Research article

A global 'greening' of coastal dunes: An integrated consequence of climate change?

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ABSTRACT

In the context of global climate change and sea-level rise, coastal dunes are often important elements in the coastal response to storm wave and storm surge impacts on coastal lowlands. Vegetation cover, in turn, has profound impacts on coastal dune morphology and storm-buffering function; it binds existing sediment, promotes fresh sediment accumulation and thereby increases dune volume and dune crest elevation where a sediment-plant interaction plays out with vegetation growth attempting to out-pace the vertical sediment accumulation.

A global analysis shows that vegetation cover has increased substantially on multiple, geographically dispersed, coastal dune fields on all continents in the period 1984–2017. The observed 'greening' points to enhanced dune stability and storm buffering effects at a time when, paradoxically, coasts are being subjected to increased flood and erosion risk from rising sea levels and changing patterns of storminess.

Causal attribution of biological trends to climate change is complicated, but we contend that the global scale 'greening' of coastal dunes is driven by a combination of changes to climate and atmospheric composition and reflects the cumulative effects of changes in temperature, precipitation, nutrient concentration and reduced windiness (global stilling). Global-scale increases in temperature, nutrients and precipitation (all of which are vegetation growth stimulants) and widespread reduction in windiness ("stilling") (which reduces sediment activity, promoting the spread of vegetation) coincide in time with the observed changes in vegetation cover. The observed changes in coastal dunefields enhance contemporary and near-future coastal resilience to climate change and may represent a previously unrecognised morphological feedback mediated by climate change.

1. Introduction

Global climate change and sea-level rise are producing a general landward migration and loss of sedimentary coastlines (Parmesan and Yohe, 2003; FitzGerald et al., 2008; Ranasinghe and Stive, 2009; Mentaschi et al., 2018). Rising sea level causes the permanent inundation of low-lying areas and/or increases their exposure to episodic flooding during storm surges, tsunamis, and extreme astronomic tides (Jevrejeva et al., 2016; Vousdoukas et al., 2018). As sea level rises, extreme water level recurrence intervals are reduced and more frequent wave overtopping of natural and artificial barriers occurs (Jevrejeva et al., 2018). Established natural ecosystems, as well as human infrastructure are at risk of rapid change as a result. Coastal dunes, however, can help enhance the degree of structural protection against these threats (Martínez and Psuty, 2004). The physical resistance of dune-fringed coasts to wave erosion events is enhanced by vegetation that better stabilises and binds the dune sediment and traps additional wind-blown sand, causing dune height and volume to increase in general (Goldstein et al., 2017). Dune crest elevation is a key determinant of

overwash vulnerability (Houser et al., 2008), while increased dune volume leads to greater inertia and slows the rate of retreat of barrier shorelines. Coastal dunes exhibit various forms and behaviour in response to changing environmental variables. These are often recorded by changes from stable, vegetated conditions to periods when active sand-blow causes dunes to breakdown and migrate. Actively migrating (unvegetated) coastal dunes were prevalent during the Last Glacial Termination (Costas et al., 2016) (~ 22 to 11.5 ka) and subsequent climatic periods of the Holocene. For example, a Europe-wide pulse of coastal dune activity (marked by sand-blow) during the Little Ice Age (LIA) between 1300 and 1850 (Costas et al., 2012; Clarke and Rendell, 2009; Clemmensen and Murray, 2006; Jackson et al., 2019) prompted significant human intervention (deliberate afforestation) to halt their inland advance. The end of the LIA coincided with a general decline in dune activity that is reflected in an increase in the extent of dune vegetation and stability.

Several local and regional analyses of coastal dune activity in the past few decades have pointed to a reduction in dune mobility. For example, increasing vegetation cover and drift potential in southern

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Brazilian dunes was linked to changes in rainfall and wind speed over a 34-year period (da Silva and Hesp, 2013). In the SE USA, the vegetation dune cover gradually increased by 38% from 1996 to 2016, maintaining a steady increase regardless of routine tidal incursion (Ajedegba et al., 2019a). In NW Spain, changes in dune vegetation cover were attributed to changes in wind strength (and direction) and associated the impact of storms since 1945 (González-Villanueva et al., 2013). Several other coastal dunes in Europe, less impacted by human activities such as from agricultural practices and landscape modification, also show a clear stabilisation trend in recent decades that has been linked to changing climatic variables (Jackson and Cooper, 2011; Provoost et al., 2011). Jackson and Cooper's (2011) work, focussing on Ireland's remote coastal dunes on its western seaboard, showed remarkable changes in just a single decade of observations with significant revegetation patterns clearly evident.

Prompted by these examples, we investigate whether this is a global pattern and if so, might it be driven by changing environmental conditions that favour vegetation growth at a global scale. In this, we follow the assertion by Parmesan and Yohe (2003, p.40) regarding the logic of a global focus, i.e. "*With climate change, attribution of recent warming trends to changes in atmospheric gases comes from analysis of global patterns, not from detailed data from individual meteorological stations. Similarly, when assessing biological impacts, the global pattern of change is far more important than any individual study*".

In this study we pick up on these examples of changes in coastal dune dynamics occurring around most continents of the planet (see Fig. 1) and further explore this using a time series of landsat images to quantify a pattern of dune surface changes, focussing on coastal dunes at various locations around the world to quantify trends in vegetation cover between 1984 and 2017. Therefore, we have selected seventeen sites meeting a number of conditions to evaluate the trends in the vegetation cover using the Normalized Difference Vegetation Index

(NDVI) derived from the Landsat scenes to enable quantification of vegetation cover at biannual intervals (1984–2017).

