context for dune mobility and vegetation cover

The climate of a region, and specifically rainfall amounts and annual distribution, exert a primary control on dune vegetation growth (Hesp, 2002), which in turns controls dune mobility (e.g., Arens *et al.*, 2013; Pye *et al*., 2014;). Several authors have developed dune mobility indices based on average wind strength and precipitation (e.g., Ash and Wasson, 1983; Lancaster, 1988) or wind power and drift potentials (Tsoar, 2005). Vegetation cover also responds to climate variability leading, in turn, to cycles of dune activity (Hugenholtz and Wolfe, 2005; Yizhaq *et al*., 2008). Most mobility indices have been developed for continental dunes. However, coastal dune fields (just like their continental counterparts) are affected by their regional climate, which is a main driver for the growth of vegetation (Jackson and Cooper, 2011; Miot da Silva *et al.*, 2013). Although further research is needed on the application of mobility indices to coastal zones (see section 7.1), it is possible to use some dune mobility functions to understand climatic controls on coastal dune field dynamics (e.g., Smith *et al*., 2018; García-Romero *et al.*, 2018). The mobility index (M) developed by Lancaster (1988) was adopted here as a starting point due to its simplicity and easy application:

$$M = \frac{W}{P/_{PE}} \tag{1}$$

where W is the annual percentage of the time the wind is above the threshold for sand transport, P (mm) is precipitation, and PE (mm) is potential evapotranspiration calculated using the method developed by Thorntwaite and Mather (TM; 1957). The TM method uses mean monthly temperatures and accounts for latitudinal differences in sunshine to calculate PE. Once the M index has been calculated the expected mobility state of a dune field can be estimated using Table 1.

Table 1. Critical values for M and qualitative category descriptors developed by Lancaster (1988).

M values	***Qualitative category***
> 200	Fully active dunes
100 – 200	Mostly active but with vegetated interdunes and lower slopes
50 – 100	Mostly vegetated but with active dune crests
< 50	Fully inactive dunes

The use of M in general, is not without limitations. Lancaster (1888) originally developed the index for desert dunes and hence descriptors in Table 1 are associated with limited vegetation compared to many coastal dunes. The index is sensitive to wind thresholds and does not perform well at a yearly scale (Lancaster and Helm, 2000). M can over- or under-estimate mobility due to complex landscape dynamics including lag response times, morphological resistance, elasticity variability leading to different stabilization rates, and the hysteretic behaviour of dune mobility (Hugenholtz and Wolfe, 2005; Yizhaq *et al.*, 2009). However, the aim here is not to use M as a precise predictor of actual dune state, but to provide a broad climatic context for different dune fields. This helps informing qualitative estimations of the relative amount of vegetation cover that could be expected because of climate (V). We use M to provide valuable information on the combined effect of T, P, and W at a regional level and over time, and whether categorical changes to dune mobility should be expected or not. M provides good estimations of long-term dune mobility at timescales of decades (Lancaster and Helm, 2000) and responds well to natural oscillations in climatic variables or even climate change (Muhs and Maatt, 1993). The index is also capable of accounting for the impact of aridity and droughts (Wolfe, 1997) and episodic and temporally variable wind activity (Bullard *et al.*, 1997).

2.2 Estimating disturbance

Dune vegetation is sensitive to drivers not included in M and can be disturbed both because of natural processes and anthropogenic activities (e.g., Hesp and Martínez, 2007; Hernández-Cordero *et al.*, 2017). *Disturbance* (D) is therefore understood here as changes to vegetation cover not explained because of climate, and its magnitude can be calculated as:

$$D = V - V_o \qquad \text{eq (1)}$$

where V_o is the observed vegetation cover and V is that expected due to climate. When observed vegetation is close to that expected disturbance is small. Medium to large magnitude disturbances increase the percent of bare sand ($D > 0$) or the percent of vegetation cover ($D < 0$) and have the potential to change mobility levels. The magnitude of disturbance is sensitive to the size of the dune area under consideration. Therefore, the significance of a particular disturbance is a combination between its magnitude and extent (Table 2). For example, large storm surges eroding kilometres of coastal dunes can significantly affect the percent of dune vegetation cover (D+, large scale), *vs.* a walking trail used by small numbers of people with little significance for overall vegetation cover (D+, small scale). Management interventions leading to large magnitude, but localised disturbances may score low to moderate significance in Table 2. These include, for example, planting with vegetation areas of dune fields that are naturally mobile (D -) resulting in increases in vegetation cover that are not expected due to climate, or creating artificial notches and removing vegetation in naturally vegetated dune fields (D+). A third element should be included in analyses of cases such as these: disturbance *location*. The relevance of this in the context of coastal dunes is discussed in section 7.2.

Table 2. Matrix to characterise observed disturbance or to estimate the degree of disturbance expected from different drivers in table 3. Disturbance levels range from low (green) to moderate (yellow) and high (red). The table should be combined with an assessment of the disturbance location.

Disturbance Significance		***Extent***		
		Limited	Medium	Extensive
Magnitude	Small	🟩	🟩	🟨

	Moderate	🟩	🟨	🟥
	Large	🟨	🟥	🟥

2.3 Identifying causes of disturbance

Table 3 includes natural and human drivers of disturbance and controls on vegetation cover, both specific to coastal dunes (e.g., littoral sediment budgets or changes in sea level) and common to dunes elsewhere (e.g., grazing or farming). Table 3 is not an exhaustive list and it does not consider all variables cited in the literature, such as changes to ground water levels or nutrient excess (e.g., Arens *et al*., 2013), which could be added in future studies. Instead, the objective here is to propose a technique to examine reasons for disturbance and to indicate the trajectory one might expect if disturbances are reduced.

Table 3. Types of natural processes and anthropogenic actions promoting changes to the percent of vegetation cover and their relationship with disturbance magnitude (D).

		↑ bare sand	***Driver***	**↑ vegetation cover**
Natural Disturbance	Geomorphology	negative	*littoral sediment budget*	positive
		negative (extreme positive)	*foredune sediment budget*	positive
		rising	*sea level*	stable - falling?
		frequent	*storm surges*	infrequent
	Vegetation	no burial/salt tolerant	*pioneer grasses*	burial/salt tolerant
		few to no salt tolerant	*shrubs*	burial/salt tolerant
		grazers & burrowers	*animals*	few/no grazers & burrowers

Human Disturbance	Anthropogenic interventions	high	*grazing*	low to absent
		active	*farming*	low to absent
		unauthorised trails, vegetation trampling	*recreation*	limited to none
		high	*ATV and 4-wheel drive activity*	low to absent
		high	*Other land-uses (e.g., sand mining, military activities)*	low to absent
		present	*Management activities leading to artificial mobility (e.g., dynamic restoration)*	absent
		absent	*Management activities leading to artificial stabilization (e.g., planting, fencing)*	present
	D magnitude	+		-

Natural disturbances such as changes to coastal sediment budgets or variability of some animal populations (e.g., grazers and burrowers like rabbits) can change the proportion of vegetation cover and affect dune mobility. Some of these natural disturbances can be linked to human activities (e.g., human-induced rising sea-levels, or negative littoral budgets generated because infrastructure updrift interferes with longshore currents and sediment delivery to beaches downstream). However, Table 3 separates these from direct anthropogenic interventions in the landscape, which helps in identifying changes to vegetation cover due to land use and management. Most drivers have the potential of generating disturbance at a range of scales by affecting vegetation cover locally or extensively (e.g., active farming can be limited to a small enclosure or extend over the entire dune field).

3 APPROACH APPLICATION AND WORKFLOW

Figure 1 includes a workflow diagram to apply the approach introduced in this paper. The procedure is currently semi-quantitative. The first step is to calculate M (section 2.1) and compare it with the categories established by Lancaster (Table 1). This can be used to obtain a general estimation of the expected degree of vegetation cover due to climate (V; step 2) and whether temporal changes to this could be expected based on climatic trends. The third step consists of quantitative and/or qualitative estimations of actual dune mobility and/or observed vegetation cover (V_o). This can be done using a variety of raw data including estimations of active sand (e.g., Muhs and Maat, 1993), measured rates of sand transport (Lancaster and Helm, 2000), or quantification of vegetation / bare sand (e.g., Jackson and Cooper, 2011; this article). The fourth step identifies potential causes for disturbance based on information contained in Table 3.

Estimations of V_o in step 3 can be sensitive to area sizes, with localized disturbances in large dune fields being less pronounced because of the extent of the area under investigation. It is recommended that the percent of vegetation cover is estimated first for the entire dune field (e.g., $V_{oSefton}$ in this paper) to gain an understanding of broad patterns in vegetation cover. This can then be followed by analyses at smaller spatial scales and at different locations (V_{oi}). These smaller areas for investigation should still be large enough for the analyses to remain at a landscape (not landform) scale and areal coverage can be simply selected to suit the objectives of the assessment. For example, in situations where dune fields are sub-divided into different land uses, managers may want to assess the significance of disturbance for individual sectors (e.g., section 6.1.2), or to examine trajectories in mobility when stressors are removed, or management interventions are introduced.

The application of the procedure offers some flexibility. For example, it is possible to complete step 1 and then proceed directly into calculating V_{oi} at a smaller area in a particular dune field to compare its evolution / state with respect to a predicted M. It is also possible to start at step 4 and assess the likely effect of potential interventions in the landscape identified in Table 3. The significance of particular disturbances can be estimated using Table 2 to compare the magnitude of the disturbance (i.e., how much vegetation cover changes because of the disturbance) vs. extent (i.e., the area affected by the disturbance).

