ARTICLE IN PRESS
RSE-09326; No of Pages 12
Remote Sensing of Environment xxx (2015) xxx–xxx
Contents lists available at ScienceDirect
Remote Sensing of Environment
journal homepage: www.elsevier.com/locate/rse

Quantification and implications of change in organic carbon bearing coastal dune cliffs: A multiscale analysis from the Northumberland coast, UK

Michael Lim [a,*], Stuart A. Dunning [a], Matthew Burke [b], Helen King [a], Nigel King [c]

[a] Engineering and Environment, Ellison Building, Northumbria University, Newcastle Upon Tyne NE1 8ST, United Kingdom
[b] Geography and Planning, Gordon Stephenson Building, University of Liverpool, Liverpool L69 7ZQ, United Kingdom
[c] QuestUAV Ltd, Unit 7B, Coquetdale Enterprise Park, Amble, Northumberland NE65 0PE, United Kingdom

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form 19 January 2015
Accepted 21 January 2015
Available online xxxx

Keywords:
Coastal erosion
Carbon contribution
Change detection
Dune cliff
Geomorphology
Terrestrial laser scanning
Unmanned aerial vehicles
Ground penetrating radar

ABSTRACT

Eroding coastlines composed of sequences of till, carbon rich peat and sand layers are characteristic of many formerly glaciated coastlines due to the interplay of relative land and sea levels. Dune cliffs cut into these materials represent one of the most sensitive systems to the processes of coastal change. Establishing appropriate scales for the quantification and analysis of change in coastal dune cliffs remains limited by the speed and nature of change, the intensity of environmental processes and the challenges of achieving adequate survey control. This paper presents the results from multi-scale analyses into the behaviour of dune cliffs on the northeast coast, UK, over a 118 year period. Repeat unmanned aerial vehicle (UAV) survey differences have been used to identify and quantify system behaviour, set in context with historic map comparisons. At the landform scale, monthly dune cliff dynamics have been analysed over the course of a year with terrestrial laser scanning (TLS) in order to gain insights into the drivers of contemporary dune cliff behaviour. Finally, pseudo three-dimensional ground-penetrating radar (GPR) data are used to trace subsurface stratigraphy from which the potential extent of stored carbon (in excess of 100 t over 50 m of monitored dune cliff) at risk of release by coastal erosion over the next 50 years can be calculated. The consideration of multi-scale changes over time periods relevant to well-constrained sea level change has revealed a complex combination of failure mechanisms that have resulted in an acceleration in dune cliff recession (particularly over the last decade) and a form change to shallower, divergent profiles. This potential acceleration in contemporary dune cliff response holds significant implications for both coastal management and the contribution of this poorly quantified input to the coastal carbon flux.

1. Introduction

The interplay of glacial–interglacial environments has left many modern mid- to high-latitude coastlines dominated by interleaved deposits of till (glacial), peat (interglacial) and sand (Holocene accumulations). The beach and dune systems that result from erosion and reworking of these deposits are thought to account for 34% of ice-free coastlines globally (Hardisty, 1994). They are widely distributed, occurring at every latitude (Barbier et al., 2011), and dominate shorelines throughout Northern Europe (de Ceunynck, 1985; Wilson, Orford, Knight, Braley, & Wintle, 2001), the coastal lowlands of Australia (Taffs, Logan, Parr, & Jacobsen, 2012; Whinam et al., 2003) and even the Great Lakes of North America (Hill, 1974) for example. Despite their pervasive distribution across European coastlines (Ritchie, 2001), the cessation of large quantities of sand to the coastal zone and the onset of marine influence has led to the widespread erosion of mature dune systems. Subjected to rising and accelerating sea levels (Shennan, Milne, & Bradley, 2009) and a predicted increase in extreme (storm) events (Min, Zhang, Zwiers, & Hegerl, 2011), low coastal cliffs that are cut into these interleaved deposits currently form some of the most rapidly eroding coastlines worldwide (Wilson et al., 2001).

Barbier et al. (2011) suggest that the economic value of dune systems is amongst the highest of any coastal system, providing an accumulation of 'ecological services' including limiting marine erosion, the provision of materials, protection of the coastal hinterland, the capture and filtration of water contaminants, habitat provision, carbon sequestration, tourism, recreation and education. The benefits of dune systems, both direct and indirect, remain poorly quantified and often specific aspects are considered individually rather than collectively (Brown & McLachlan, 2002; Zarnetske, Seabloom, & Hacker, 2010) and are fixed both spatially and over time (Koch et al., 2009).

The importance of understanding the true rates and nature of dune cliff erosion and its consequences for low-lying hinterlands has long

* Corresponding author. Tel.: +44 191 243 7094.
E-mail address: michael.lim@northumbria.ac.uk (M. Lim).

http://dx.doi.org/10.1016/j.rse.2015.01.034

Please cite this article as: Lim, M., et al., Quantification and implications of change in organic carbon bearing coastal dune cliffs: A multiscale analysis from the Northumber..., *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.01.034

been acknowledged in a management context (Lemauviel & Roze, 2003). However, the activation of significant amounts of stored organic carbon within these systems also adds impetus to the need to monitor and interpret the behaviour of these systems (Beaumont, Jones, Garbutt, Hansom, & Tobermann, 2014; Grayson, Holden, Jones, Carle, & Lloyd, 2012; Romankevich, Vetrov, & Peresypkin, 2009). Peat accounts for up to 50% of all the carbon stored in soils globally (Holden, 2005; Limpens et al., 2008), but the rate at which it is eroded is a poorly understood component of the carbon flux (Grayson et al., 2012). Coastal peatlands, in particular, are a significant but often underrepresented component within the global carbon budget (Taffs et al., 2012). Dating and palynological evidence from peat layers within dune systems has been used to reconstruct former coastlines and make tentative connections to periods of marine transgression and regression associated with several kilometres of coastal erosion (de Ceunynck, 1985). Estimates of global terrigenous organic carbon from coastal erosion processes have put the amount at 25×10^6 tons a^{-1} (Romankevich et al., 2009), although establishing the true figure remains constrained by the limited availability of quantitative monitoring data (Grigoriev, Rachold, Hubberten, & Schirmeister, 2004). It is evident that peat bearing coastlines are often highly erosive and thus may respond rapidly to changes in sub-aerial or marine conditions (Semiletov et al., 2011).

The potential for continuous morphological changes to both the cliff and the fronting beach (Short & Hesp, 1982) make the collection of accurate, quantitative data on dune cliff systems particularly challenging (Carter, 1991). Therefore, changes in dune cliffs need to be considered over a range of spatial and temporal scales (Feagin, Williams, Popescu, Stukey, & Washington-Allen, 2012). The aim of this paper is to quantify the rates and mechanisms of change in a monitored section of coastal dune cliffs and to consider the implications for understanding dune cliff behaviour, sensitivity to environmental processes and potential contribution to the coastal carbon flux.

2. Dune cliff systems

There is a fragile relationship between physical and biological agents acting to shape and stabilise dune systems, resulting in ecosystems that are particularly sensitive indicators of environmental change. Alterations in sediment supply, vegetation characteristics (such as composition, structure or extent) or destabilising processes produced by waves, wind or rainfall can lead to significant morphological adjustments over relatively short periods of time (Clemmensen, Fornos, & Rodriguez-Perea, 1997). These changes can be instantaneous and event driven or gradual long term shifts associated with altered process conditions such as a marine transgression or regression (Psuty, 2008). Dune system sensitivity has been shown to operate over time periods of individual storm events (Splinter & Palmsten, 2012; Zhang, Whitman, Leatherman, & Robertson, 2005), seasonal forcing (Esteves, Brown, Williams, & Lymbery, 2012) and even decadal trends in storm tide occurrence (Pye & Blott, 2008). In rare considerations of post-storm behaviour there have been conflicting results. Feagin et al. (2012) demonstrate rapid recovery potential over several months following hurricane erosion, whereas Suanez, Cariolet, Cancouët, Ardhuin, and Delacourt (2012) identify an ongoing recovery period where hydrodynamic changes to the post-storm system result in a secondary development stage and an altered equilibrium beach profile over a two year recovery period.

The connectivity and sensitivity of dunes and dune cliffs mean they cannot be considered in isolation from the coastal system, but questions remain over the most appropriate spatial and temporal scales at which to consider their changes. Distinct thresholds for significant erosion of dunes have been identified that suggest sea level often provides a fundamental control on the geomorphic effectiveness of storms (Esteves et al., 2012; Furmańczyk, Dudzińska-Nowak, Furmańczyk, Paplińska-Swerpel, & Brzezowska, 2012). Pye and Neal (1994) also identify a close relationship between dune behaviour and beach characteristics; a negative dune sediment budget was associated with falling beach levels and a reduction in dune erosion rates was expected following rising beach levels. Geochemical analyses of 'perched' (cliff top) dune systems has shown the close coupling between cliff and dune sediments and their contribution to the coastal system (Saye, Pye, & Clemmensen, 2006). Other factors such as precipitation characteristics can influence dune morphology, both directly through sheet wash and rain splash erosion and indirectly through controls on vegetation development and the redistribution of chemicals and minerals within the dunes (Saye et al., 2006). Mountney & Russell (2009) also highlight the potential influence of the water table in controlling dune development and behaviour.