2. Methods

Dune sites were selected according to a number of conditions or criteria which included having a large transgressive dunefield that was spatially extensive enough (on the order of kilometres) to be adequately imaged by Landsat and with clear evidence of inland migration. Sites excluded desert regions where vegetation is otherwise too sparse to be visualised. Human occupation should also be null/minimal to minimise sites containing significant localised human disturbance and therefore reducing any artificial impact as much as possible; site selection was, therefore, made on the following basis: 1. contain a large-scale coastal dune field (> 5km^2) with a significant inland extension, 2. have limited or no human intervention, 3. be located in non-arid and non-polar locations.

Changes in vegetation cover were quantified at 17 geographically dispersed sites using vegetation indexes derived from Landsat images, covering a 30-year period. A description of each selected site is included in Online Resource 1 The approach used in this work included a series of steps applied to each selected study site (Fig. 2). The first step involved the selection of the test case studies, which includes the morphological assessment of large dunefields across the globe.

Many forms of direct and indirect human intervention affect dune morphology. Direct impacts include afforestation, deforestation, introduction of exotic species, agriculture, mining, landscaping and a myriad of associated activities. Indirect human effects include modification of incident wind fields, changes in water table, sediment supply. These impacts are often difficult to discern, and we have sought to exclude sites where such impacts are documented from our analysis.

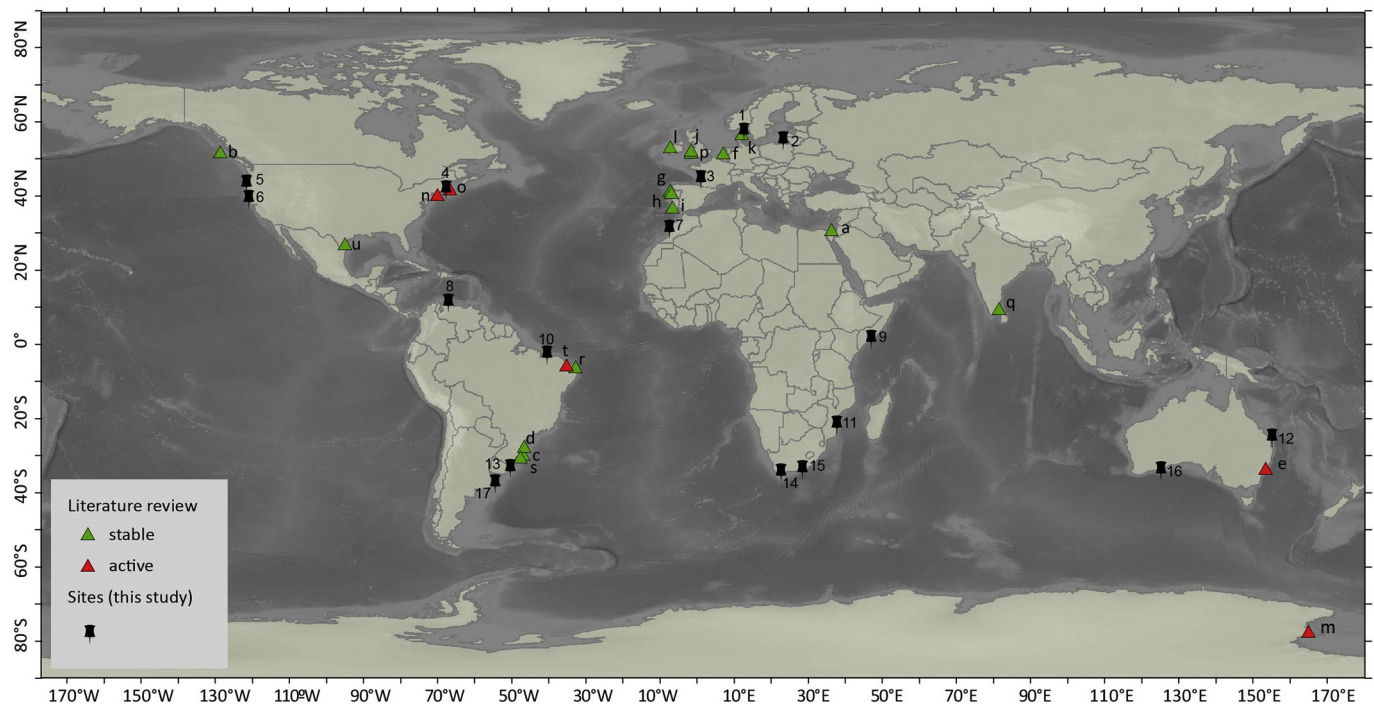These criteria are important because: 1) The size of the site was very