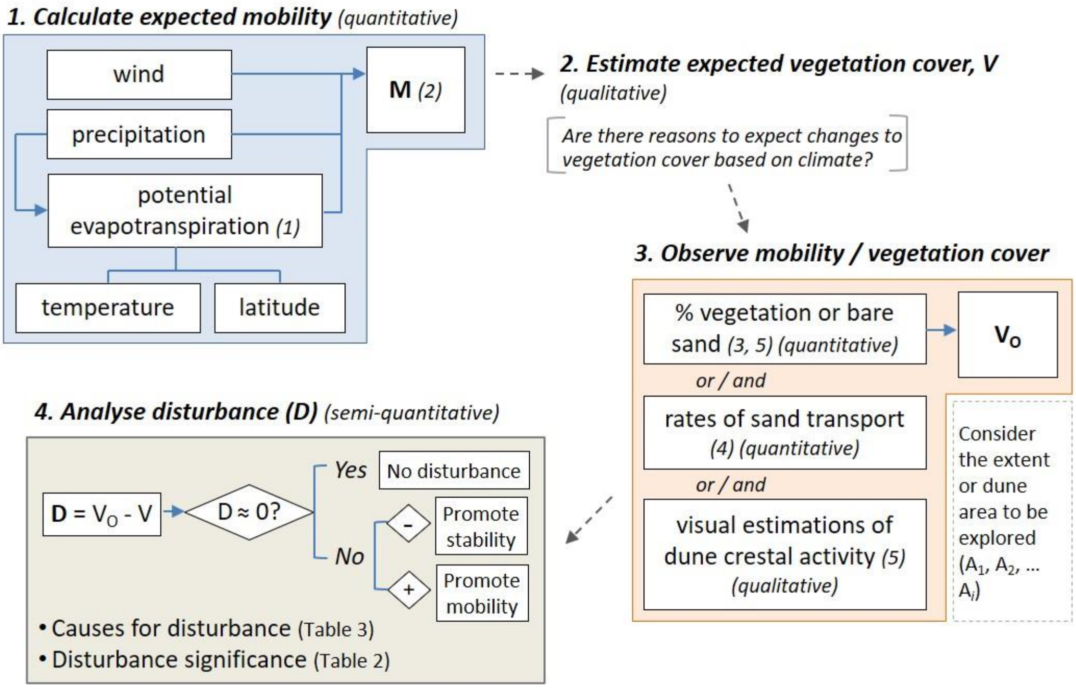

Figure 1. Workflow for the application of a routine to identify disturbance in dune systems. Step 1 only needs to be completed once for a dune field, with the evolution of M showing potential changes to mobility categories (Table 1) over time, and informing estimations of V (step 2). Steps 3 and 4 can be repeated for different sections of a dune field. Inserted numbers in brackets make reference to the following publications: (1) Thornthwaite and Mather (1957), (2) Lancaster (1988), (3) several authors including this paper, Jackson and Cooper (2011), and Pye *et al*. (2014), (4) Lancaster and Helm (2000), (5) Muhs and Maat (1993).

The analysis of disturbances remains semi-quantitative as there is currently no methodology (known to the authors) to calculate expected V. Step 4 was completed both as shown in Figure 1 (i.e., semi-quantitatively) and using a numerical value for V. The first allowed testing the procedure 'as is', with disturbance examined using measured vegetation cover (V_0) against trends in mobility and qualitative estimations of V. The second allowed illustrating how the approach could work if quantification of expected vegetation cover was possible. An average value of observed vegetation cover over the entire dune field was used for this purpose (section 6.3.1).

4 CASE STUDY SITE: THE SEFTON DUNES

The approach was tested at the Sefton dunes (Merseyside, UK) (Figure 2), the largest coastal dune field in England (Esteves *et al.*, 2012). The dunes extend for over 16 km along the coast and up to 4 km inland. They currently cover a total area of 2,150 ha although the dune complex has lost up to half its original extent to past development (Smith, 2009). The site is divided into areas managed by different landowners including Sefton Council (ca. 610 Ha), Natural England (ca. 370 Ha) and the National Trust (ca. 170 Ha), with other sections occupied by golf courses, the Ministry of Defence (MoD), or the Lancashire Wildlife Trust.

The Sefton dunes are subject to intense visitor pressure associated with the proximity to large urban centres, with issues such as traffic jams and long queues for parking cited as a primary management concern in planning documents (e.g., National Trust Public Consultation Report, 2017). An estimated 1.2 million people visit the coast every year (Sefton Coast Economic Plan, 2016) with the 3-km coastal walk around Formby ranked as the 4th most popular in Britain (Sefton's Natural Coast Tourism Marketing Plan, 2010).

The Sefton dunes were selected as a case study for two reasons: (1) the dunes benefit from the existence of the information required in Figure 1, including aerial photography since 1945 (to measure V_o), long-term climate data (to calculate M and estimate V), and historical records of anthropogenic activities (to explore D); (2) the division of the dune into areas managed by different landowners provides an opportunity to test the performance of D at smaller spatial extents, and to investigate landscape complexities introduced by some of the drivers included in Table 3.

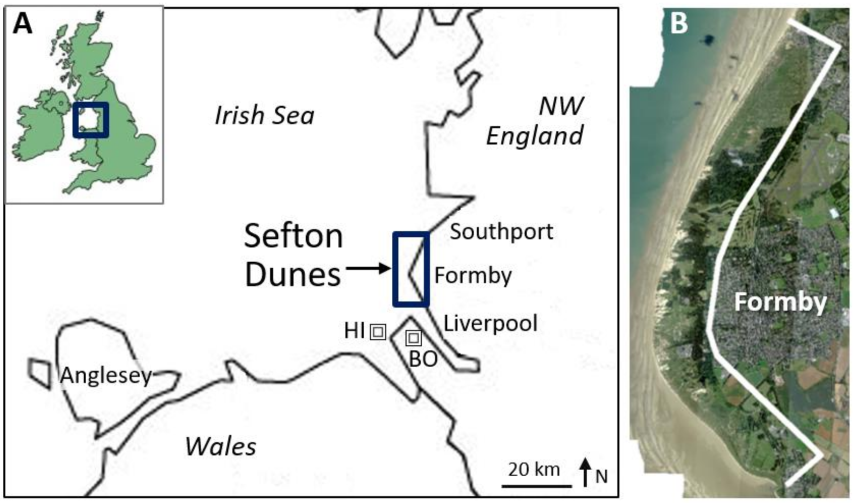

Figure 2. A) Location of the Sefton dunes, NW England (UK), main urban centres, and climate stations from the National Oceanography Centre (NOC): HI = Hilbre Island; BO = Bidston Observatory; B) Landward and alongshore extent of study area. Background photographic mosaic from 2010 courtesy of Sefton Council.

5 METHODS

5.1 Climate and predicted dune mobility

Climate analyses followed two steps. The first step focused on the calculation of M values for the Sefton dunes (section 2.1) for the period 1930 to 2015. This required access to conversion and computational tables developed by Thornthwaite and Mather (1957), mean monthly records of temperature (Tmean) and precipitation (P), and wind speed (U). Sediment sizes between the foredune and 100 m inland at Formby Point range between 0.22-0.28 mm (Pye and Blott, 2010) and were used to calculate the frequency of winds exceeding the minimum speed threshold (W) of 6.25 m s^{-1} (Bagnold, 1941). A 2-year period of hourly wind data from a local station at Crosby (N of Liverpool) was used to compare wind records from the weather stations at Hilbre Island and Bidston (located further away but including long-term data not available from Crosby; see below) with winds measured in the vicinity of the Sefton dune field. The TM method has been widely applied to calculations of water balances (e.g., Calvo, 1986; Stephenson, 1990; Black, 2007; Petalas, 2017) and it allows obtaining values for potential evapotranspiration (PE) adjusted to latitude. Full details and a step by step guide on how to apply the TM method can be found in Thornthwait and Mather’s (1957) original publication.

The second step consisted of statistical analyses of a range of meteorological variables to investigate potential changes to the region’s climate. A total of 8 variables were investigated, including the three variables cited above (Tmean, P, U), humidity (HU), wind gusts (Ug), atmospheric pressure (AP), and maximum (Tmax) and minimum (Tmin) temperatures. Data were retrieved from two meteorological stations approximately 15 km

SW of the Sefton dune field (Figure 2): the Bidston Observatory (BO; monthly values from 1930-2004) and Hilbre Island (HI; hourly values from 2005-2015), both available from the UK National Oceanography Centre (NOC) Database. There were additional meteorological stations in the region but only BO and HI were selected for the purpose of this article because of their combined long-term records and completeness (≈100% in both cases). The only exception was humidity, available from BO only from 1976.

Statistical analyses were based on the procedure by Gocic and Trajkovic (2013) and included: (1) exploratory analysis using Mann-Kendall (MK) tests to identify the existence of significant annual trends; and (2) quantification of trends using the Sen's slope estimator. Mann-Kendall (MK) tests (Mann 1945; Kendall 1975; Gilbert 1987) are a nonparametric form of monotonic trend regression analysis that have been applied widely in meteorology and hydrology (e.g., Douglas *et al.,* 2000*;* Tabari *et al.,* 2011*).* The MK test assumes that observations are independent and representative of true conditions at sampling times and permits analysis of upwards or downwards trends in climate data (e.g., Zhang *et al*., 2000; Su *et al*., 2006) even when time series have some missing observations (Helsel and Hirsch, 2002). Matlab codes developed by Burkey (2006, 2012) were applied to detect annual trends and to calculate Sen's slope. All tests were run at 5% and 1% significance levels.

5.2 Measured vegetation cover and observed dune mobility

Recent historical-scale (decadal) change in dune vegetation cover was examined using 16 aerial ortho-mosaics from 1945 to 2015 (Table 4). Previous studies applied unsupervised classifications and pixel aggregation to quantify bare sand based on pixel brightness at a variety of sites (e.g., Sellinger *et al*., 2000; Delgado-Fernandez and Davidson-Arnott, 2011;

Pye *et al.*, 2014). This technique was tested at Sefton but it led to considerable error. Most mosaics included over 10 individual aerial photographs taken with varying environmental conditions (e.g., changes in cloud cover or sun angle during the same flight) which led to differences in illumination within the mosaic and incorrect pixel classification. The percent of vegetation cover was therefore quantified by digitizing all areas of bare sand in each mosaic in ArcGIS (Jackson and Cooper, 2011), which ensured greater accuracy. The process was conducted by an expert analyst and independently reviewed by two different GIS users for consistency.

Table 4. Ortho-mosaics analysed in this study (Courtesy of Sefton Council, ©Crown Copyright). Pixel resolution (PR) ranged from 0.25 to 1 m and the number of bands (NB) correspond to black and white images (1), RGB photographs (3), and a Compact Airborne Spectrographic Imager (CASI) flight (28).

Year	1945	1961	1979	1982	1984	1989	1992	1996	1997	1999	2000	2002	2005	2010	2012	2015
PR	0.25	0.25	0.25	0.12	0.25	0.25	0.25	0.43	0.25	0.25	0.25	0.25	0.12	0.25	1	1
NB	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	28

Following general guidelines in section 3, observed vegetation V_o was first calculated for the entire Sefton dune field system ($V_{OSefton}$). To gain insights into temporal changes to vegetation cover at smaller spatial extents, the evolution of bare sand was analysed for different ownership zones (section 6.1.2). The effect of decreasing the extent of the area of observation on measured vegetation cover was further explored using the 2015 dataset. The Buffer tool in ArcGIS was used to create buffer areas of 500 m, 250m, and 125 m from the beach-dune boundary (i.e., the seaward limit of the dune field) inside ownership zones. This allowed exploring disturbances at smaller spatial scales, and their relationship with some of the variables identified in Table 3.