Williams et al. (2001) use a multi-parameter checklist including dune and beach morphology, vegetation and anthropogenic impact to assess and classify vulnerability to change. Such studies have demonstrated that dune systems often reflect regional trends, although these can become muted by local processes (Davies, Williams, & Curr, 1995; Williams et al., 2001). Despite significant advances to the understanding of dune cliff development and evolution (Gilbertson, Schwenninger, Kemp, & Rhodes, 1999; Knight, Orford, Wilson, Wintle, & Braley, 1998; Orford, Wilson, Wintle, Knight, & Braley, 2000; Wilson & Braley, 1997), there remains a scarcity of detailed monitoring studies, particularly along the late-Holocene dune systems that are found extensively across the Atlantic coasts of northwestern Europe (Wilson et al., 2001).

3. Quantifying dune cliff morphology

The importance of coastal dune cliffs as both ecosystems and protective barriers or buffers to marine influence has led to numerous attempts to map and monitor responses over time. Olivier and Garland (2003) monitored foredune development with total station topographic surveys and Esteves et al. (2012) used differential global positioning system (DGPS) surveys to quantify thresholds for dune erosion beyond a measurement accuracy of 2 m, although both approaches achieve sparse spatial coverage. The generally smooth undulations of dune fields have proven suitable for the application of airborne light detection and ranging (lidar) survey data. Saye, van der Wal, Pye, and Blott (2005) used lidar surveys at five sites to map changes in dunes and fronting beach systems and suggested that critical beach characteristics (width and slope) were site specific and, where present, tended to lead changes in dune morphology. A critical element in the quantification of change in geomorphic systems is the relative accuracy achieved between surveys (Zhang et al., 2005). Richter, Faust, and Maas (2013) used airborne lidar to map dune cliff retreat and highlighted the problem of comparing multiple lidar datasets with various degrees of post-processing and interpolation, which have the potential to result in significant offsets and positional errors. The sharp breaks of slope on dune cliffs can be missed by lidar point posting and, although this error can be reduced in some circumstances (Brzank, Lohmann, & Heipke, 2005), it often poses particular problems for identifying and interpreting change. Perhaps the greatest limitation for airborne lidar surveys of dune cliff systems has been the logistical limitations (such as expense and planning) that often make surveys of sufficient frequency impractical.

The application of repeated ground based lidar or terrestrial laser scanning (TLS) has enabled the quantitative investigation of a wide range of environments, primarily involving the geomorphological analysis of slope changes (Abellan et al., 2013). Feagin et al. (2012) discuss both the potential and the limitations of TLS surveys for quantifying and monitoring dune systems. Using apparently stable features, concordant across survey datasets, dune changes were identified beyond standard error ranges of sub-metre to sub-decimetre. However, the challenges associated with establishing stable benchmarks and the variation in processing approaches have limited the effectiveness of TLS monitoring of change. For example, despite the strong relationships between vegetation and dune behaviour (Camacho-Valdez, Murillo-Jimenez, Nava-Sanchez, & Turrent-Thompson, 2008), vegetation poses particular problems for the alignment of TLS surveys (Feagin et al., 2012) and should be masked from convergence procedures and change analysis rather than removed with ground extraction algorithms that can enhance interpolation errors. It has been shown that careful planning, error assessment and validation can produce higher levels of confidence in the results produced from TLS data (Day, Gran, Belmont, & Wawrzyniec, 2013a). Whilst TLS surveys remain the most consistently accurate and high resolution method of quantifying dune cliff change, they are generally restricted to short time periods and, when viewed in isolation, do not allow patterns identified to be set with a wider spatial and temporal context (Feagin et al., 2012).

New methods of aerial survey in the form of unmanned aerial vehicles (UAVs) now offer the potential to practicably collect more frequent surveys at high spatial resolutions, comparable to that achieved by TLS surveys (model cell size of a few centimetres is possible; Lejot et al., 2007). Recent developments in UAV platforms, digital cameras and image processing have facilitated the effective use of UAV surveys for applications such as landscape classification (Laliberte, Goforth, Steele, & Rango, 2011), DEM extraction (Eisenbeiss and Sauerbier, 2011), feature mapping (Mozas-Calvache, Pérez-García, Cardenal-Escarcena, Mata-Castro, & Delgado-García, 2012) and erosion monitoring (d'Oleire-Oltmanns, Marzolff, Peter, & Ries, 2012). The use of UAV imagery addresses a critical scale of analysis, covering areas up to several square kilometres in size, which fits between conventional aerial and ground surveys. However, significant challenges remain in the collection, processing and error-checking of UAV derived data (Aber, Marzolff, & Ries, 2010; Hardin & Jensen, 2011; Niethammer, James, Rothmund, Travelletti, & Joswig, 2012) and the results produced need to be viewed with caution. As with other aerial surveys, use of UAV imagery requires a sufficient number and distribution of ground control points to be collected. This can be time consuming and limit applications where accessibility is restricted (e.g. intertidal environments), hazardous, or constantly changing during and between surveys (Laliberte, Winters, & Rango, 2008). New image processing approaches such as structure from motion (SfM) can derive high resolution surface models from overlapping images with minimal ground control (Niethammer et al., 2012), although careful and considered validation is required when such high levels of automation exist within the processing workflow.

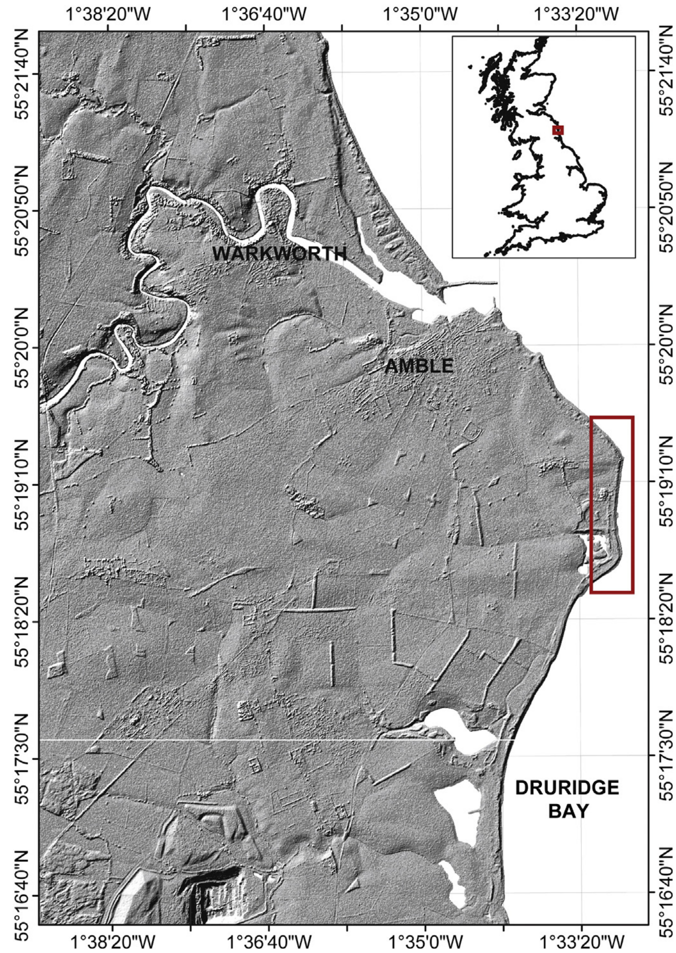

Fig. 1. Hauxley dune cliff headland (red box) located on the northeast coast of England (inset map) between Amble and Druridge Bay. Dune cliff systems front almost the entire coast within this area. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Regional setting

The Northumberland coastline in the northeast of the United Kingdom contains extensive coastal dune systems, extending over 45 km and covering 1374 ha (Wilson et al., 2001). The dune cliffs selected for the multi-scale analyses of geomorphic behaviour form a headland section within a 10.5 km long dunefield that buffers wetlands, croplands, visitor centres, infrastructure and settlements from marine processes (Fig. 1). The cliffs reach a height of 5.5 m, with cuspate scars cut into weakly cemented sand anchored on sheer-sided peat (up to 1.6 m thick) and till units (up to 1 m exposed above average beach level). The Holocene accumulations of peat have been documented (Raistrick & Blackburn, 1932) and dated (Frank, 1982), forming between 4900 ^{14}C yr BP and 2800 ^{14}C BP (Innes & Frank, 1988). The peat has been used to determine an environmental chronology through the intercalated deposits to establish a record of marine transgression and regression (Plater & Shennan, 1992) and vegetation changes associated with human activity during the Bronze Age (Innes & Frank, 1988). The dune systems are also of considerable archaeological interest, having produced flints from the Mesolithic (O'Sullivan & Young, 1995). Recent (unpublished) studies claim to have identified tsunami deposits produced by Storegga slide activity that make the site of particular interest for understanding the development and response of the coast to extreme events (also identified and analysed 16 km to the north at Howick by Boomer, Waddington, Stevenson, & Hamilton, 2007).