Fig. 1. Spatial distribution of examples from the literature with reference to the recent trend of dune field systems; stable or active. The numbers represent the reference from the literature review: a (Bar, 2013), b (Darke et al., 2013), c (Mendes and Giannini, 2015), d (da Silva and Hesp, 2013), e (Pucino and Condurso, 2016), f (Arens et al., 2013), g (González-Villanueva et al., 2013), h (Costas et al., 2006), i (Costa et al., 2016), j (Pye et al., 2014), k (Clemmensen et al., 2014), l (Jackson and Cooper, 2011), m (Bristow et al., 2011), n (Girardi and Davis, 2010), o (Abhar et al., 2015), p (Bailey and Bristow, 2004), q (Alappat et al., 2011), r (Pinto and Fernandes, 2011), s (Mendes and Giannini, 2015), t (Hilbert et al., 2016), u (Ajedegba, J.O. et al., 2019a). The global relief model integrates land topography and ocean bathymetry (ETOPO1: doi:https://doi.org/10.7289/V5C8276M). The map was created using ArcGIS software version 10.3 (ESRI; http://www.esriportugal.pt/ArcGIS-for-Desktop).
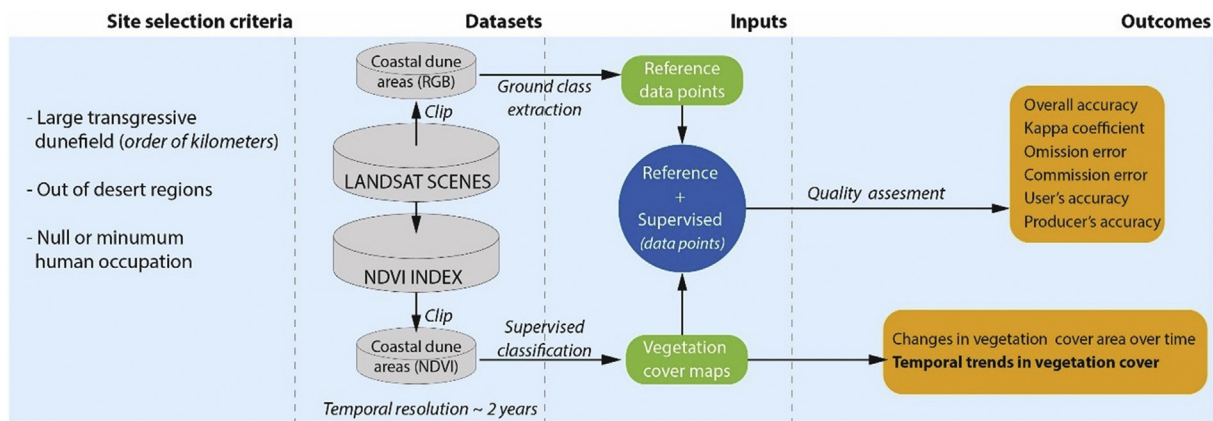
Fig. 2. Main methodology followed in the extraction of vegetation cover from Landsat imagery.

important to avoid limitations from the low resolution of the Landsat images (30 x 30 m) so areas had to big enough to align with the resolution limitation, 2) areas showing evidence of inland migration are important as we focus on measuring the shift of this trend to include those extending from moving dune types to fixed by vegetation, 3) they are away from desert areas where many dune sites are no longer moving and are not fixed by vegetation, and 4) avoiding areas occupied by humans helps reduce examination of highly modified dunes. This, however, is the most difficult criteria to enforce as in many cases previous anthropenic impacts/activities may not be immediately obvious.

Once sites are identified, a set of Landsat images or scenes were selected for each site, covering the whole period of available Landsat coverage (i.e. 1984 to 2017), and at a two-year temporal resolution where possible. Because of some limitations with the quality of the images (cloud coverage or pixels missing), it was not possible to examine the same years for all the sites, and in some cases that also prevented the desired temporal resolution. Images selected corresponded to the same season to minimise errors or changes in vegetation cover derived from a seasonal response in the vegetation growth with seasonal differences in vegetation growth.

Once Landsat scenes were selected, the derived corresponding vegetation index was requested at http://espa.cr.usgs.gov/ to map the vegetation coverage. In this work, the NDVI (Myneni et al., 1997; Rouse Jr et al., 1974) was chosen to quantify the concentrations of green leaf vegetation around the globe coastal dunes at a biannual interval (1984–2017).

The NDVI is a product of the Landsat images provided by the USGS and calculated as the ratio between the red (R) and near-infrared (NIR) values in traditional fashion: NDVI = (NIR - R) / (NIR + R). The area of the coastal dune to evaluate was clipped from each NDVI image to maximise the quality of the results; excluding other land uses from the analysis such as water bodies or agriculture. The clipped areas were classified in ArcGIS using an Interactive Supervised Classification. This tool automatically classifies the images using training samples defined by the user for each site and year, which in this case represented the vegetated areas (high values or higher reflected radiation in near-infrared wavelengths than in visible wavelengths), and the bare sand (low values or lower reflected radiation in near-infrared wavelengths than in visible wavelengths).

After the images were classified, the accuracy of the resultant classification was assessed. In supervised image classification, it is assumed that there exists a priori reference data with the information about the extent to which a value can be assigned to the different classes under study. In this case, due to the large extension covered, these reference data were obtained by generating a set of random points to extract the ground class value, which would be later contrasted or validated with the type of land cover derived from the corresponding real colour image. The validation was performed by a different user to

avoid potential biases in the analysis. The error matrix approach was used for accuracy assessment and consists of a table used to compare the information given by the reference data and the classification information, showing the degree of mis-classification among classes. From this error matrix, accuracy assessment statistics can be derived, such as overall accuracy, kappa coefficient, omission error, commission error, user's accuracy and producer's accuracy. The computation methods of these statistics have been defined in previous works (Sen, 1968; Cohen, 1960). The overall accuracy represents the total number of correctly classified samples divided by the total number of reference samples. The Kappa coefficient ranges from 0 to 1 and is a measure of how the classification results compare to values assigned. It is generally thought to be a more robust measure than simple percentage agreement calculation since it takes into account the possibility of the agreement occurring by chance. Fleiss et al. (2013) proposed a scale for interpreting the magnitude of the kappa coefficient where: if kappa coefficient is ≤ 0.40, the strength of agreement is poor, if the values are ≥ 0.40 and 0.75, it represents an intermediate to good extent of agreement while all values above 0.75 indicate an excellent extent of agreement. The accuracy of a specific class is given by the producer accuracy that corresponds with the error of omission and by the user accuracy, which in turn corresponds to the error of commission. All estimated parameters regarding the classification of each image have been included in Online Resource 2. All observations were fitted to a linear model in order to obtain the temporal trends of the vegetation cover. The confidence intervals (99.5%) for each model were also represented for each site.