5.3 Recreation and other anthropogenic activities

The 2010 mosaic was acquired on a sunny weekend (Saturday 22nd May) with large visitor numbers, hence providing an opportunity to investigate the spatial distribution of people, and the potential relationship between this driver and bare sand. The use of only one image prevents temporal analysis, nonetheless snapshots or temporally limited visitor surveys can provide important information about landscape trends and visitor behaviour (e.g., Tzatzanis *et al.*, 2003; Roca and Villares, 2008). Three datasets were digitized into point shapefiles: 1) cars parked and the number of empty spaces, which allowed estimating saturation levels in coastal car parks; 2) caravan sites; and 3) visitors, which were grouped into ‘beach’ or ‘dune’ visitors. The 0.25 m pixel resolution of the mosaic made it possible to identify individual visitors when these were separated from each other but not when they were clustered (Figure 3). Hence, results presented in section 6.3.2 likely underestimate visitor numbers because point features used to identify them represent both individuals and groups of people. The Point Density tool from ArcGIS Spatial Analyst was used to obtain visitor density maps by calculating point feature densities for each cell of an output raster file (ESRI, 2016). Two-dimensional cross-shore transects were extracted from these output density maps to highlight differences in visitor concentrations around beach access points.

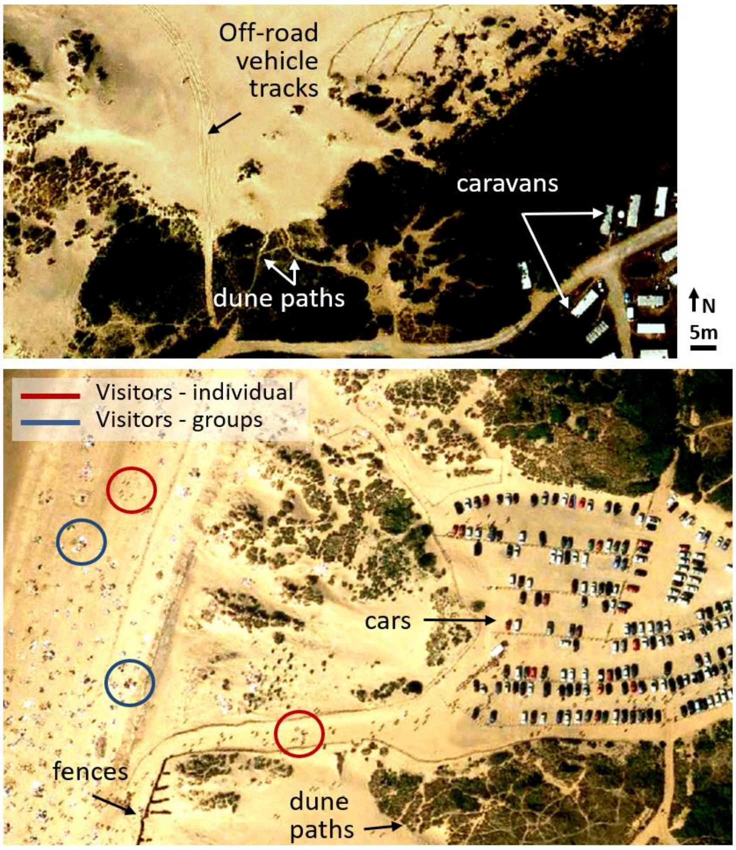

Figure 3. Example of features visible in the 2010 mosaic (images have been enhanced to improve visibility).

The Sefton dunes have experienced human interventions leading to artificial dune stabilization (Smith, 2015). However, elaborating a comprehensive map of all of these was challenging due to several limitations not least that management interventions aiming to stabilise the dunes were not always visible in the aerial mosaics, or that fencing and planting were also conducted in previously vegetated areas (and hence did not lead to a loss of bare sand but to a loss of other surface types). Despite limitations, a quantitative estimation of the effects of dune fencing on the rates of dune stabilization was attempted by focusing on an area managed by Sefton Council where this process was clearly visible from 1979 to 1999 (section 6.3.3). Finally, the role played by other natural disturbances including coastal erosion / accretion and types of colonizing plants was assessed qualitatively.

6 RESULTS

6.1 Observed changes in vegetation cover vs. bare sand

6.1.1 Entire Sefton dune field

Figure 4 includes three examples of the evolution of bare sand with dates separated roughly every 3 decades. Most bare sand areas identified in 1945 had almost completely disappeared by 2015. Visual inspection of the images suggests two processes leading to a generalised loss of bare sand: 1) dune stabilization, especially to the N of Formby Point and in landward areas of the dune field; and 2) costal erosion, with the recession of Formby Point being responsible for the loss of many mobile dunes at this location from 1945 to 2015. Coastal accretion to the N and S of Formby Point resulted in mostly vegetated coastal dunes, with bare sand concentrating predominantly at the foredune stoss slope in these two areas and rapidly decreasing landwards from the frontal dunes. Bare sand patches around Formby Point in 2015 were larger and extended inland to a greater degree.

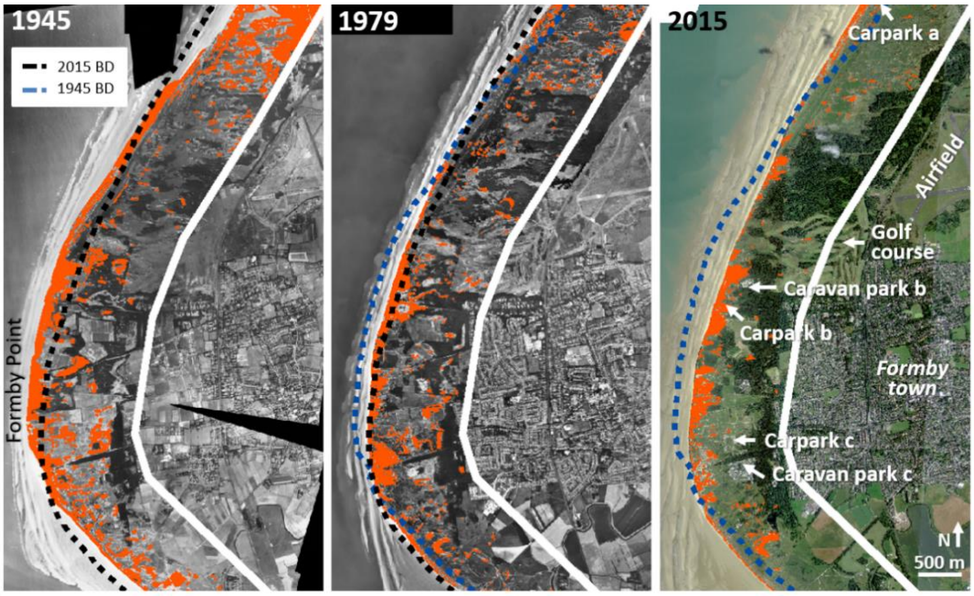

Figure 4. Examples of maps of bare sand every ca. 3 decades showing the location of bare sand patches. The 1945 beach-dune boundary (BD) is included in 1979 and 2015 maps, and the 2015 BD is included in 1945

and 1979 to show shoreline changes. Large amounts of mobile dunes were lost due to coastal erosion at Formby point from 1945 to 1979. Coastal accretion to the N and S was in the form of mostly stable coastal dunes.

Detailed temporal analyses of the percent of vegetation cover *vs*. bare sand indicates that $V_{oSefton}$ values were always above 80% when considering the full extent of the dune field and ranged from a minimum of 83% (1945) to a maximum of 98% (1989) (Figure 5).

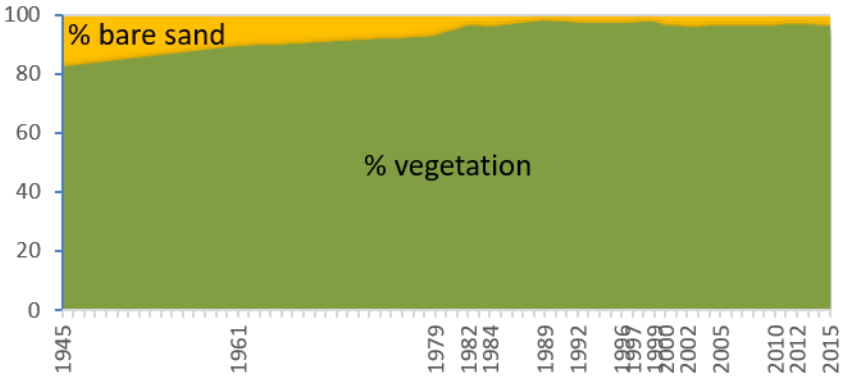

Figure 5. Percent change in area of vegetation cover vs. bare sand at the Sefton dunes (1945-2015).

6.1.2 Ownership sectors and buffer zones

Figure 6 focuses on the overall decrease of bare sand from the Sefton dunes, subdivided into ownership sectors. In general, the dune field lost 120 ha of bare sand from 1945 to 1989 at a rate of 2.7 ha yr^{-1} but gained 20 ha of bare sand from 1989 to 2015 at a rate of 0.8 ha yr^{-1}. In 1945, most bare sand concentrated in areas managed by Natural England (37%) and Sefton Council (38%), with the National Trust and MoD each accounting for 8.5% of the total amount. By 1982, only negligible quantities of bare sand remained in golf courses, MoD, and other small dune areas. The gain in bare sand during the second part of the study period was driven by changes in the National Trust zone. This area alone concentrated over half (59%) of the total bare sand in the entire dune system by 2015.

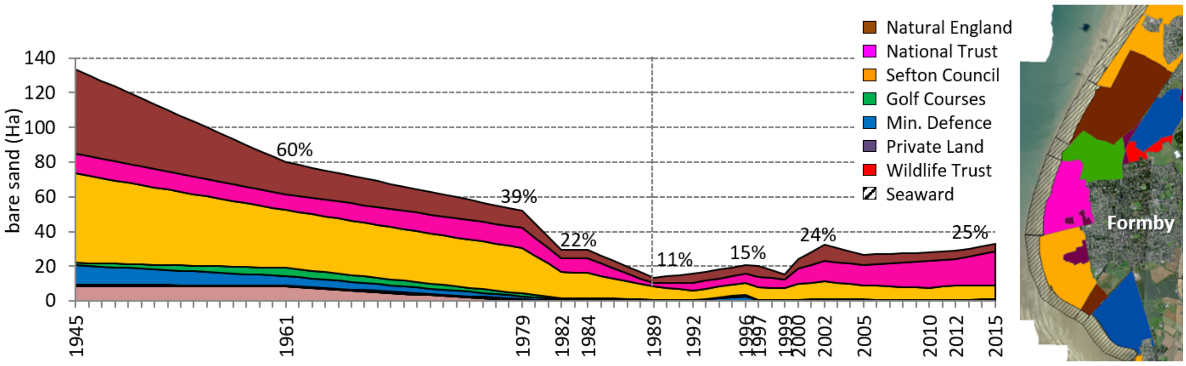

Figure 6. Temporal patterns in dune stabilization for the Sefton dune field subdivided by ownership areas (inset). The contribution to the total reduction of bare sand cover (ha) is expressed by the width of areas within the graph. Numbers at various points above the graph indicate %bare sand cover at differing times compared to that present in 1945..