The dune cliffs are cut into the most seaward dune that fringes a narrow (<350 m) zone of more stable (vegetated), low hummocky dunes as is typical for dune systems associated with headlands in the area (Wilson et al., 2001). Vegetation succession ranges from marram grasses and shrubs on the dune cliffs to hawthorn, nettles, brambles and wetland vegetation in the lee of the foredunes. The dune cliffs are fronted by a sand beach and inundated by a mean spring tidal range of 4.3 m (neap range 2.1 m). Mean spring high tide reaches 2.4 m above British ordnance datum, submerging the till and partially inundating the peat layers. However, the easterly aspect of the cliffs means they are sheltered from the prevailing westerly-south-westerly winds (Wilson et al., 2001). Wind velocity and rainfall at Hauxley generally peak in winter months at around 6.2 m s^{-1} (January mean) and 78 mm (November mean) respectively, although strong convectional storms can also lead to high summer rainfall.

5. Data collection and results

5.1. Long-term (centennial) dune cliff change

A comparison of the dune cliff position at Hauxley in historic maps dating back to the 1897 Country Series (1:2500) production demonstrates a continuously retreating headland, although the calculated annual rate varies both spatially and between map epochs (Fig. 2). A comparison of the position of permanent features with within each of the mapped datasets produced mapping and registration errors of 5.4 m (1897–1923), 4.3 m (1923–2005) and 0.7 m (2005–2013) respectively. The retreat distances have been derived from averaging the shortest

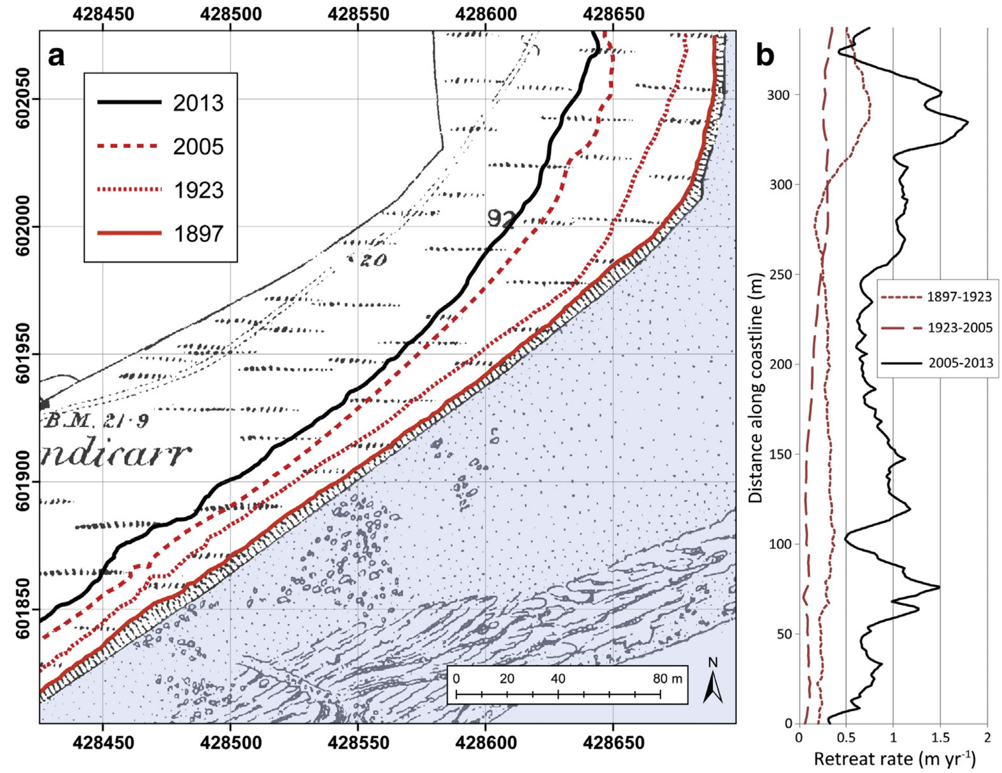

Fig. 2. Historic map cliffline positions at Hauxley dune cliffs (a) and derived annual retreat rate data measured northwards up the headland (b). Note the southern half of the headland (pictured) has been selected for detailed monitoring and analysis because the northern half of the dune system has been modified by management practises. Based on Digimap Historic Map data © Crown Copyright and Landmark Information Group Limited (2014). All rights reserved (1897; 1923; 2005).

distance to a point on the (more recent) comparison line at 0.1 m intervals, providing near continuous records of mapped cliffline positions and highlighting localised failures rather than the coarser intervals used where shoreline behaviour is more uniform (Ford, 2013). The period between 1897 and 1923 reflects a general tendency at the site for the area of peak headland amplitude to record greater cliff top retreat than the southern section, which has retreated at approximately half the base rate of retreat. The next epoch, from 1923 to 2005 shows a reduced (mean retreat 49% lower) and more spatially consistent site response with retreat rates increasing progressively to a maximum of 0.35 m a^{-1} at the headland crest. The average retreat during this period is comparable to that of the earliest mapped change. The most recent cliff line comparison is between 2005 MasterMap data (provided by Edina) and a DGPS survey conducted in May 2013. The rates of retreat since 2005 have significantly increased (average rate over five times higher) and show a more flashy distribution across the headland. The higher resolution of the 2013 line resulted in greater roughness, which may account for some of the greater variability noted, but the magnitude and multiple scales at which the variations occur appear to suggest genuine responses beyond any methodological differences. It is not possible to get reliable volumetric estimates from the historic map data but the cliffs appear to be undergoing a reduction in face gradient, with the distance between the cliff base and cliff top increasing across the epochs (cliff toe positions not presented). The average distance between the top of the cliff to the base increases from 5.04 m in 1897, through 7.07 m in 1923, to 7.18 m in 2005 and 7.41 m in 2013. However, the lack of contiguous fixed control (i.e. buildings) near the dune cliff base mean that mapping accuracy cannot be ascertained, nor can it be determined whether, if genuine, these changes in top to base horizontal distance are due to a relative reduction in the retreat rate of the till and peat base or an acceleration of the sand crest retreat.

5.2. Medium-term (interannual) dune cliff change

A key challenge in quantifying change in dynamic systems such as dunes is to identify the patterns of difference at representative scales (landform or greater) and at sufficient monitoring frequency (regularly sub-seasonal). A Panasonic DMC-LX3 digital camera was mounted into a Quest 100 UAV and (semi-)autonomously flown over a pre-defined flight path at a height of 90 m, collecting 10 MP images of the study area with a minimum 60% overlap between images. Identifiable ground features located throughout the area of interest have been surveyed with a Trimble R4-3 DGPS rover and corrected to a fixed base station to generate ground control points (GCPs). The GCPs produced a mean horizontal post-processed accuracy of 0.02 m and 0.05 m in the vertical. Of the surveyed features, six were selected as GCPs due to their distribution across the survey area and the remaining four where used as check points for error assessment. AgiSoft PhotoScan, a structure from motion (SfM) processing package, was used to model surface elevations from the UAV image sequences: aligning images automatically with a scale invariant transform procedure, automatically detecting common features and extracting 3D structure, positioned, scaled and orientated with the GCP network. The surveys, collected in April 2010 and again in July 2013, were processed to produce DEMs with a ground sample distance of 0.1 m. The processed DEMs had a mean computed control point error of 0.13 m once blunders were excluded (Agisoft Software), although the limited check points available had a significantly higher mean error (0.87 m). The increase in errors recorded in the check point data suggest that further investigation is required into interpolation effects and the potential variability in accuracy achieved by SfM elevation data, although this is beyond the scope of the present study. Given these uncertainties, the volumetric differences between surveys beyond an error threshold of 1 m have been calculated by rasterising