The classification of the images was then used to finally estimate the total area occupied by each class and to assess the changes in coverage of each class over time. Trend analyses were conducted using Mann-Kendall tests to identify the existence of significant temporal trends in vegetation cover. Trends were quantified using the Sen's slope estimator (e.g., Gocic and Trajkovic, 2013). Mann-Kendall tests (Mann, 1945; Kendall, 1975) are a nonparametric form of monotonic trend regression analysis (Gilbert, 1987) widely applied in hydrology and meteorology (e.g., Douglas et al., 2000; Partal and Kahya, 2006; Tabari et al., 2011). They are based on the assumption that observations are representative of true conditions at sampling times. Together with Sen's slopes estimators, they allow for analysis of upwards or downwards trends in climate and environmental data, including time series with some missing observations (e.g., Helsel and Hirsch, 2002). Mann-Kendall tests were performed at 0.05 and 0.1 significance levels using Matlab codes by Burkey (2006), which also allow the calculation of Sen's slopes.

3. Results and discussion

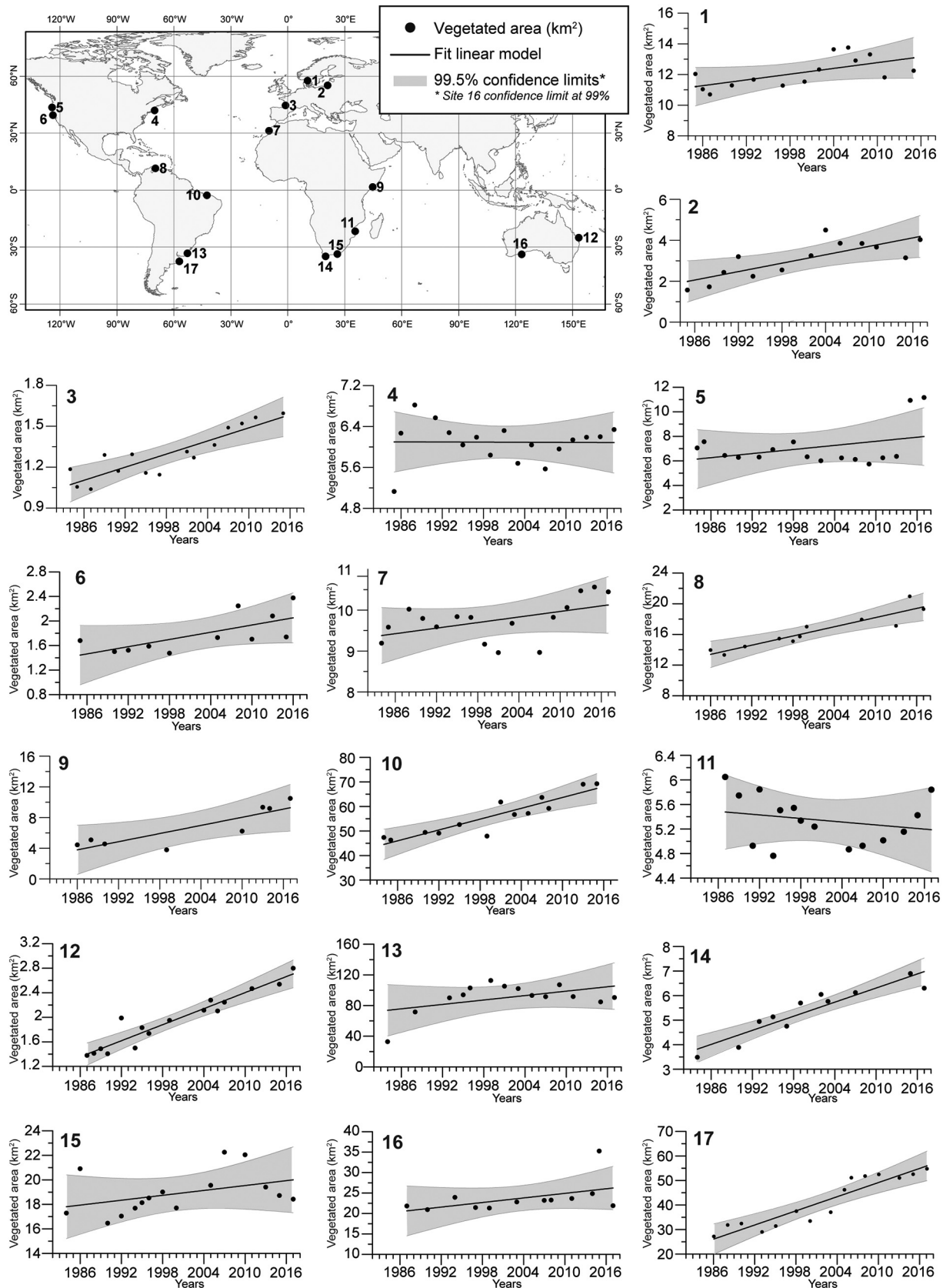The location and trends in vegetation cover (1984–2017) on coastal