Spatial analyses using buffer zones on the 2015 aerial mosaic (Figures 7A, B) suggest that some of the general patterns described above were more distinct when adjusting the size of the area under investigation. Despite larger concentrations of bare sand in the National Trust sector, percentages in vegetation cover over this and other zones were similar and ranged from 89 to 99% when the 1 km buffer zone was used (i.e., the original study site landward extent shown in Figure 2B). The decrease in area extent with progressively smaller buffer zones accentuated the differences between the percent of vegetation cover in different ownership sectors. In general, vegetation cover decreased with buffer size in all sites, suggesting that bare sand tended to concentrate closer to shore. However, vegetation cover in most ownership sectors remained relatively high and above 85% when using a 125 m buffer. The exception to this was the National Trust, with vegetation covering only 49% of its 125 m buffer zone.

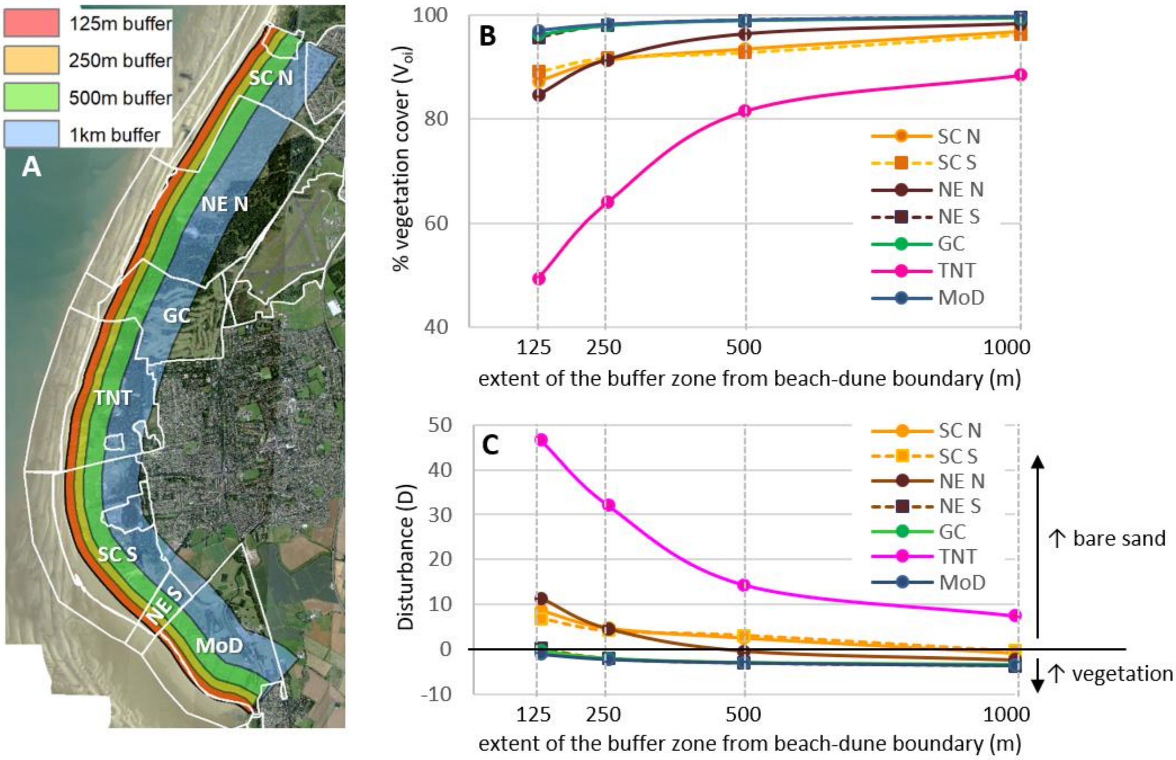

Figure 7. A) Buffer zones (calculated from the beach-dune area) over the 2015 aerial mosaic; B) Spatial changes in V_o with different buffer zones and C) associated disturbance levels.

6.2 Predicted dune mobility and climate

Statistical analyses showed significant changes in all climate variables at 1% significant levels (Table 5; Figure 8), with the exception of precipitation, which did not show any significant trends. Wind speeds and maximum wind gusts decreased at rates of -0.01 ms^{-1} and -0.03 ms^{-1} yr^{-1}, respectively, or the equivalent to a decrease of -0.77 ms^{-1} and -2.1 ms^{-1} over 70 years. Mean temperatures increased by 0.01 °C yr^{-1} and maximum and minimum temperatures increased by 0.02 °C yr^{-1}, adding to +0.7 °C and +1.12 °C over 70 years, respectively. Humidity showed an increasing trend from 1979 to 2015 of +0.19% yr^{-1}.

Table 5. Results of statistical tests for changes in climate variables included in Figure 8.

Variable (year average)	***Sen's slope***
Wind Speed (U)	-0.011
Max Wind Gust (Ug)	-0.030
Minimum Temperature (Tmin)	0.016
Maximum Temperature (Tmax)	0.016
Mean Temperature (Tmean)	0.010

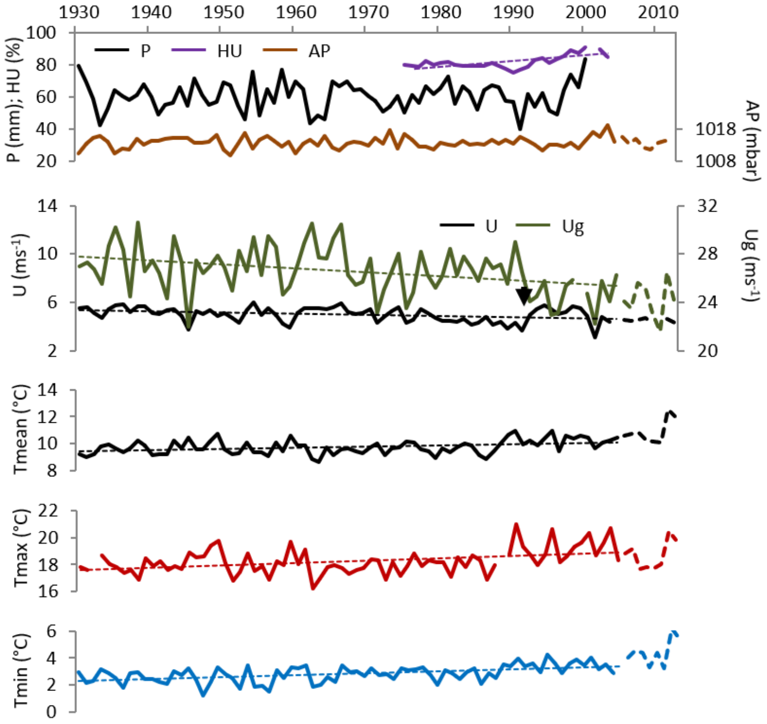

Figure 8. Annual records of precipitation (P), humidity (HU) and atmospheric pressure (AP) (top); wind speed (U) and maximum wind gust (Ug) (middle); and mean (Tmean), maximum (Tmax) and minimum (Tmin) temperatures (bottom) using data from from BO (solid line) and HI (dash line). Trend lines added only for time series showing statistically significant changes (Sen slopes in table 4).

The average predicted mobility index for the Sefton dunes was M = 24, indicating fully inactive dunes (Table 1). Figure 9A shows yearly and 5-yr moving averages, with M values always below the threshold of 50, suggesting that climatic conditions from the 1930s have consistently favoured a fully stable dune field, and that changes to M were not expected given rainfall and PE values.

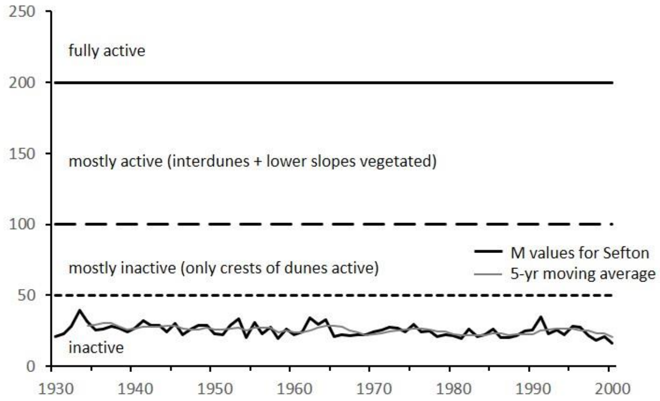

Figure 9. Temporal analysis of dune mobility (M) for the case of the Sefton dunes based on Lancaster's (1988) M categories.

6.3 Disturbance and driver analyses

6.3.1 Disturbance significance

The comparison of M with changes to bare sand (e.g., Figure 6) allows identifying areas where trends in observed vegetation cover do not follow those expected due to climate. Examples of these disturbances include increases in bare sand in the National Trust zone since the 1990s, or the gradual decrease of bare sand in most other zones within the dune field from 1945 to 1989. Additional to qualitative analyses, disturbance could also be quantified if calculations of expected V due to climate were possible. Following the rationale in section 3 and with the objective of illustrating a fully numerical procedure, the average value of measured vegetation cover for the entire Sefton dune field since 1989 ($V_{oSefton}$ = 96%; Figure 5) was used as a general estimation of V (see discussion section 7.1). This value is representative of relatively constant vegetation cover during the last 30 years of the study period and allowed calculating disturbance levels (D; Eq. 1) for different ownership sectors and buffer zones. Results are displayed in Figure 7C. $D_i \approx 0$ for all sectors when large areas of the dune field were considered (1000 - 500 m buffers). D_i increased to ≈ 5-10 for areas managed by Sefton Council and Natural England using 250 m and 120 m buffers. The National Trust (TNT) zone showed disturbance levels that clearly exceeded the range of D_i values observed elsewhere in the dune system with D_{TNT} = 32 to 47 for buffer zones of 250 m and 125 m, respectively.