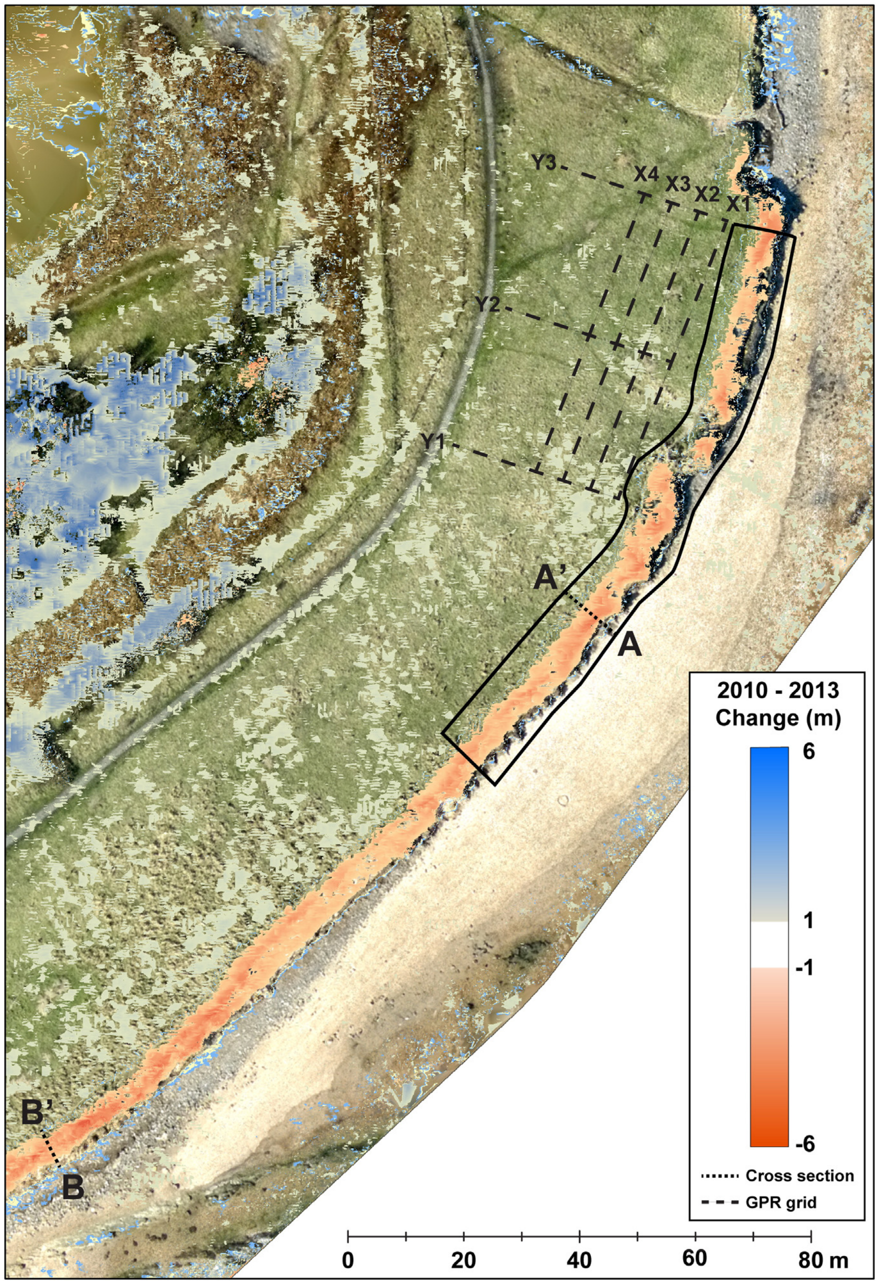

Fig. 3. An orthophoto overlain by recent changes at Hauxley, Northumberland, detected with UAV survey data, beyond a unified control and check point error threshold of 1 m for each 0.1 m^2 cell. The profiles labelled A–A′ and B–B′ relate to Fig. 8, the boxed area to the TLS survey extent (Fig. 4) and the labelled dashed line to the GPR grid in Fig. 5.

the SfM elevation data at 0.1 m cell sizes and summing the differences (Fig. 3). It should be noted that shadowing and lighting differences may have resulted in variations in inter- and intra-survey quality (point density and accuracy) and the lack of permanent identifiable features seaward of the dune system restricted the distribution of both control and check points.

The changes detected between April 2010 and July 2013 show large scale dune cliff erosion and isolated area of vegetation gain. The gains may be partly due to genuine growth but the imagery also shows that leaf coverage and shadowing may have contributed to the differences detected. The monitored dune cliff area recorded a volumetric loss of 1914.33 m^3 and a maximum step-back distance of 5.22 m over the 40 month period, producing an average retreat rate of 0.39 m a^{-1}. The change model also highlights areas of gain at the base of the dune cliffs, likely to be failed dune cliff material. However, it is notable that these gains increase towards the northern and southern extremities of the survey area where ground control was limited and occur on the beach where reduced image texture and features may potentially reduce model quality. Caution is therefore exercised over cliff toe and beach level changes detected between UAV surveys. Despite the planimetric viewpoint produced from the airborne data collection, the darker red banding in the middle and upper (particularly to the south) portions of the cliff face suggest that the less cohesive upper sand units have suffered greater losses between surveys than the more cohesive basal peat and till layers.

5.3. Shot-term (intra-annual) dune cliff change

To complement the wider scale changes detected with UAV imagery, high spatial and temporal resolution losses have been monitored with TLS. Monthly repeat surveys were conducted to establish changes occurring in a 100 m section of dune cliffs throughout a year-long monitoring period (January–December 2013). In accordance with the methodology for bluff erosion described by Feagin et al. (2012) the scanner, a Reigl LMS-Z620, was positioned at multiple locations (the precise number varied between four in winter and 6 in summer) in front of the cliff face using large overlap to reduce shadowing from the discrete clusters of vegetation wherever possible. Cylindrical targets were located throughout the scanning scene, across the beach area and over a network of cliff top ground stakes, surveyed with DGPS. In addition, fixed 'benchmark' (Day, Gran, Belmont, & Wawrzyniec, 2013b) features within the scanning scene such as a Coastguard lookout mast were used to check inter- and intra-survey errors. Each survey contained three scan positions, which were internally registered and iteratively converged in RiScan Pro (all to within a standard deviation error of 0.04 m). The DGPS control point network was used for the registration and check point assessment of the separate monthly surveys because the dynamism of the dune cliff system and seasonal changes in vegetation limited the success of iterative convergence procedures. The monthly datasets were then transformed and translated into a local coordinate system (in accordance with Lim et al., 2005) for volumetric change analyses. The monthly losses beyond a maximum check point error threshold of 0.1 m are presented in Fig. 4. Only losses are presented because the majority of gains over a monthly period represented loose material deposited on a lower tier of the dune cliff system, such as sand cones deposited onto the protruding peat layer (higher sand retreat rates mean there is often a step in the cliff line) or peat and till blocks that have collapsed onto the fronting beach. It should be noted that some of the losses reflect the subsequent removal of failed material and that lateral changes along the base of the till relate to fluctuations in beach level (see November change for example, Fig. 4). The losses are characterised by seepage fluting as well as occasional undercutting and cantilever collapse within the till, shallow (face-parallel) stress relief sheet failures and block removal from the peat and more

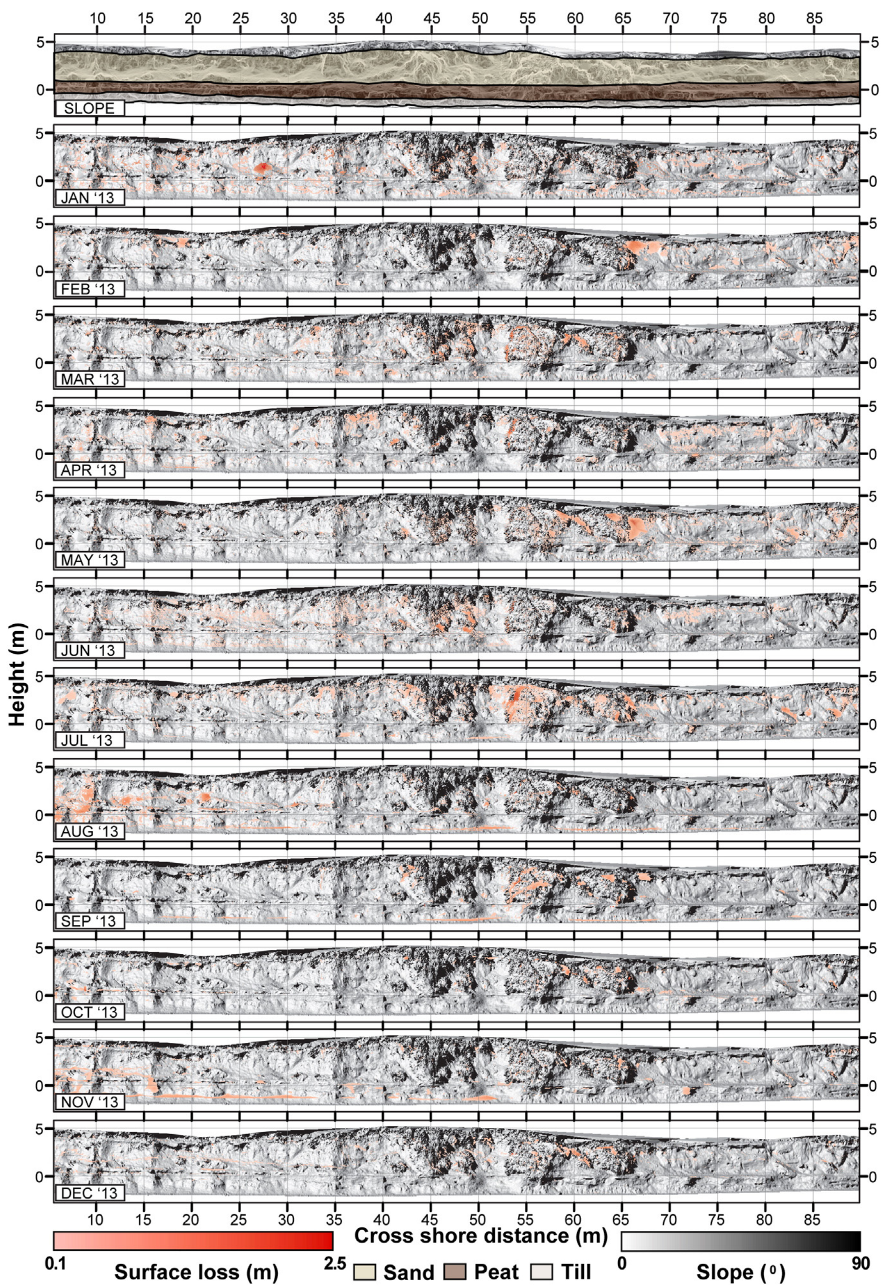

Fig. 4. Dune cliff slope model (top) and monthly dune cliff losses at Hauxley, Northumberland, identified with TLS data differencing and presented over a January 2013 dune cliff hill shade model.

continuous, curvilinear losses from the sand. There are concentrations of erosion at layer boundaries, particularly at the interface between the till and peat layers.