Fig. 3. Changes in vegetation cover [km²] over the evaluated period of time and over different time scale intervals tested at the 17 sites. Graphs are showing for each site at all eleven temporal points of vegetation area over the same time period, with a trend line and 99.5% confidence limit. Map created using ArcGIS software version 10.3 (ESRI; http://www.esriportugal.pt/ArcGIS-for-Desktop). Sites are 1: Skagen Odde, DENMARK, 2: Curonian Spit, RUSSIA, 3: des Marais d'Hourtin, FRANCE, 4: Provincelands Hook at Cape Cod, U.S.A., 5: William Tugman State Park dunes, U.S.A., 6: Ten Mile Dunes, U.S.A., 7: Essaouira, MOROCCO, 8: Médanos de Coro, VENEZUELA, 9: Mudug, SOMALIA, 10: Pequenos Lençóis Maranhenses, BRAZIL, 11: Bazaruto, MOZAMBIQUE, 12: Fraser Island, AUSTRALIA, 13: Mangueira, BRAZIL, 14: Arniston, SOUTH AFRICA, 15: Port Elizabeth, SOUTH AFRICA, 16: Cape Arid, AUSTRALIA, 17: Faro Querandí, ARGENTINA.

Table 1

Summary of the trends observed at each of the sites over the study period (a full listing, including site description and partial changes observed, is available in supplemental information). The sites are listed from high N latitudes to high S latitudes. The assessment of the trend obtained was achieved by applying the Sen's slope estimator; a nonparametric trend regression analysis. The results of this analysis are documented by the slope of the trend (Sen's slope), the significance level of the analysis (alpha), the rejection of the null hypothesis (h = 0), the significance of the analysis (sig), and the number of samples (n) or analysed images. The Kappa coefficient is a measure of the accuracy of the classification. Net change refers to the change of vegetated covered area relative to the total assessed area between the first and the last analysed year.

Country	Code	Sen's slope	alpha	h	sig	n	Kappa coefficient ranges	Surface (km^2)	Net change (km^2)
Denmark	1	0.058	0.05	1	0.0285	14	0.50–1.00	16.70	+ 0.21
Russia	2	0.0761	0.05	1	0.006	13	0.69–0.93	11.71	+ 2.47
France	3	0.0153	0.05	1	6.29E-04	15	0.51–1.00	07.02	+ 0.41
USA	4	− 0.0027	0.05	0	0.9015	17	0.77–1.00	09.53	+ 1.21
USA	5	− 0.0125	0.05	0	0.4995	16	0.53–1.00	22.01	+ 4.11
USA	6	0.0156	0.05	1	0.0195	11	0.66–1.00	5.40	+ 0.70
Morocco	7	0.025	0.05	1	0.0584	16	0.53–0.92	12.45	+ 1.26
Venezuela	8	0.204	0.05	1	3.42E-04	11	0.62–1.00	25.00	+ 5.43
Somalia	9	0.1894	0.05	1	0.0354	8	0.63–1.00	17.30	+ 6.05
Brazil	10	0.6926	0.05	1	3.19E-04	13	0.76–1.00	95.20	+ 21.89
Mozambique	11	− 0.0178	0.05	0	0.4273	15	0.62–1.00	29.26	− 0.21
Australia	12	0.0445	0.05	1	6.58E-06	16	0.55–0.91	05.00	+ 1.42
Brazil	13	− 0.313	0.05	0	0.7603	15	0.78–1.00	308.70	+ 57.58
South Africa	14	0.0967	0.05	1	3.42E-04	11	0.53–1.00	11.80	+ 2.82
South Africa	15	0.0731	0.05	1	4.78E-02	15	0.73–1.00	105.30	+ 1.13
Australia	16	0.1412	0.1	1	0.0335	12	0.60–1.00	62.03	+ 0.09
Argentina	17	0.9325	0.05	1	2.08E-05	15	0.83–1.00	103.90	+ 27.57

dunes across several continents are shown in Fig. 3. Statistical results, including the estimated trends on vegetation cover for each site, are tabulated in Table 1. Fig. 4 shows an exemplar of temporal changes of dune vegetation changes in South Africa, site 14 over time, and is just one of the sites that matched the selection criteria well. Taking this as an example Fig. 4 shows the mapped areas over successive satellite images demonstrating the progression of vegetation cover and the demise of areas of bare sand. Rapid vegetation spread is evident across the entire dune field over the 30-year study period. This includes both elements of the seaward margin and the mobile transverse dunes in the main body of the dunefield. Initial large areas of bare mobile sand within the main dune field are broken into isolated basins separated by vegetation. These basins then gradually reduce in size as vegetation colonises the margins, creating a predominantly stable dune landscape. A plot of the entire data set (lower panel) shows a strong linear trend of progressive lateral expansion of vegetation cover from $3.5\,km^2$ to $63\,km^2$ over a 30-year period (a 53% increase in vegetation extent).