6.3.2 Anthropogenic activities leading to increases in bare sand

Figure 10 shows visitor patterns observed from the 2010 aerial mosaic and co-located bare sand areas. A total of 3,012 visitors (or groups of visitors) were identified, including 2550 ‘beach visitors’ and 462 ‘dune visitors’. Up to 86% of all visitors concentrated around carparks, with most (81%) concentrating close to carparks *a* and *b*. All carparks were over 70% full. Despite similar visitor numbers close to carparks *a* (Sefton Council N) and *b* (The National Trust), disturbance levels in these two areas were different (Figure 7C), indicating potential differences in recreation pressures. Carpark *a* was at the beach and extended for over 1,700 m alongshore hence providing easy access to more distant areas.

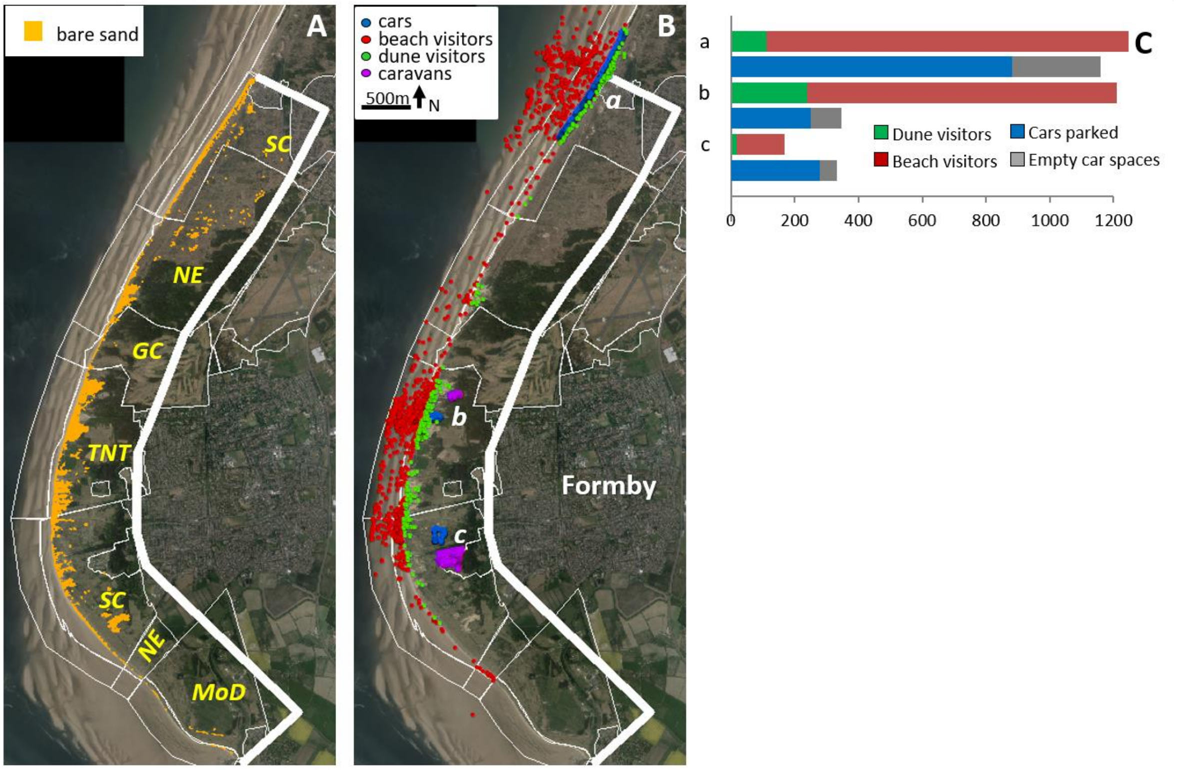

Figure 10. Spatial patterns of bare sand (A), visitor distribution (B), and visitor numbers (C) along the Sefton coast on the 22 May 2010. Extent of the study site and limits of ownership sectors have been included. SC: Sefton Council; NT: Natural England; GC: Golf Courses; TNT: The National Trust; MoD: Ministry of Defence.

This was associated with lower visitor densities around its entry point (Figure 11A). Carpark *b* was located inside the dune system and was associated to larger visitor densities over the dunes and at its beach entry point (Figure 11B). Carpark *c* was also located inside the dune field and visitor patterns here were similar to those at carpark *b*. Visitor densities were however lower than in *b* because of smaller visitor numbers (compare Figures 10C and 11B). Visitor densities around *b* were 2.5 times larger than around the other two sites (Figure 11C) but peak densities were roughly at the same distance cross-shore at the three locations (ca. 50 m seawards from the beach-dune boundary).

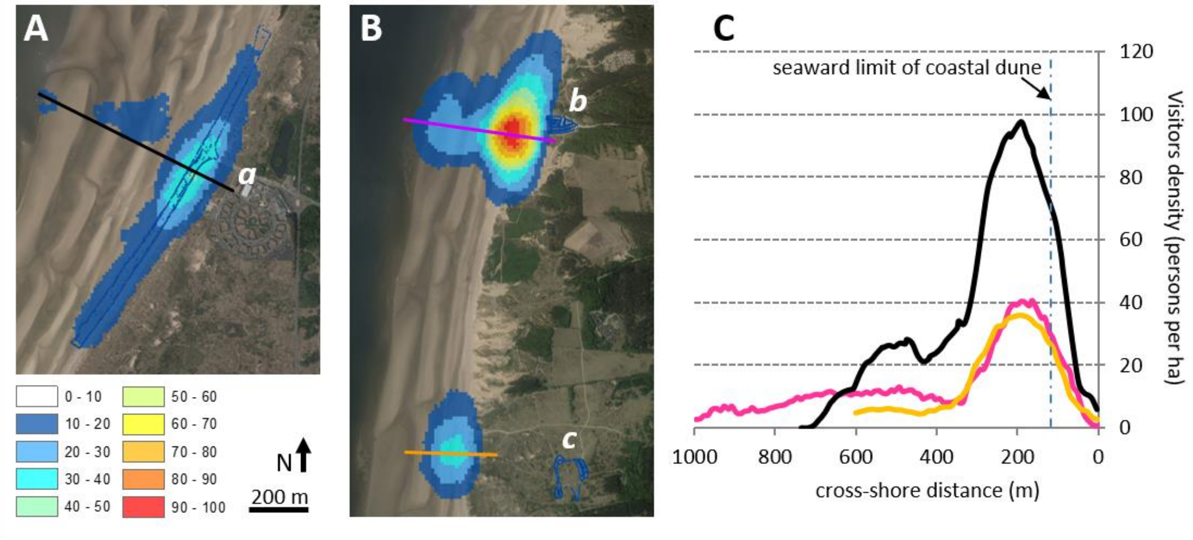

Figure 11. A-B) Visitor density maps (locations in Figure 10). C) Cross-shore variation in visitors' density along transects, from 150 m landwards from the beach-dune boundary to the end of the density map at the beach.

6.3.3 Anthropogenic activities leading to dune stabilization and other natural disturbances

The aerial mosaic in 1979 showed the presence of fences across a bare sand area located close to carpark *c* (Figure 12). Fencing was followed by rapid vegetation colonization by 1989 and the stabilization of up to 91% of bare sand by 1999, at a rate of 4.6 % yr^{-1}. This was double stabilization rate observed when considering the entire Sefton dune field, which lost bare sand at a rate of 2.7 ha yr^{-1} from 1945 to 1989 (section 6.1.1). It is worth mentioning that stabilization in this area was also caused by the removal of stressors which led to dune instability in the past. This included a relatively steady coastline at this location (Figure 4) and a reduction of visitor pressure, with a clear path leading from carpark *c* to location 1 at the beach being established in 1984 and resulting in less people spreading over the dunes.

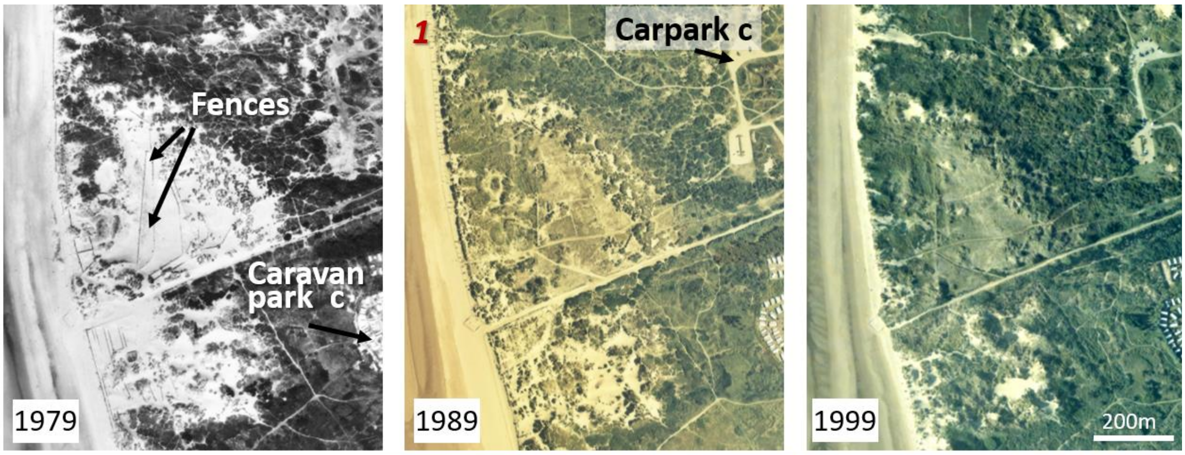

Figure 12. Effect of fencing close to carpark *c* (location sin Figures 3 and 10), showing rapid dune stabilization in 10-20 years after the intervention. Dune stabilization in this area also reflects the partial removal of past stressors including less visitor pressure in 1999 compared to 1979, and a relatively stable coastline providing greater carrying capacity to drivers of positive disturbance compared to areas close to carpark *b* (Figure 10).

The predominant colonizing plant at the site is *Amophila arenaria* or marram grass, a native species that thrives under sand burial (Table 3). Accreting areas with plenty of sediment supply are hence likely to stabilize rapidly. At the Sefton coast, zones subject to coastal progradation were also subject to dune stabilization, with several examples of newly formed foredunes being rapidly colonized by grass. Areas subject to coastal retreat (e.g., the National Trust) were less vegetated, with marine erosion likely magnifying the contribution of visitor pressure.

7 DISCUSSION

7.1 Advantages and limitations of M, V, and D

An improved methodology to predict coastal dune field activity is beyond the scope of this paper, but mobility calculations could be refined further in the future by considering other models (e.g., Hugenholtz and Wolfe, 2005; Yizhaq *et al*., 2009). We highlight here that the purpose of this work was not to test the application of existing mobility indices to the case of coastal dunes, but to provide a framework that allows separation of what is natural from what is not, and informs coastal dune managers of the 'expected' dune mobility state based on climate. The objective of our use of an M-type approach is to establish a threshold, based on potential evapotranspiration, with vegetation cover decreasing as the magnitude of the difference between PE and actual evapotranspiration increases.