5.4. Dune cliff carbon stores

The erosion of soil and peat within dune cliffs releases stores of organic carbon into the coastal system, but there remains much uncertainty over the extent and significance of these carbon pools (Mitra, Wassmann, & Vlek, 2003). Site stratigraphy was investigated using a Sensors and Software Inc. pulseEKKO PRO Ground-penetrating radar (GPR) system (Fig. 5). A total of 275 m of 200 MHz common offset (CO) GPR lines were collected as a pseudo three-dimensional grid ~4 m inland (closest line, X1, Fig. 5) from the cliff section that was surveyed using the TLS. During CO data collection, antennas were kept at a constant separation of 1 m and data were collected in step mode (0.25 m) along the lines to improve ground coupling and trace stacking (32 traces). The GPR antennas were co-polarised and perpendicular broadside to the survey line in order to reduce reflections from offline sources (Arcone, Lawson, & Delaney, 1995). A subsurface radar wave velocity of 0.1 m/ns was used to convert two-way travel time into depth and for further data processing. The optimal velocity has been established by applying a range of velocities to the data (the range applied was that expected for the materials at the site: cf. Neal, 2004) and using that which resulted in reflection depths that best corresponded with those surveyed in the exposed cliff section. GPR processing was carried out in REFLEXW v6.0 and included static correction, 'dewow' filtering, bandpass filtering, migration, background removal filtering, application of a gain function and topographic correction (topographic data were collected simultaneously using a DGPS).

Three radar elements are identified (labelled A–C in Fig. 5b and referred to as RE-A to RE-C in the text) and these correspond to the unit boundaries in section (Fig. 5a). RE-A, which corresponds to the till in section, is traced through the grid by a sub-horizontal, but slightly irregular upper bounding surface below which the GPR signal rapidly attenuates due to the high fine content within the till (Fig. 5b, labelled 'A'). RE-B is composed of strong, continuous sub-horizontal reflections that are conformable to the lower bounding surface. It forms an ~1–3 m thick radar element, the position and characteristics of which corresponds to that of the peat in section (Fig. 5b, labelled 'B'). Large diffractions (point source reflectors) are occasionally observed in un-migrated data, which likely correspond to the large wood fragments or root structures embedded within this peat. Local variations in thickness largely correspond to irregularities in the basal till. RE-C is composed of discontinuous sub-horizontal reflections that correspond to the aeolian sediments in section, and it has an irregular geometry that thins in a landward direction, conforming to the morphological expression of the dunes here (Fig. 5b, labelled 'C').

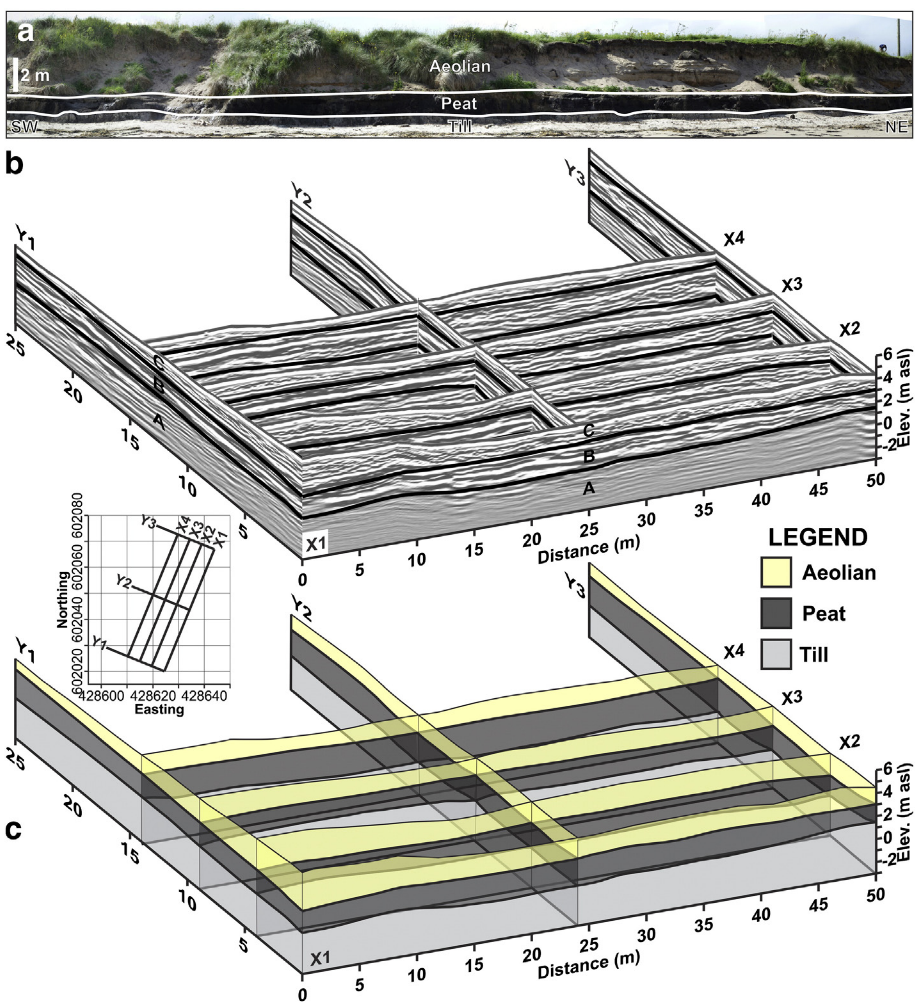

Fig. 5. Photomosaic of the Hauxley cliff section, with the main units demarcated by the white lines (a). Fence diagram of processed GPR profiles. Bounding surfaces are indicated by the bold black lines and the principle radar elements are labelled A–C (b). Interpretation of GPR data (c): A (Till), B (Peat) and C (aeolian Sand), with each radar element colour-coded to correspond to the observed units (image a). Grid line positions and orientation are shown in the inset map and the location is shown in Fig. 3.

6. Analysis and discussion

6.1. Dune cliff behaviour

Over the 118 year period for which data exist (sea level records, cliff line mapping, UAV surveys and TLS data), an average dune cliff retreat rate of 0.27 m a^{-1} has been recorded at Hauxley, Northumberland under rising sea level. The historical data show a generally consistent rate of between 0.3 m $a^{-1}$and 0.2 m a^{-1}, followed by a five-fold acceleration in the post 2005 rate (Fig. 6). The new 3D survey data (Fig. 6, inset) also record higher rates than those mapped pre-2005, but neither the inter-annual UAV surveyed retreat (0.39 m a^{-1}) nor the intra-annual TLS surveyed retreat rates (0.61 m a^{-1}) reached the post-2005 rate generated by cliff line mapping (0.92 m a^{-1}). The broad agreement across the different datasets (all higher than the pre-2005 average retreat rates) indicates that there has been a genuine increase in the rate of cliff recession over the last decade (and potentially beyond, within the confines of historic map data). The three year change map (Fig. 3) illustrates the widespread retreat that occurred over the dune cliff with all exposed areas incurring losses over this period, although the change was not uniform. However, the significance of larger failures in determining these variations is difficult to establish in such dynamic systems due to the tendency for eroding areas to coalesce, superimpose or infill. The increase in variability may also reflect a reduction in data smoothing over time with more recent data having a higher spatial resolution (and greater accuracy).

It has been noted above (Section 5.2) that higher concentrations of change in recent years have occurred at the (mapped) cliff top relative to the rest of the cliff. Indeed, a cliff line analysis conducted on the UAV survey data derived an annual retreat rate of 0.84 m a^{-1} (within 10% of the rate produced from map data). These data indicate that cliff line mapping may be sufficient to record long term change in dynamic systems, but is not appropriate to gain an understanding of geomorphic behaviour, particularly when interacting processes and multiple constituent materials are involved. Furthermore, caution should be exercised over the comparison between the one-dimensional retreat detected by cliff line mapping and the three-dimensional change resulting from DEM differencing. The differences noted in the three-dimensional datasets highlight the variability of dune cliff system response. The recession rate monitored during a year with TLS was 64% higher than that recorded by UAV surveys over an overlapping 40 month period. This suggests that a one year monitoring strategy may not be adequate to avoid the influence of short term events. However, the sub-annual frequency achieved with TLS surveys has provided valuable insights into the event driven variability of dune cliff behaviour.