All but one of the seventeen geographically dispersed sites show a progressive increase in dune vegetation cover between 1984 and 2017. The trends are significant within 99.5% confidence limits. The range of change across all sites was between + 0.7% and + 34.98%, with an average increase of 16 ± 7% overall (excl. Site 11). Rates of vegetation encroachment are variable but consistently positive. Trend analysis shows 13 of the 17 of sites examined had strongly positive trends (alpha = 0.05 or 0.1 significance levels). Some exceptions (sites 4, 5, 11 and 13) show a less significant long-term trend; however, even within these datasets, a strong increase in vegetation cover is evident in the last decade. There may be an element of hysteresis involved in as much as dunes with initially large vegetated areas show somewhat slower rates of vegetation encroachment.

Environmental factors can act (at times in tandem) as key drivers in coastal dune field dynamics and directly influence how a dune field behaves over time. For example, sediment availability is essential for providing the overall dune field bulk volume and is a requirement for its continued growth (if given the space to establish). Dunes, where sand supply is limited or in deficit may not be maintained or expanded. It is, therefore, an important element in the natural dynamics of dune landform evolution over time. Corresponding aeolian flux (events) also helps drive the physical modification and landform diversity of dune systems, both spatially and temporally (Delgado Fernandez et al.,

2018). Changes in vegetation structure and succession, of course, have the potential to change dune morphology (Ruggiero et al., 2018, Zarnetske et al. 2015). In this study, we are concerned with the amount, rather than the nature of vegetation cover and so have discounted this component from our observations. Additionally, the pixel size being examined does not allow examination of species differentiation. Several other environmental parameters are known to influence the form and processes of coastal dune field dynamics as well. These include: (i) atmospheric temperature, which is a key influence on the duration of the annual dune plant growing season (normally the total number of daily temperatures greater than or equal to 5 °C); (ii) Carbon dioxide (CO_2) and other greenhouse gas levels which influence plant growth rates; (iii) rainfall which determines water table elevations and thus water and humidity supply, (iv) wind regimes (which determines the capacity to transport sand and ultimately dictates plant living conditions and substrate and (v) reduced beach sediment supply to dunes (where a quarter of the world's sandy beaches are more depleted in recent years (Luijendijk et al., 2018)) can decrease volumetric and lateral spread of dunes helping with fixation of the dune field through reduced sand throughput across the dune surface. Changes in any of these parameters have the potential to alter vegetation growth patterns. Global trends (Fig. 5) in many of these parameters are moving in a direction favourable to the promotion of coastal dune vegetation growth. A summary of the conceptual linkages for these is shown in Fig. 6.

Worldwide, continental wind speeds have decreased by 5–15% during the last 30 years, and are generally expected to continue decreasing during the 21st-century (McVicar et al., 2012; Vautard et al., 2010; Tian et al., 2019). The large-scale slowing of the global wind field of $-0.14\,ms^{-1}$ per decade Vautard et al., 2010; Miller and Kleidon, 2016) has been termed 'stilling'. Global mean surface temperatures have increased by 0.6 °C since the late 19th-century, and by 0.2–0.3° over the past 40 years (Hansen et al., 2010). This has been accompanied by the earlier onset of the annual growing season in some locations (Xu et al., 2016).

Global precipitation has increased by ca. 1% during the 20th-century but with strong regional variability (Lehmann et al., 2015). Robust increases in precipitation have also been indicated by both observations and climate models over the past six decades (Donat et al., 2016). Climatic projections for the 21st-century show continued amplification of daily precipitation extremes and increases in total with extreme
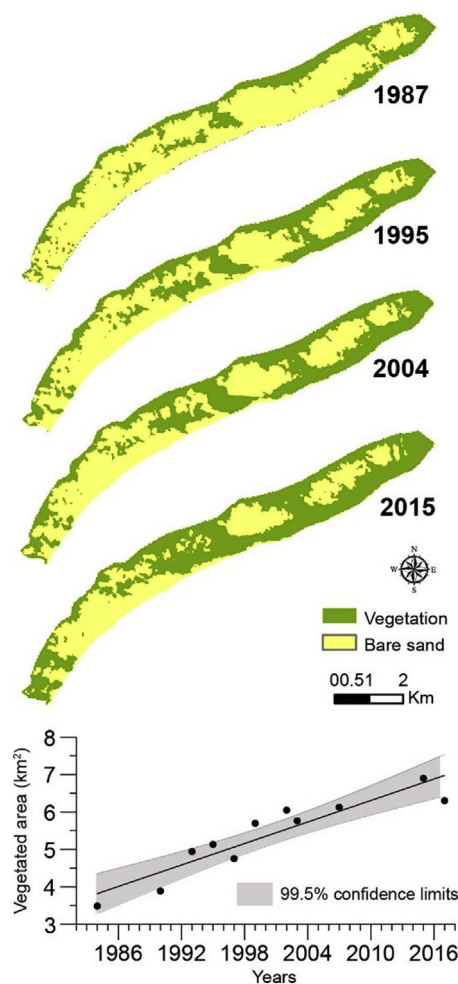
Fig. 4. NDVI-quantified changes in vegetation cover [km^2] over the evaluated time period for site 14 (South Africa). This shows the classification of land cover based on NDVI values and the land cover from the NDVI index over four time periods. The lower graph shows data from all eleven temporal points, with a trend line and 99.5% confidence limits. Map created using ArcGIS software version 10.3 (ESRI; http://www.esriportugal.pt/ArcGIS-for-Desktop).

precipitation in dry regions related to model-specific global temperature change, so that global warming predictions partly explain the spread in precipitation intensification in these regions.