Quantitative analyses of disturbance significance in the future could be explored by developing methods to calculate V. Tests conducted on the Sefton dunes demonstrate that the current semi-quantitative D index is effective at identifying disturbances and excessive deviations of the system from its expected mean state. The index performed well in the case of disturbances leading to increases in bare sand (+D) and could be applied to predict the likely trajectory of coastal dune systems following interventions leading to the removal of native or invasive plant species (e.g., Konlecher, 2018; Ruessink *et al*., 2018) or following large-scale storm impacts destroying dune vegetation (e.g., Carter *et al*., 2018). Disturbances leading to stabilization (-D) were negligible at the spatial extents explored here (Figure 7C) but observations on an area subject to fencing suggested that this management intervention was effective at speeding up dune stabilization (Figure 12), in line with experiences elsewhere (e.g., Dahm *et al*., 2005). It is argued here that a clear -D signal was not detected in the case of Sefton because the dunes were in general already stable. The range of positive and negative D values depends on V. At locations with low predicted M and hence high estimated V, it is unlikely to have excessive disturbances leading to artificial stabilization. The D index should be tested in arid or semi-arid coastal dune fields, where its application to detect disturbances leading to increases in bare sand will be limited but its ability to detect disturbances leading to dune stabilization not explained by climate could be high. In arid to semi-arid coastlines, rainfall (a key variable in M) plays a primary role in determining the existence of nebkha *vs* foredune ridges, with variables such as vegetation species and sediment supply controlling foredune type and nebkha density (Hesp *et al*., 2018). Recent analyses by García-Romero *et al.* (2018) suggests the potential for the D index to perform well in arid dune fields, with localized increases in vegetation cover linked to direct human impacts and the growth of urbanization at their study site instead of changes to climate (M).

7.2 Disturbance location

The damage that pedestrians, cyclists, and motorbikes cause to coastal dune vegetation has long been recognized (e.g., Boorman and Fuller, 1977; McDonnell, 1981; Andersen, 1995; Fenu *et al*., 2013; Hesp *et al*., 2010). This damage can be enhanced by its location within the dune field. The seaward-most sections of coastal dunes (embryo dunes and foredunes) are subject to both marine and wind action. In these locations, highly specialized pioneer grasses play a key role in dune building by binding the sand together. Uncontrolled recreation destroys dune vegetation (McDonnell, 1981; Tzatzanis *et al*., 2003; Dahm *et al*., 2005; Jackson and Nordstrom, 2011; El Mrini *et al*., 2012), and can completely prevent or slow down plant colonization at the beach-dune boundary where the vegetation is most sensitive to disturbance and only just establishing itself. This weakens coastal dunes making them more vulnerable to both wave and aeolian erosion. In the case of Sefton, significant disturbance (D+) observed at the National Trust zone (Figure 7C) were associated with bare sand areas at the frontal dunes, with visitor pressure magnifying the contribution of marine erosion.

Additionally, certain locations may be more resilient to the stressors they are subject to. For example, two locations may experience comparable levels of a cause for disturbance, but the magnitude and longevity of the disturbance may be less or more due to its resilience. At Sefton, longshore areas with positive sediment budgets (i.e., coastal accretion) appeared to 'cope' better with the same stressor (e.g., pedestrians over the dunes), or to recover from it more rapidly, compared to areas prone to coastal erosion with lower resilience to disturbances (Figure 4, areas around carpark *a* and *b*, respectively).

7.3 Historical complexities, dune cycles, and additional drivers

In line with global trends in increasing temperature (Hughes, 2000; Xu *et al.*, 2016) and decreasing wind speeds (McVicar *et al.*, 2012; Vautard *et al.*, 2010), there was significant warming and wind stilling in the Sefton region from 1930 to 2015. However, predicted M values for the same study period did not significantly change and hence there are no indications that the observed climate variability is related to changes in vegetation cover at this location. This is in line with long-term trends in species composition of Scottish coastal dunes (Pakeman *et al.*, 2015) and suggests that climate change favouring vegetation growth plays a secondary role when mobility is already limited.

Low M values for the Sefton dunes in the 1930s suggest a climate that favoured a fully stable landscape at the beginning of the study period. It is worth noting that this agrees with actual observations of vegetation cover for the entire dune field around the same time, with

$V_{OSefton} \approx 83\%$ in 1945 (Figure 5). There was, however, more bare sand in 1945 compared to the present day (i.e., 2015). The lack of evidence supporting that this reduction in bare sand was linked to climatic change could be explained in several ways:

(1) Other variables not included in table 3 could have driven increases in vegetation cover during the study period. There is strong evidence of changes to atmospheric composition including increases in CO_2 and atmospheric nutrients at a planetary level (Bennett *et al*., 2001; Galloway *et al*., 2008; Keenan *et al*., 2016) with more bio-available nitrogen and phosphorous leading to soil and plant fertilization (e.g., Keenan *et al*., 2016), and hence potentially dune stabilization.

2) Disturbances leading to increases in bare sand in the past (instead of, or additional to disturbances leading to stabilization in recent decades) could have been responsible for larger amounts of bare sand in 1945. At Sefton, land uses promoting artificial vegetation disturbance are well-documented, including large-scale sand-winning and rabbit-warrening (e.g., Cowell, 2008; Smith, 2009, 2012; Roberts, 2014; Table 3). The latter was a major land-use for several centuries, with rabbit populations markedly decreasing due to myxomatosis from the late 1950s onwards. Sand extraction also disappeared during the 1950s and 1960s, allowing the landscape to recover from this disturbance. The decline in rabbit populations has recently been identified as a primary cause for dune stabilization in dune fields in Australia (Moulton *et al*., 2018), and human activities have been cited as responsible for vegetation degradation and dune mobility in large regions in China over timescales of centuries (Guo *et al*., 2018). It is worth stressing that natural disturbances can also lead to significant divergencies from expected coastal dune mobility states. For example, aerial photography from the 1930s at Greenwich Dunes (Canada) shows transgressive dunes extending hundreds of metres inland, and limited vegetation cover. Analyses conducted by

Matthew *et al*. (2010) indicated, however, that observed dune mobility in the 1930s was a result of a catastrophic storm overwash event in the 1920s and hence a natural disturbance. As expected from the climate of the region, vegetation gradually re-colonized the site, decreasing the disturbance significance over time. The process of dune healing and post-storm dune recovery varies for different locations (Houser *et al*., 2015) and can take up to several decades (Matthew *et al*., 2010).

3) Coastal dunes go through cycles of activity and inactivity in response to large-scale climate fluctuations (Monaghan *et al*., 2018), and evolve into various stages characterised by different landscape complexity and vegetation richness (Hesp, 2013). Many coastal dunes worldwide have gone through a period of declining dune activity and adaptation to relatively warmer conditions since ≈ 1850, following the termination of a pulse in aeolian events during the Little Ice Age (LIA; Clemmensen and Murray, 2006; Dezileau *et al*., 2011; Costas *et al.*, 2016; Dillenburg *et al*., 2018). Historical records on weather and climate in Sefton indicate multiple periods of past dune activity alternating with dune stability over the last 1,500 years, and lag times in dune response to climatic changes (Lewis, 2010).

All arguments above can co-exist, giving rise to complex landscapes that evolve as a result of many drivers. Since V_o is a function of V and D (Eq. 1), some of the trends in dune stabilization identified in many locations around the world (section 1) could be explained by the predominant role played by one variable, or by the combination of several drivers acting together. At any given time, V_o reflects the climate of a region, drivers listed in Table 3, changes to atmospheric composition, historical disturbances, lag responses, and dune cycles.

7.4 Implications for management

It is important that the relative contribution of drivers for coastal dune field vegetation change is understood prior to adopting intervention strategies aimed at influencing dune field evolution. The failure to recognize that cycles of dune mobility and blowout development can be part of the natural evolution of a dune system has led in the past to artificial stabilization of naturally active dunes. In these systems, previous planting and fencing efforts, as well as the introduction of invasive species, are disturbing the landscape, and hence mitigation of those impacts would seem desirable. Similarly, it is important to tease out the reasons for increases in vegetation cover before attempting to intervene in the landscape. On naturally inactive dunes where stability is expected based on the general climate (e.g., humid coasts of the Caribbean), efforts to de-stabilize coastal dunes are in fact a disturbance. In these cases, the likely trajectory that the system will follow once the disturbance is removed is that of trying to re-stabilize itself. This explains why management approaches aiming to artificially creating bare sand in temperate dune field systems are ineffective in the long-term, with vegetation growing back only a few years after the intervention (e.g., Arens *et al.*, 2013) because the system is simply restoring itself.

Finally, the role played by different vegetation communities has not been considered in this study but should be included in future analyses and in attempts to calculate V. Coastal dune plant communities vary with succession, exposure, and water levels (Miller *et al.*, 2010; Kamps *et al.*, 2008; Curreli *et al.*, 2013). Ecological niche modelling suggests that plant communities behave differently with climate change (Mendoza-González *et al.*, 2013) but some studies suggest that anthropogenic disturbances (e.g., invasion or removal of woody species) and changes due to succession (Pakeman *et al.*, 2015) are primary drivers for community shifts.

8 CONCLUSIONS

Identifying a single variable driving changes to vegetation cover in coastal dune fields is challenging because variations to bare sand result from the interaction of multiple drivers (i.e., climate, sediment budgets, management actions, atmospheric composition, etc.). It is likely that drivers act together with different degrees of predominance depending on the location and characteristics of the coastal dune field under investigation. However, it is possible to assume that the climate of a region (including climate perturbations, oscillations, and climate change) is a primary control on dune vegetation cover, and that deviations from the predicted mobility/stability state are due to disturbances (natural and/or anthropogenic). This facilitates exploration of natural *vs*. human causes for changes in vegetation cover and allows predicting the likely trajectory of a dune system if disturbances are removed.

The approach adopted in this study was tested at the Sefton dunes, the largest coastal dune field in England. Artificial disturbances included increases in bare sand generated by visitor pressure (+D), and relatively minor increases in the rate of vegetation growth via fencing and planting (-D). A comparison between estimated and observed vegetation cover during the 1940s suggested that the dune system could have been disturbed prior to the study period, with past artificial disturbances primarily consisting of sand mining and rabbit-warrening, and natural disturbances consisting of lag effects from previous cooler and windier conditions.