The processes controlling dune cliff erosion and sediment production, particularly those systems containing vegetation or where dunes are perched on layers with different geotechnical competence such as rock, till or peat, are poorly understood (Feagin et al., 2012). The dune behaviour and the interaction between the different constituent material layers can now be distinguished over monthly timescales (Fig. 7). Frequency density profiles show the normalised distribution of change with height up the cliff face for each month (Fig. 7a). The total amount (volume) of material lost from the dune cliffs peaked in August, with in excess of 48 m^3 removed from the monitored cliff section. The greatest losses within the basal unit of till also occurred during August, although the peaks in erosion in both the peat and the sand layers were recorded in January. This appears to be a response to the highest astronomical tides and winter storms that occur in January and, although the till also recorded significantly higher (almost twice the average) monthly losses, the full extent of the damage may have partially obscured by beach level changes. The linkages between dune cliff behaviour and environmental drivers are discussed below (Section 6.2). The power law scaling exponent provides a measure of the gradient of the relationship between the size and frequency of changes occurring each month (Fig. 7b). The exponents of the peat and sand changes are broadly similar throughout the year suggesting that both the pattern and the timing of responses remain consistent. However, the exponents of the size distribution of till losses are generally greater, indicating a steeper gradient that may reflect a curtailed distribution caused by variations in the till exposure, often masked by fluctuating beach levels. In the months of largest change the exponents of all three layers converge and produce values generally within the range (−1.5 to −3.5) usually associated with sliding type slope failures (Turcotte, 1999). The high exponents may also

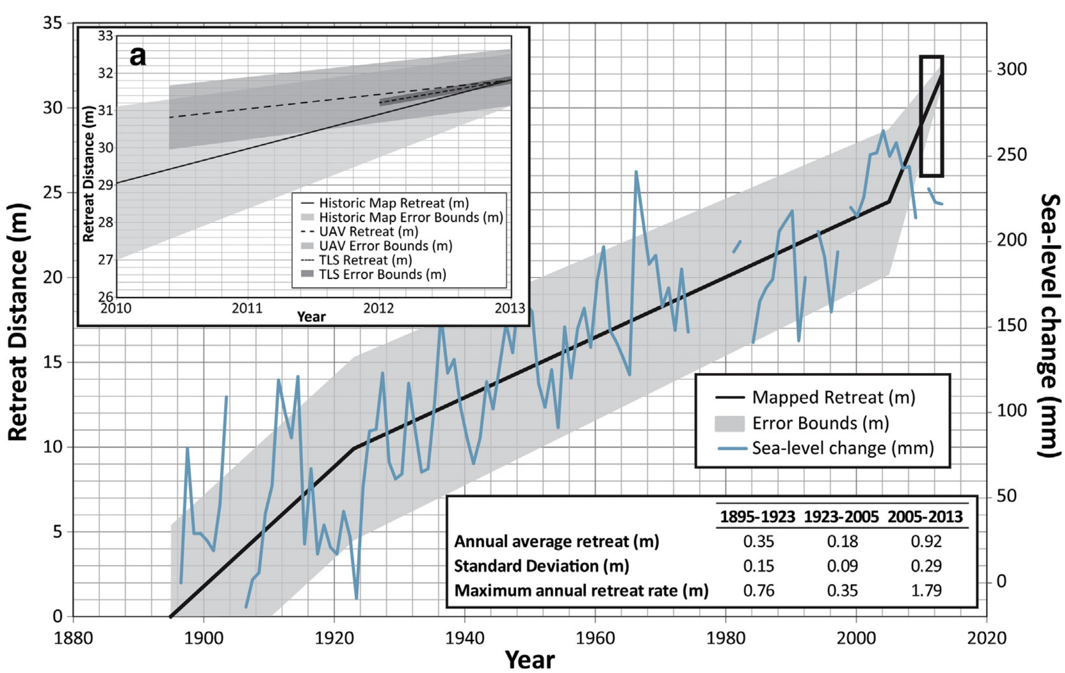

Fig. 6. Retreat rates produced from historic maps and, most recently, a DGPS survey (2013) with site-based error bounds calculated from permanent features and, additionally, recent retreat rates (extent shown in the black box) derived from UAV and TLS surveys (inset, a). Superimposed on these data are local (North Shields, ~30 km to the south) sea-level change data (secondary Y-axis), downloaded from the Permanent Service for mean sea-level (http://www.psmsl.org/data/).

Please cite this article as: Lim, M., et al., Quantification and implications of change in organic carbon bearing coastal dune cliffs: A multiscale analysis from the Northumber..., *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.01.034

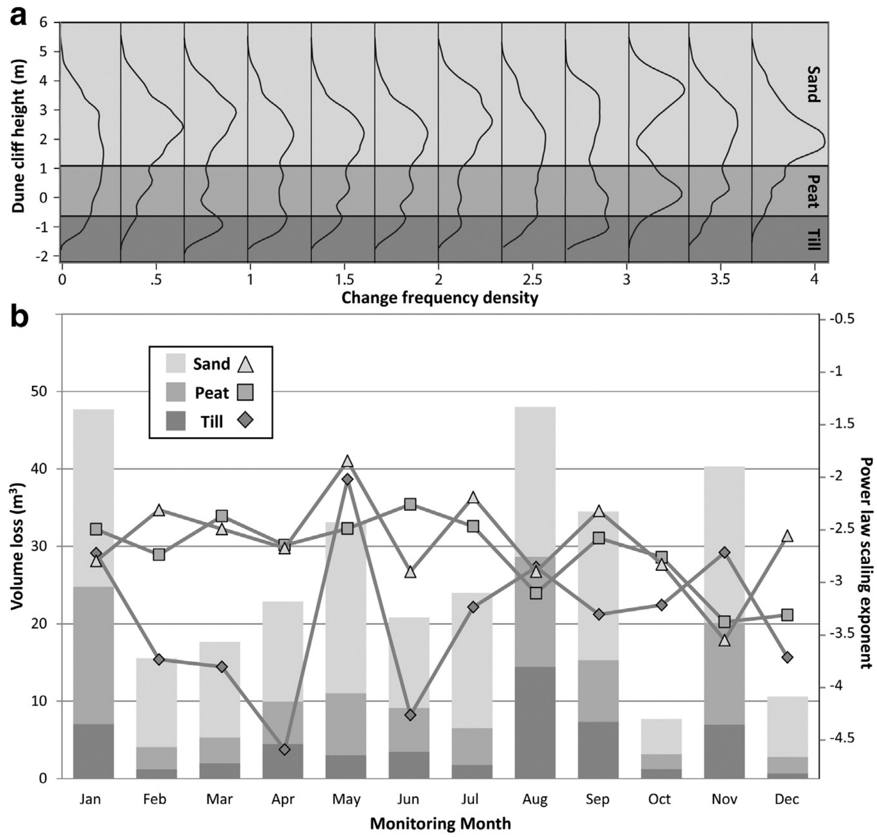

Fig. 7. Frequency density profiles for each month (showing where on the dune cliffs changes are most concentrated) separated by an arbitrary distance (a) and the volumetric losses recorded from the dune cliffs each month superimposed with the power law scaling exponents calculated for the monthly failure magnitude–frequency relationships (b).

result from the difficultly of isolating discrete events, particularly from the aeolian layers that have little cohesion. The convergences in scaling exponents coincide with frequency density profiles that are more normally distributed (Fig. 7a), suggestive of a coherent dune cliff system response. These data demonstrate that the entire dune cliff system can respond to single periods of high energy events.

6.2. Sensitivity to environmental drivers

Historic map comparisons and recent geospatial survey data indicate that there has been an increase in both the rate and the variability of dune cliff retreat (Figs. 2 & 6). The amount and nature of recorded changes are beyond method-specific error bounds, raising important questions regarding the processes driving change. The main drivers of dune cliff changes are thought to be associated with wave, rain and, in particular, wind processes (Lindenbergh, Soudarissanane, de Vries, Gorte, & de Schipper, 2011). During the last 118 years sea level is estimated to have risen at the study area by approximately 0.22 m (Shennan & Horton, 2002; see also Fig. 6), but other drivers of change over this period are less well quantified. The incidence of storms is thought to have risen since the 1950s (Alexander, Tett, & Jonsson, 2005), but the sequencing and patterns of events (such as flood rich and flood poor periods that can last several years) and the interaction of multiple factors and processes limit the effectiveness of such metrics.

There appears to be a greater and distinct sensitivity in the weakly cemented aeolian (sand) deposits than in the compact, cohesive till and, to a lesser extent, the humified organic carbon (peat) located within the intertidal zone (Fig. 7b). However, when normalised by area, greater dynamism is recorded in the basal layers (particularly the peat) during isolated months (Fig. 8). Whilst the basal erosion events occur during months where sea levels submerge the cliff base for longer periods than average (January, May, August and November), other months of similar inundation amounts did not trigger such responses. High rainfall events in general are not associated with large dune cliff responses, the most significant of which occur during dry periods, potentially when the cliff material has lowest cohesive strength. In addition, desiccation cracks in the peat and upper portion of the till are suggestive of wetting and drying processes. There is little evidence for environmental drivers of change on a monthly timescale, therefore, accelerations in recession may be linked to individual storm events (in agreement with Splinter and Palmsten, 2012) rather than periods of altered forcing conditions. Accordingly, a key control on these responses appears to be wind directions between approximately 200°–260°, which produce wave approaches perpendicular to the coastline.

The material responses may be triggered by extreme weather events (for example months where sea level exceeds the cliff toe for a higher proportion of time and wind directions between 200 and 260 that drive higher waves), but they also seem to follow an internal mechanistic response, with a month of quiescence following a large recession event. This may be caused by the protective effects of large amounts of failed material armouring the intact cliff face. The peaks in basal till and peat erosion are followed by a switch in dominance to sand recession, suggestive of an upwardly propagating cliff response. Both the TLS and the UAV survey data demonstrate an increase in sand cliff retreat relative to till and (to a lesser extent) peat in recent years, resulting in a reduction of dune cliff face gradient. This can be seen in repeated profiles through the UAV elevation models (Fig. 9) and the retreating sand is likely to increase the exposure of the peat and till layers in the future. There are several areas along the coastline where the more sensitive response of the sand has led to the abandonment of basal layers including peat, relict forest and till outcrops that persist within the intertidal zone (Wilson et al., 2001), a process that will be compounded by predictions of sea level rise and increases in storm occurrence and intensity.