Additionally, increased annual fluxes of bio-available nitrogen (N) and phosphorus (P) on the continents have occurred from anthropogenic influences (Bennett et al., 2001). Elevated N deposition can stimulate plant growth in N-limited areas such as in tropical sub-Saharan Africa (Galloway et al., 2008). Production of reactive Nitrogen increased by 120% between 1970 and 2008 (Galloway et al., 2008) and N deposition from global emissions is strongly concentrated in Asia, Central and southeast Africa, Eastern South America and eastern North America. Rising CO_2, one of the chief signatures of global climate change, also contributes to enhanced plant growth (Hughes, 2000; Keenan et al., 2016), in turn stimulating terrestrial carbon uptake and reducing the growth rate of atmospheric CO_2 (Keenan et al., 2016).

In combination, decreased wind speeds and sediment supply, plus increases in rainfall, atmospheric temperature, CO_2 and nutrient supply all have the potential to promote coastal dune vegetation growth (Fig. 5). This might be stated:

VG = f(CO_2, N, T, R, 1/U, 1/S) where: VG = vegetation growth; N = nutrients;   T = temperature;   R = rainfall;   U = wind   speed; S = Sediment supply (from beaches).

Coastal dunes therefore often display complex responses to a myriad

of environmental circumstances, including some of the global trends summarised above, but also local or regional conditions such as changes in storminess, sediment budgets, and feedbacks between these and different plant communities.

Compared to more transgressive dune states, coastal dunes that are largely fixed by vegetation (and therefore less mobile), effectively provide a much-reduced potential for accommodation space to store any fresh beach sand attempting to gain inland access. This may result in a 'backing up' of sand at the back beach zone and if conditions are suitable (tidal reach allows new aeolian deposition) sand may accumulate more readily at supratidal zones under this stabilised main dune state. Larger foredune (vertical) growth is likely to result in an enhanced buffering effect thereby giving coastlines an enhanced sacrificial dune line for future dune trimming events that may take place either through storm activity or increased sea-level rise.

This stabilisation of coastal dunes in response to climate change has several important implications in terms of dune maintenance and impact from storms. Increased vegetation cover brings higher potential for sediment retention at the coast as sediment is trapped and dunes grow vertically and laterally (seaward). Coastal dunes that are strongly vegetated have been shown to be > 30% more resilient to marine storm erosion (Feagin et al., 2015; Sigren et al., 2014; Ajedegba et al., 2019b) and therefore increases in vegetation may help slow coastline retreat along dune coasts. Any increase in dune height directly enhances its flood-defence capacity (van Gent et al., 2008) while the overall increase in sediment volume retained in the dune system acts as an enhanced reservoir of sand that can be drawn upon during high energy storms and increases the resilience of the shoreline to storm wave erosion. Large volumes of sediment in the littoral zone also help slow landward retreat during periods of sea-level rise (Zhu et al., 2016). At a time of accelerating global environmental change involving relatively rapid sea-level rise (DeConto and Pollard, 2016; Jackson, 2016; Vermeer and Rahmstorf, 2009) and increases in storm magnitude and frequency (Paerl et al., 2019; Easterling et al., 2000) this will add to the vulnerability of low-lying coastal areas. An enhanced pattern of dune vegetation growth in response to climatic drivers is something of a paradox in that it may, in fact, represent a previously unidentified geomorphic feedback in the system that could help regulate shoreline response to predicted secular sea level rise through heightened physical buffering potential.

4. Conclusions

Our analysis points to a clear 'greening' of coastal dunes over the past three decades, mirroring the global 'greening' of the earth observed by Zhu et al. (2016). This time period has been characterised by global increases in precipitation, temperature and CO_2, all of which promote vegetation growth on dunes. The synchronous period of global wind stilling reduces fluxes of wind-blown sand and creates the stability necessary to enable vegetation to colonise bare dune sand. We cannot realistically isolate the relative importance of the changing climate parameters (they are likely to vary regionally and over different temporal and spatial scales), but regardless of driver specifics, their change is coincident with a significant proliferation in coastal dune vegetation cover globally. As noted by Parmesan and Yohe (2003, p.40-41), when examining the biological response to climate change, investigating global patterns are by far much more relevant than only using individual studies of response.