Detailed analyses by ownership sectors permitted identification of system deviations from expected (average) vegetation cover. Human disturbances such as vegetation trampling and uncontrolled visitor pressure had different effects along the coast and were responsible for increases in bare sand in the area managed by The National Trust. Management implications here consist on steps towards removing dune stressors to allow the system to restore itself, should the aim of management be to preserve natural dune evolution. Hence, it is recommended that visitor pressure is controlled, and human trampling is minimized or prevented. There are many examples of successful dune restoration experiences worldwide, including the use of boardwalks, information stalls and virtual fencing. Preventing further artificial disturbances is particularly important at the seaward limit of coastal dune fields, where human activities can interfere with beach-dune interaction and increase coastal vulnerability to storms and extreme events.

9 ACKNOWLEDGEMENTS

This work was supported by the REF-IF programme at Edge Hill University [grant number RDDELG13]. Aerial mosaics were kindly provided by Paul Wisse (Sefton Council © Crown Copyright; Licence number 1000181192 2010). The authors are grateful to Phil Smith (Sefton Coast Landscape Partnership), Paul Ashton (Biology Department, EHU) and Paul Aplin (Geography Department, EHU) for comments on earlier material, as well as references to unpublished information. Aneurin O’Neil (Centre for Ecology & Hydrology, Lancaster) and Susan Jones (Geography Department, EHU) assisted on climate and GIS analyses.

10 LITERATURE CITED

Ash, J.E., and Wasson, R.J., 1983. Vegetation and sand mobility in the Australian desert dunefield. *Zeitschrift fur Geomorphologie, 45*(Supp.), pp. 7-25.

Andersen, U.V., 1995. Resistance of Danish coastal vegetation types to human trampling. *Biological conservation*, *71*(3), pp. 223-230.

Arens, S.M., Mulder, J.P., Slings, Q.L., Geelen, L.H. and Damsma, P., 2013. Dynamic dune management, integrating objectives of nature development and coastal safety: examples from the Netherlands. *Geomorphology*, *199*, pp. 205-213.

Avis, A.M., 1989. A review of coastal dune stabilization in the Cape Province of South Africa, *Landscape and Urban Planning 18*, pp. 55-68.

Bennett, E.M., Carpenter, S.R. and Caraco, N.F., 2001. Human Impact on Erodable Phosphorus and Eutrophication: A Global perspective increasing accumulation of phosphorus in soil threatens rivers, lakes, and coastal oceans with eutrophication. *BioScience, 51*(3), pp. 227-234.

Black, P. E., 2007. Revisiting the Thornthwaite and Mather Water Balance[1]. *JAWRA Journal of the American Water Resources Association, 43*, pp. 1604–1605. doi:10.1111/j.1752-1688.2007.00132.x

Boorman, L.A. and Fuller, R.M., 1977. Studies on the impact of paths on the dune vegetation at Winterton, Norfolk, England. *Biological Conservation*, *12*(3), pp. 203-216.

Bullard, J.E., Thomas, D.S.G., Livingstone, I. and Wiggs, G.F.S., 1997. Dune field activity and interactions with climatic variability in the southwest Kalahari Desert. *Earth Surface Processes and Landforms, 22*, pp. 165-174.

Burkey, J., 2006. A non-parametric monotonic trend test computing Mann-Kendall Tau, Tau-b, and Sen's Slope written in Mathworks-MATLAB implemented using matrix rotations. King County, Department of Natural Resources and Parks, Science and Technical Services section. Seattle, Washington. USA. http://www.mathworks.com/matlabcentral/fileexchange/authors/23983

Burkey, J., 2012. Seasonal Kendall Trend Test for Data with and without Searial Dependance. King County, Department of Natural Resources and Parks, Science and Technical Services section. Seattle, Washington. USA. https://uk.mathworks.com/matlabcentral/fileexchange/22389-seasonal-kendall-test-with-slope-for-serial-dependent-data

Calvo, J.C., 1986. An evaluation of Thornthwaite's water balance technique in predicting stream runoff in Costa Rica*, Hydrological Sciences Journal, 31*(1), pp. 51-60, DOI: 10.1080/02626668609491027

Carter, G.A., Otvos, E.G., Anderson, C.P., Funderburk, W.R. and Lucas, K.L., 2018. Catastrophic storm impact and gradual recovery on the Mississippi-Alabama barrier islands, 2005–2010: Changes in vegetated and total land area, and relationships of post-storm ecological communities with surface elevation. *Geomorphology*, *321*, pp. 72-86.

Clemmensen, L.B. and Murray, A., 2006. The termination of the last major phase of aeolian sand movement, coastal dunefields, Denmark. *Earth Surface Processes and Landforms, 31*(7), pp. 795-808.

Costas, S., Naughton, F., Goble, R. and Renssen, H., 2016. Windiness spells in SW Europe since the last glacial maximum. *Earth and Planetary Science Letters, 436*, pp. 82-92.

Cowell, R.W., 2008. Coastal Sefton in the prehistoric period. In: J.M. Lewis & J.E. Stanistreet (eds.) *Sand and sea*: *Sefton's coastal heritage*. *Archaeology*, *history and environment* *of a landscape in north west England*. pp. 20-27. Sefton Council Leisure Services Department, Bootle.

Curreli, A., Wallace, H., Freeman, C., Hollingham, M., Stratford, C., Johnson, H. and Jones, L., 2013. Eco-hydrological requirements of dune slack vegetation and the implications of climate change. *Science of the total environment*, *443*, pp. 910-919.

Dahm, J., Jenks, G. and Bergin, D., 2005. Community-based dune management for the mitigation of coastal hazards and climate change effects: a guide for local authorities. *Environment Bay of Plenty*.

Darke, I.B., Eamer, J.B.R., Beaugrand, H.E.R. and Walker, I.J., 2013. Monitoring considerations for a dynamic dune restoration project: Pacific Rim National Park Reserve, British Columbia, Canada. *Earth Surface Processes and Landforms,38*, pp. 983–993

Dezileau, L., Sabatier, P., Blanchemanche, P., Joly, B., Swingedouw, D., Cassou, C., Castaings, J., Martinez, P. and Von Grafenstein, U., 2011. Intense storm activity during the Little Ice Age on the French Mediterranean coast, Palaeogeography, Palaeoclimatology, *Palaeoecology*, 299(1–2), pp. 289-297, http://dx.doi.org/10.1016/j.palaeo.2010.11.009

Delgado-Fernandez, I. and Davidson-Arnott, R.D.A., 2011. Meso-scale aeolian sediment input to coastal dunes: The nature of aeolian transport events. *Geomorphology,* 126(1), pp. 217-232.

Dillenburg, S., Hesp, P.A., Barboza, E., Rosa, M.L., Caron, F., Sawakuchi, A. and Forman, S., 2018. Records of Aeolian activity potentially related with the Little Ice Age in Regressive Coastal Barriers of Southern Brazil. *International Conference on Aeolian Research (Abstract),* 25-29 June, Bordeaux, France

Douglas, E.M., Vogel, R.M. and Kroll, C.N., 2000. Trends in floods and low flows in the United States: impact of spatial correlation. *Journal of Hydrology*, 240, pp. 90–105.

El Mrini, A., Anthony, E.J., Maanan, M., Taaouati, M. and Nachite, D., 2012. Beach-dune degradation in a Mediterranean context of strong development pressures, and the missing integrated management perspective. *Ocean & coastal management*, *69*, pp. 299-306.

Elliott, M., Burdon, D., Hemingway, K.L. and Apitz, S.E., 2007. Estuarine, coastal and marine ecosystem restoration: confusing management and science–a revision of concepts. *Estuarine, Coastal and Shelf Science*, *74*(3), pp. 349-366.

Environmental Systems Research Institute (ESRI), Inc., 2016. How Point Density Works - http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-point-density-works.htm [Date Accessed 24th August 2018]

Esteves, L.S., Brown, J.M., Williams, J.J. and Lymbery, G., 2012. Quantifying thresholds for significant dune erosion along the Sefton Coast, Northwest England. *Geomorphology*, 143–144, pp. 52-61

Fenu, G., Cogoni, D., Ulian, T. and Bacchetta, G., 2013. The impact of human trampling on a threatened coastal Mediterranean plant: The case of Anchusa littorea Moris (Boraginaceae). *Flora-Morphology, Distribution, Functional Ecology of Plants*, *208*(2), pp. 104-110.

Galloway, J.N., Townsend, A.R., Erisman, J.W., Bekunda, M., Cai, Z., Freney, J.R., Martinelli, L.A., Seitzinger, S.P. and Sutton, M.A., 2008. Transformation of the Nitrogen cycle: recent trends, questions and potential solutions. *Science, 320*(5878), pp. 889-892.

García-Romero, L., Delgado-Fernández, I., Hesp, P.A., Hernández-Calvento, L., Hernández-Cordero, A.I. and Viera-Pérez, M., 2019. Biogeomorphological processes in an arid transgressive dunefield as indicators of human impact by urbanization. *Science of the Total Environment*, *650*, pp.73-86.

Gilbert, R.O., 1987. Statistical Methods for Environmental Pollution Monitoring, Wiley, NY.

Gocic, M. and Trajkovic, S., 2013. Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. *Global and Planetary Change*, *100*, pp. 172-182. doi:10.1016/j.gloplacha.2012.10.014

Guo, L., Xiong, S., Wu, J., Ding, Z., Chen, Y., Zhu, L. and Ye, W., 2018. Human activity induced asynchronous dune mobilization in the deserts of NE China during the late Holocene. *Aeolian Research*, *34*, pp. 49-55.

Helsel, D.R. and Hirsch, R.M., 2002. Chapter 12 – Trend Analysis, in *Statistical methods in water resources* (Vol. 323). Reston, VA: US Geological survey.

Hernández-Cordero, A.I., Hernández-Calvento, L., Pérez-Chacón Espino, E., 2017. Vegetation changes as an indicator of impact from tourist development in an arid transgressive coastal dune field. Land Use Policy, 64: 479-491.

Hesp, P.A., 2002. Foredunes and blowouts: initiation, geomorphology and dynamics. *Geomorphology, 48*(1-3), pp. 245-268.

Hesp, P.A. and Martínez, M.L., 2007. Disturbance processes and dynamics in coastal dunes. In Johnson, A., and Miyanishi, K. (Eds), *Plant disturbance ecology. The process and the response*. Elsevier. P. 215-247.

Hesp, P.A., Schmutz, P., Martinez, M.M., Driskell, L., Orgera, R., Renken, K., Revelo, N.A.R. and Orocio, O.A.J., 2010. The effect on coastal vegetation of trampling on a parabolic dune. *Aeolian Research*, *2*(2), pp. 105-111.

Hesp, P.A., 2013. Conceptual models of the evolution of transgressive dune field systems. *Geomorphology*, *199*, pp. 138-149.