Please cite this article as: Lim, M., et al., Quantification and implications of change in organic carbon bearing coastal dune cliffs: A multiscale analysis from the Northumber..., *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.01.034

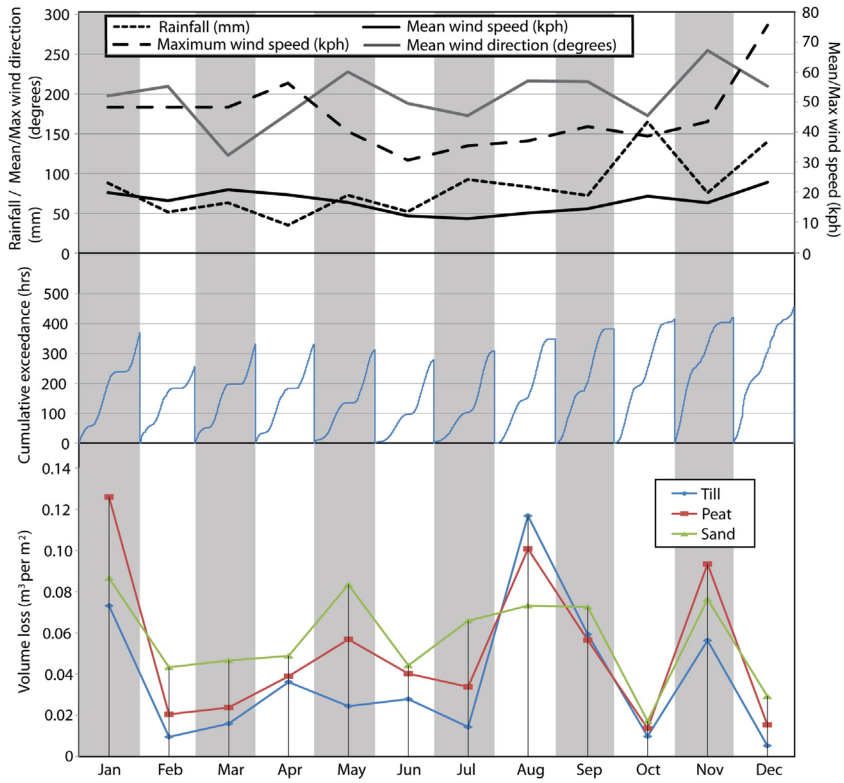

Fig. 8. Monthly rain and wind variations through the year (top), cumulative sea level exceedance of the dune cliff toe (middle) and volumetric losses normalised by monitored surface area (bottom).

6.3. Carbon contribution

The historic data and contemporary monitoring results presented in this paper have highlighted the significant and increasing rate of dune

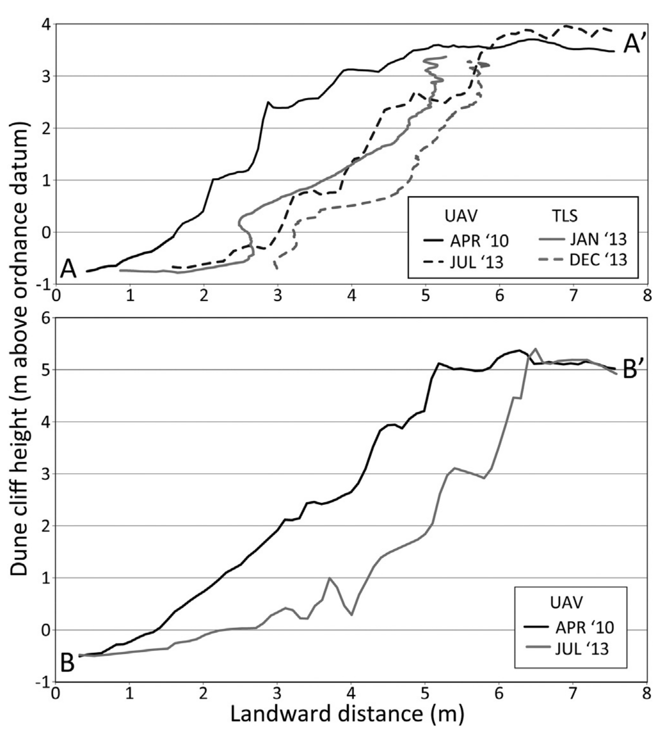

Fig. 9. Comparison of cross sections through DEMs produced from SfM processing of UAV imagery at the headland crest (A–A′) and at the minimum headland amplitude (B–B′); refer back to Fig. 3 for cross section locations.

cliff erosion at Hauxley. In addition to potential impacts of land (habitat), infrastructure and asset losses, the dune cliffs also contain variable amounts of peat, rich in organic carbon. The contributions of major carbon sources such as tundra melting (Schuur et al., 2009), fluvial erosion of upland peat catchments (Worrall, Reed, Warburton, & Burt, 2003) or landslide processes within forested mountain belts (Hilton, Meunier, Hovius, Bellingham, & Galy, 2011) have been well documented but the release of stores through coastal erosion remains poorly constrained (Taffs et al., 2012). The unit of peat has been identified throughout the GPR grid and the geometry of the contacts between the upper (to aeolian deposits) and lower (to till deposits) layers has been used to constrain the volume of peat within the dune cliffs over the surveyed section (Fig. 5). The radar reflections suggest that the peat thickness continues landward, with localised increases that appear to reflect both the uneven topography of the basal till and the undulations of the palaeo dunes. The next 5 m to be eroded from the surveyed sub-section (50 m) of cliffs will release 481 m^3 of peat followed by a significant (20%) increase with the following 5 m of landward retreat, mobilising 579 m^3. In total the dune cliff area investigated has the potential to yield 2264 m^3 of organic carbon. A retreat rate of 0.39 m a^{-1} as derived from UAV surveys (producing a total of 19.5 m landward retreat in 50 years) could release 106.38 tonnes of organic carbon from the 50 m stretch of dune cliffs, based on an approximation and formula suggested by Cannell, Dewar, and Pyatt (1993). This figure does not consider the additional potential for sea-level rise over the next 50 years (estimated to be in excess of 0.3 mm yr^{-1}; Shennan et al., 2009), or the increased exposure of peat contained in the cliffs resulting from enhanced sand retreat (Sections 6.1; 6.2). Exposed peat can be eroded by subaerial and marine processes and also provides a mature carbon source for the leaching of dissolved organic carbon and methanogenesis (Mitsch & Gosselink, 2007). Beyond the direct loss of peat and soil layers, dune cliff systems also buffer extensive wetland areas from marine inundation and erosion, as is the case throughout many coasts of northwestern Europe (Wilson et al., 2001). Therefore, the activation of wetland carbon could hold the greatest global significance in terms of long-term dune system retreat (Ramsar Convention Secretariat, 2006). In a first attempt to value the both the sequestration potential (18.36–45.9 £/ha/yr) and the potential losses resulting from dune erosion, Beaumont et al. (2014) estimate that between 2000 and 2060 the UK will incur a £257 m loss with continued trends of erosion. Achieving consistently collected, multi-scale analyses remains essential to addressing the pervasive uncertainties in both establishing dune wetland carbon pool size and flux rates and the responsiveness of dune cliff systems to environmental changes (Mitra et al., 2003).

7. Conclusion

The dynamism associated with dune systems means that few datasets achieve sufficient accuracy, spatial coverage and temporal frequency to adequately quantify dune cliff behaviour. This study combines historic map analyses with airborne and ground based remote sensing approaches to quantify over a century of dune cliff changes. The use of unmanned aerial imagery processed with SfM provides an effective method with which to rapidly quantify trends in coastline change over wide areas, although (sub-)monthly TLS surveys adds valuable detail on the mechanics of change at the process scale. The layers within the dune cliff system appear to be responding as a whole to specific storm events, with wind direction acting as an overriding control (in accordance with the findings of Saye et al., 2006). Dune cliff recession appears to be both increasing in rate and getting more variable when compared to historic behaviour. Within this driver-response relationship internal mechanisms play a significant role in determining behaviour. Periods of increased basal retreat have been observed to precede slumping and enhanced mobilisation of the perched sand dunes that, in turn, armour the cliff base and produce a negative feedback to the short-term dune cliff response. There is evidence that over recent years this coupling may be breaking down with relative increases in the rate of sand recession potentially leading to the abandonment of the basal layers; a process that appears to have occurred elsewhere along the coast during the late-Holocene (Wilson et al., 2001). In addition to well-documented management and conservation impacts, the erosion of coastal peat volumes quantified with GPR has the potential to rapidly release significant amounts of organic carbon from concentrated source locations that are currently unaccounted for in global carbon budgets.

Acknowledgements

The authors would like to thank and acknowledge the assistance of Chris Walton with the collection of field data and convey our thanks to the insightful and positive comments of the anonymous reviewers.

References

Abellan, A., Oppikofer, T., Jaboyedoff, M., Rosser, N. J., Lim, M., & Lato, M. J. (2013). Terrestrial laser scanning of rock slope instabilities. *Earth Surface Processes and Landforms*, *39*(1), 89–97.

Aber, J. S., Marzolff, I., & Ries, J. B. (2010). *Small-format aerial photography: Principles, techniques and geoscience applications.* Amsterdam: Elsevier, 266.

Alexander, L. V., Tett, S. F. B., & Jonsson, T. (2005). Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophysical Research Letters*, *32*(L13704). http://dx.doi.org/10.1029/2005GL022371.