Our study demonstrates a general increase in vegetation cover on coastal dunes worldwide. Since this is a global phenomenon, it is likely that the general driver of coastal dune vegetation expansion is global environmental change, with differences in the response rate and magnitude caused by local drivers and regional climatic patterns. The expansion of vegetation on coastal dunes, therefore, appears to represent an *integrated* response to several climate trends. This ironically may have implications for how coastal erosion scenarios play out in the
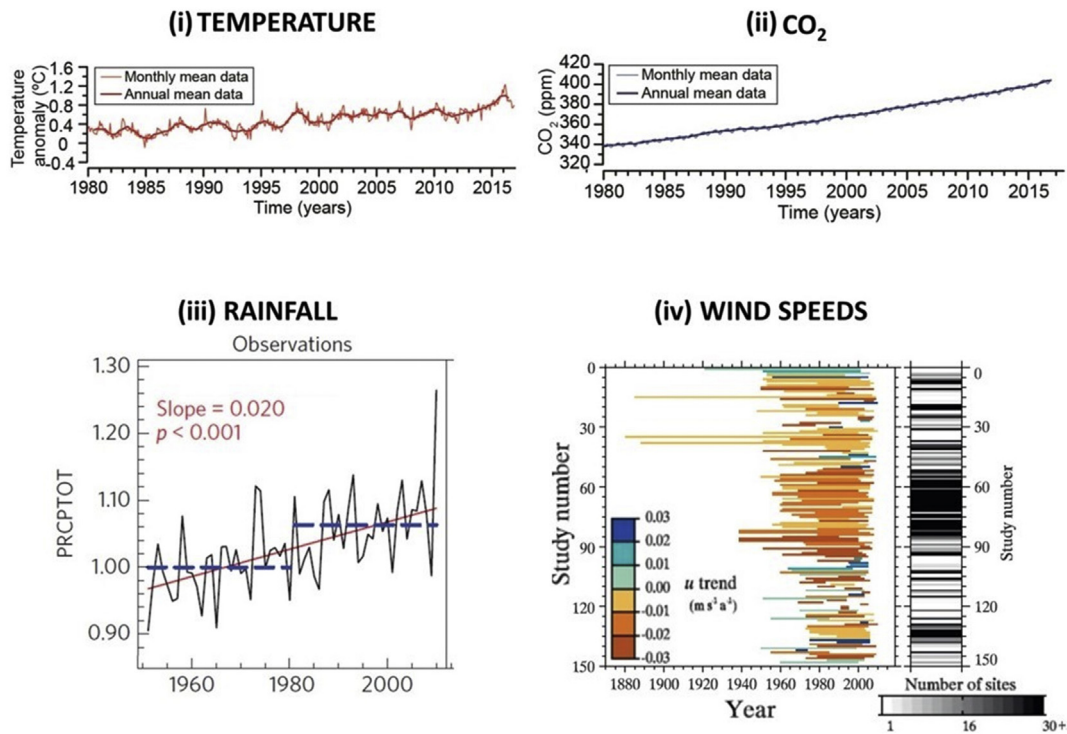
(i) TEMPERATURE

(ii) CO₂

(iii) RAINFALL

(iv) WIND SPEEDS

Fig. 5. Global trends of climatic variables showing significant changes in (i) Air temperature (NOAA National Centers for Environmental information, Climate at a Glance: Global Time Series, published July 2017, retrieved on July 24, 2017 from http://www.ncdc.noaa.gov/cag/) (ii) CO2 levels (Ed: Dlugokencky and Pieter Tans, NOAA/ESRL (www.esrl.noaa.gov/gmd/ccgg/trends/)) (iii) Precipitation (figure sourced from Donat et al., 2016) and (iv) Wind speeds (figure sourced from McVicar et al., 2012) over recent decades. Units are in ms^{-1} a^{-1}.

future with sediments not being allowed to migrate inland and some dune fringed coasts may accumulate more sand at their seaward edge than normal, effectively lessening their erosional potential as a result of buffering up dune erosion response to storms.
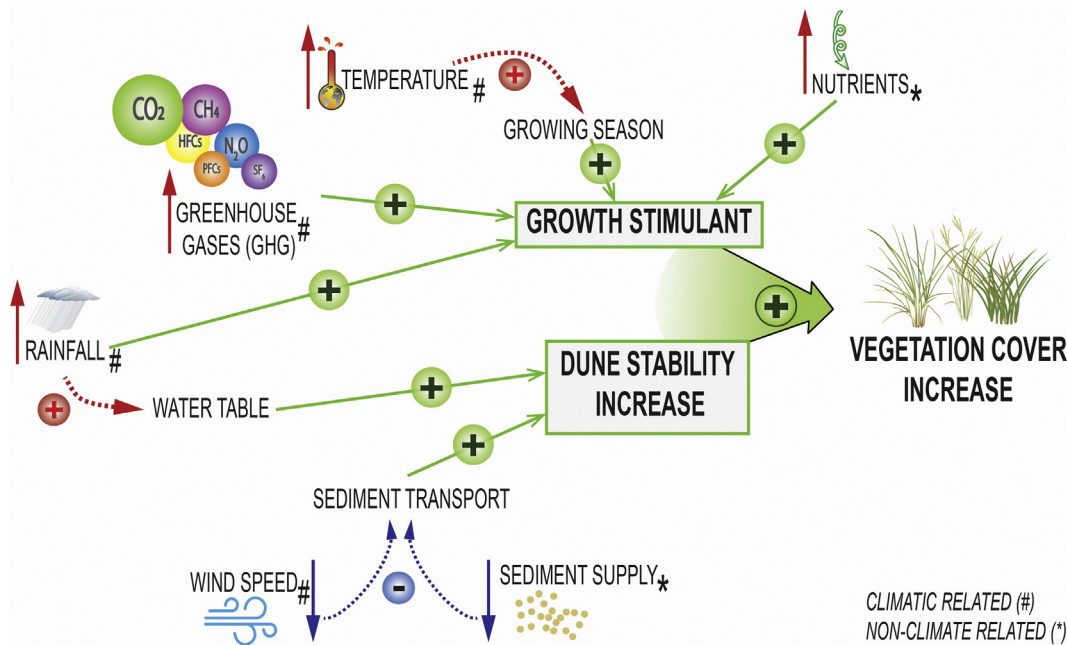
Fig. 6. Likely relationships envisaged between the drivers and dune vegetation growth. Our study contends that the impact of these combined effects may be greater than the sum of the individual contributions. For example, Frosini et al. (2012) show the combined effect of sediment transport and nutrient availability on dune vegetation.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2019.103026.

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