Hesp, P.A., Hernández-Calvento, L., Hernández-Cordero, A.I. and Gallego Fernández, J.B., 2018. Nebkha or not: the role of rainfall and sediment supply in controlling nebkha vs foredune ridge formation. *International Conference on Aeolian Research (Abstract),* 25-29 June, Bordeaux, France

Hugenholtz, C.H. and Wolfe, S.A., 2005. Recent stabilization of active sand dunes on the Canadian prairies and relation to recent climate variations. *Geomorphology*, *68*(1-2), pp.131-147. Hughes, L., 2000. Biological consequences of global warming: is the signal already apparent? *Trends in Ecology & Evolution, 15*(2), pp. 56-61.

Jackson, D.W.T, and Cooper, J.A.G., 2011. Coastal dune fields in Ireland: rapid regional response to climatic Change, *Journal of Coastal Research* SI 64, pp. 293-297.

Jackson, N.L. and Nordstrom, K.F., 2011. Aeolian sediment transport and landforms in managed coastal systems: a review. *Aeolian research*, *3*(2), pp. 181-196.

Kamps, P.W.J.T., Nienhuis, P. and Witte, J.P.M., 2008. Effects of climate change on the water table in the coastal dunes of the Amsterdam Water Supply. In *Proceedings MODFLOW*.

Keenan, T.F., Prentice, I.C., Canadell, J.G., Williams, C.A., Wang, H., Raupach, M. and Collatz, G.J., 2016. Recent pause in the growth rate of atmospheric CO2 due to enhanced terrestrial carbon uptake. *Nature Communications*, 7, pp. 13428.

Kendall, M. G., Rank Correlation Methods, 4th ed., Charles Griffin: London, 1975.

Konlechner, T., 2018. Post-disturbance evolution of a prograded foredune barrier: the role of wind speed, wind direction and vegetation. *International Conference on Aeolian Research (Abstract),* 25-29 June, Bordeaux, France.

Lancaster N., 1988. Development of linear dunes in the southwestern Kalahari, southern Africa. *Journal of Arid Environments, 14*, pp. 233-244.

Lancaster, N. and Helm, P., 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. *Earth Surface Processes and Landforms*, *25*(2), pp. 197-207.

Lewis, J., 2010. A brief summary of the historical evidence for the weather and climate on the Sefton Coast from the 11th – 20th centuries. University of Liverpool, 63 p.

Matthew, S., Davidson-Arnott, R.G.D., Ollerhead, J., 2010. Evolution of a beach-dune system following a catastrophic storm overwash event: Greenwich Dunes, Prince Edward Island, 1936-2005. *Canadian Journal of Earth Sciences*, 47(3), pp. 273-290.

Mann, H.B., 1945. Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society*, pp. 245-259.

McDonnell, M.J., 1981. Trampling effects on coastal dune vegetation in the Parker River National Wildlife Refuge, Massachusetts, USA. *Biological Conservation*, *21*(4), pp. 289-301.

McVicar, T.R., Roderick, M.L., Donohue, R.J., Li, L.T., Van Niel, T.G., Thomas, A., Grieser, J., Jhajharia, D., Himri, Y., Mahowald, N.M., Mescherskaya, A.V., Kruger, A.C., Rehman, S. and Dinpashoh, Y., 2012. Global review and synthesis of trends in observed terrestrial near-surface wind speeds: Implications for evaporation. *Journal of Hydrology,* 416–417, pp. 182-205.

Mendoza-González, G., Martínez, M.L., Rojas-Soto, O.R., Vázquez, G. and Gallego-Fernández, J.B., 2013. Ecological niche modeling of coastal dune plants and future potential distribution in response to climate change and sea level rise. *Global Change Biology*, *19*(8), pp. 2524-2535.

Miller, T.E., Gornish, E.S. and Buckley, H.L., 2010. Climate and coastal dune vegetation: disturbance, recovery, and succession. *Plant ecology*, *206*(1), p.97.

Miot da Silva, G., Hesp, P., Keim, B., Martinho, C.T. and Ferligoj, Y., 2013. Changes in dunefield geomorphology and vegetation cover as a response to local and regional climate variations. *In:* Conley, D.C., Masselink, G., Russell, P.E. and O'Hare, T.J. (eds.), *Proceedings 12th International Coastal Symposium* (Plymouth, England), *Journal of Coastal Research*, (SI65), pp. 1307-1312, ISSN 0749-0208

Monaghan, G.W., Arbogast, A.F., and Lovis, W.A., 2018. Are Coastal Dune Activation Cycles in the Great Lakes (USA) Linked Across the Northern Hemisphere during the Late Holocene? If so, Why? *International Conference on Aeolian Research (Abstract),* 25-29 June, Bordeaux, France

Moulton, M.A., Hesp, P.A., Miot da Silva, G., Bouchez, C., Lavy, M. and Fernandez, G.B., 2018, Changes in vegetation cover on the Younghusband Peninsula transgressive dunefields (Australia) 1949–2017. *Earth Surface Processes and Landforms*.

Muhs, D.R., Maat, P.B., 1993. The potential response of eolian sands to Greenhouse Warming and precipitation reduction on the Great Plains of the United States. *Journal of Arid Environments, 25*, pp. 351-361.

Nordstrom, K.F., Lampe, R. and Vandemark, L.M., 2000. Reestablishing naturally functioning dunes on developed coasts. *Environmental Management*, *25*(1), pp. 37-51.

Pakeman, R.J., Alexander, J., Beaton, J., Brooker, R., Cummins, R., Eastwood, A., Fielding, D., Fisher, J., Gore, S., Hewison, R. and Hooper, R., 2015. Species composition of coastal dune vegetation in Scotland has proved resistant to climate change over a third of a century. *Global change biology*, *21*(10), pp. 3738-3747.

Petalas, C.P., Akratos, C.S. and Tsihrintzis, V.A., 2017. Hydrogeological Investigation of a Karst Aquifer System. *Environmental Processes*, pp. 1-27.

Provoost, S., Jones, M.L.M. and Edmondson, S.E., 2011. Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. *Journal of Coastal Conservation*. DOI: 10.1007/s11852-009-0068-5.

Psuty, N.P., 1988. Sediment budget and dune/beach interaction. *Journal of Coastal Research*, (3), pp. 1-4.

Pye, K. and Blott, S.J., 2010. Geomorphology of the Sefton Coast sand dunes. In Worsley, A.T., Lymbery, G., Holden, V.J.C., and Newton, M. (Eds) *Sefton's Dynamic Coast. Proceedings of the Conference on Coastal Geomorphology, Biogeography and Management*, pp. 131-160.

Pye, K., Blott, S.J. and Howe, M.A., 2014. Coastal dune stabilization in Wales and requirements for rejuvenation. *Journal of coastal conservation*, *18*(1), pp. 27-54.

Rhind, P.M., Blackstock, T.H., Hardy, H.S., Jones, R.E. and Sandison, W., 2001. The evolution of Newborough warren dune system with particular reference to the past four decades. In: Houston, J., Edmondson, S.E. Rooney, P. (eds) *Coastal dune management, shared experience of European conservation practice*. Liverpool University Press, Liverpool, pp. 345-379.

Roberts, G., 2014. The lost world of Formby Point: footprints on the prehistoric landscape, 5000 BC to 100 BC. *Alt Press*, Formby.

Roca, E. and Villares, M., 2008. Public perceptions for evaluating beach quality in urban and semi-natural environments. *Ocean & Coastal Management*, *51*(4), pp. 314-329.

Ruessink, B.G., Arens, S.M., Kuipers, M. and Donker, J.J.A., 2018. Coastal dune dynamics in response to excavated foredune notches. *Aeolian Research*, *31*, pp. 3-17.

Seeliger, U., Cordazzo, C.V., Oliveira, C.P. and Seeliger, M., 2000. Long-term changes of coastal foredunes in the southwest Atlantic. *Journal of Coastal Research*, pp. 1068-1072.

Smith, P.H., 2009. The sands of time revisited. An introduction to the sand-dunes of the Sefton Coast. *Amberley publishing*, Stroud, Gloucestershire.

Smith, P.H., 2015. History of human influence on sand stability in the Sefton Coast sand-dunes. Unpublished report, 25 pp.

Smith, A.B., Jackson, D.W., Cooper, J.A.G. and Hernández-Calvento, L., 2017. Quantifying the role of urbanization on airflow perturbations and dunefield evolution. *Earth's Future*, *5*(5), pp.520-539.

Stephenson, N.L., 1990. Climatic Control of Vegetation Distribution: The Role of the Water Balance. *The American Naturalist, 135(*5) pp. 649-670.

Su, B.D., Jiang, T. and Jin, W.B., 2006. Recent trends in observed temperature and precipitation extremes in the Yangtze River basin, China. *Theoretical and Applied Climatology*, *83*(1-4), pp. 139-151.

Tabari, H., Marofi, S., Aeini, A., Hosseinzadeh Talaee, P. and Mohammadi, K., 2011b. Trend analysis of reference evapotranspiration in the western half of Iran. *Agricultural and Forest Meteorology 151* (2), pp. 128–136.

Thornthwaite, C.W. and Mather, J.R., 1957. Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance. *Publ. in Climatology, vol.10, no.3*, C,W. Thornthwaite & Associates, Centerton, New Jersey.

Thornthwaite, C.W. and Mather, J.R., 1957. Instructions and tables for computing potential evapotranspiration and the water balance (No. 551.57 T515i). Drexel Institute of Technology, Centerton, NJ (EUA). Laboratory of Climatology.

Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. *Physica A: Statistical Mechanics and its Applications*, *357*(1), pp. 50-56.

Tzatzanis, M., Wrbka, T. and Sauberer, N., 2003. Landscape and vegetation responses to human impact in sandy coasts of Western Crete, Greece. *Journal for Nature Conservation*, *11*(3), pp. 187-195.

Vautard, R., Cattiaux, J., Yiou, P., Thepaut, J.N. and Ciais, P., 2010. Northern Hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nature Geosciences, 3*(11), pp. 756-761.

Wolfe, S.A., 1997. Impact of increased aridity on sand dune activity in the Canadian Prairies. *Journal of Arid Environments, 36*, pp. 421-432.

Xu, C., Liu, H., Williams, A.P., Yin, Y. and Wu, X., 2016. Trends toward an earlier peak of the growing season in Northern Hemisphere mid-latitudes. *Global Change Biology, 22*(8), pp. 2852-2860.

Yizhaq, H., Ashkenazy, Y. and Tsoar, H., 2009. Sand dune dynamics and climate change: A modeling approach. *Journal of Geophysical Research: Earth Surface*, *114*(F1).

Zhang. X., Vincent, L.A., Hoge, W.D. and Niitsoo, A., 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere-Ocean, 38*, pp. 395-129