Arcone, S. A., Lawson, D. E., & Delaney, A. J. (1995). Short-pulse radar wavelet recovery and resolution of dielectric constants within englacial and basal ice of Matanuska Glacier, Alaska, U.S.A. *Journal of Glaciology*, *41*(137), 68–86.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193.

Beaumont, N. J., Jones, L., Garbutt, A., Hansom, J. D., & Tobermann, M. (2014). The value of carbon sequestration and storage in coastal habitats. *Estuarine, Coastal and Shelf Science*, *137*, 32–40.

Boomer, I., Waddington, C., Stevenson, T., & Hamilton, D. (2007). Holocene coastal change and geoarchaeology at Howick, Northumberland, UK. *The Holocene*, *17*(1), 89–104.

Brown, A. C., & McLachlan, A. (2002). Sandy shore ecosystems and the threats facing them: some predictions for the year 2025. *Environmental Conservation*, *29*, 62–77.

Brzank, A., Lohmann, P., & Heipke, C. (2005). Automated extraction of pair wise structure lines using airborne laser scanner data in coastal areas. *International Archives of Photogrammetry and Remote Sensing*, *36*(3/W19), 36–41.

Camacho-Valdez, V., Murillo-Jimenez, J. M., Nava-Sanchez, E. H., & Turrent-Thompson, C. (2008). Dune and beach morphodynamics at Cabo Falso, Baja California Sur, Mexico: Response to natural, Hurricane Juliette (2001) and anthropogenic influence. *Journal of Coastal Research*, *24*, 553–560.

Cannell, M. G. R., Dewar, R. C., & Pyatt, D. G. (1993). Conifer plantations on drained peatlands in Britain: A net gain or loss of carbon. *Forestry*, *66*(4), 353–369.

Carter, R. W. G. (1991). Near-future sea level impacts on coastal dune landscapes. *Landscape Ecology*, *6*, 29–39.

Clemmensen, L. B., Fornos, J. J., & Rodriguez-Perea, A. (1997). Morphology and architecture of a late Pleistocene cliff-front dune, Mallorca, Western Mediterranean. *Terra Nova*, *9*(5–6), 251–252.

d'Oleire-Oltmanns, S., Marzolff, I., Peter, K. D., & Ries, J. B. (2012). Unmanned aerial vehicle (UAV) for monitoring soil erosion in Morocco. *Remote Sensing*, *4*, 3390–3416. http://dx.doi.org/10.3390/rs4113390.

Davies, P., Williams, A. T., & Curr, R. H. F. (1995). Decision making in dune management: Theory and practice. *Journal of Coastal Conservation*, *1*(1), 87–96.

Day, S. S., Gran, K. B., Belmont, P., & Wawrzyniec, T. (2013a). Measuring bluff erosion part 1: Terrestrial laser scanning methods for change detection and determining bluff erosion processes. *Earth Surface Processes and Landforms*, *38*, 1055–1067.

Day, S. S., Gran, K. B., Belmont, P., & Wawrzyniec, T. (2013b). Measuring bluff erosion part 2: Pairing aerial photographs and terrestrial laser scanning to create a watershed scale sediment budget. *Earth Surface Processes and Landforms*, *38*, 1068–1082.

de Ceunynck, R. (1985). The evolution of the coastal dunes in the western Belgian coastal plain. *Eiszeitalter und Gegenwart*, *35*, 33–41.

Eisenbeiss, H., & Sauerbier, M. (2011). Investigation of UAV systems and flight modes for photogrammetric applications. *The Photogrammetric Record*, *26*(136), 400–421.

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

Feagin, R. A., Williams, A. M., Popescu, S., Stukey, J., & Washington-Allen, R. A. (2012). The use of Terrestrial Laser Scanning (TLS) in dune ecosystems: The lessons learned. *Journal of Coastal Research*, *30*(1), 111–119. http://dx.doi.org/10.2112/JCOASTRES-D-11-00223.1.

Ford, M. (2013). Shoreline changes interpreted from multi-temporal aerial photographs and high resolution satellite images: Wotje Atoll, Marshall Islands. *Remote Sensing of the Environment*, *135*, 130–140.

Frank, R. (1982). A Holocene peat and dune-sand sequence on the coast of northeast England—A preliminary report. *Quaternary Newsletter*, *36*, 24–32.

Furmańczyk, K. K., Dudzińska-Nowak, J., Furmańczyk, K. A., Paplińska-Swerpel, B., & Brzezowska, N. (2012). Critical storm thresholds for the generation of significant dune erosion at Dziwnow Spit, Poland. *Geomorphology*, *143–144*, 62–68.

Gilbertson, D. D., Schwenninger, J. -L., Kemp, R. A., & Rhodes, E. J. (1999). Sand-drift and soil formation along an exposed North Atlantic coastline: 14,000 years of diverse geomorphological, climatic and human impacts. *Journal of Archaeological Science*, *26*, 439–469.

Grayson, R., Holden, J., Jones, R. R., Carle, J. A., & Lloyd, A. (2012). Improving particulate carbon loss estimates in eroding peatlands through the use of terrestrial laser scanning. *Geomorphology*, *15*, 240–248. http://dx.doi.org/10.1016/j.geomorph.2012.08.015.

Grigoriev, M. N., Rachold, V., Hubberten, H. -W., & Schirmeister, L. (2004). Organic carbon input to the Arctic seas through coastal erosion. In R. Stein, & R. W. Macdonald (Eds.), *The organic carbon cycle in the Arctic Ocean* (pp. 41–45). Berlin: Springer Verlag.

Hardin, P., & Jensen, R. (2011). Small-scale unmanned aerial vehicles in environmental remote sensing: Challenges and opportunities. *GIScience & Remote Sensing*, *48*(1), 99–111.

Hardisty, J. (1994). Beach and nearshore sediment transport. In K. Pye (Ed.), *Sediment transport and depositional processes* (pp. 216–255). London, UK: Blackwell.

Hill, J. R. (1974). *The Indiana Dunes—Legacy of sand. Department of Natural Resources Geological Survey Special Report*, *8*. (pp. 9), 9 (Bloomington, Indiana).

Hilton, R. G., Meunier, P., Hovius, N., Bellingham, P. J., & Galy, A. (2011). Landslide impact on organic carbon cycling in a temperate montane forest. *Earth Surface Processes and Landforms*, *36*, 1670–1679.

Holden, J. (2005). Peatland hydrology and carbon release: Why small-scale process matters. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *363*, 2891–2913. http://dx.doi.org/10.1098/rsta.2005.1671.

Innes, J. B., & Frank, R. M. (1988). Palynological evidence for late Flandrian coastal changes at Druridge Bay, Northumberland. *Scottish Geographical Magazine*, *104*, 14–23.

Knight, J., Orford, J. D., Wilson, P., Wintle, A. G., & Braley, S. (1998). Facies, age and controls on recent coastal sand dune evolution in north Norfolk, eastern England. *Journal of Coastal Research Special Issue*, *26*, 154–161.

Koch, E. W., Barbier, E. B., Silliman, B. R., Reed, D. J., Perillo, G. M. E., Hacker, S. D., et al. (2009). Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection. *Frontiers in Ecology and the Environment*, *7*, 29–37. http://dx.doi.org/10.1890/080126.

Laliberte, A. S., Goforth, M. A., Steele, C. M., & Rango, A. (2011). Multispectral remote sensing from unmanned aircraft: Image processing workflows and applications for range and environments. *Remote Sensing*, *3*, 2529–2551. http://dx.doi.org/10.3390/rs3112529.

Laliberte, A. S., Winters, C., & Rango, A. (2008). A procedure for othorectification of sub-decimeter resolution imagery obtained with an unmanned aerial vehicle (UAV). *Presented at the ASPRS 2008 Annual Conference, Portland, Oregon, 28th April–2nd May*.

Lejot, J., Delacourt, C., Piégay, H., Fournier, T., Trémélo, M. -L., & Allemand, P. (2007). Very high spatial resolution imagery for channel bathymetry and topography from an unmanned mapping controlled platform. *Earth Surface Processes and Landforms*, *32*(11), 1705–1725.

Lemauviel, S., & Roze, F. O. (2003). Response of three plant communities to trampling in a sand dune system in Brittany (France). *Environmental Management*, *31*(2), 227–235.

Lim, M., Petley, D. N., Rosser, N. J., Allison, R. J., Long, A. J., & Pybus, D. (2005). Combined digital photogrammetry and time-of-flight laser scanning for monitoring cliff evolution. *The Photogrammetric Record*, *20*(1), 109–129.

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., et al. (2008). Peatlands and the carbon cycle: From local processes to global implications—a synthesis. *Biogeosciences*, *5*, 1475–1491.

Lindenbergh, R. C., Soudarissanane, S. S., de Vries, S., Gorte, B. G. H., & de Schipper, M. A. (2011). Aeolian beach sand transport monitored by terrestrial laser scanning. *The Photogrammetric Record*, *26*(136), 384–399.

Min, K. -S., Zhang, X., Zwiers, F. W., & Hegerl, G. C. (2011). Human contribution to more-intense precipitation extremes. *Nature*, *470*, 378–381.

Mitra, S., Wassmann, R., & Vlek, P. L. G. (2003). Global inventory of Wetlands and their role in the carbon cycle. *ZEF Discussion Papers on Development Policy*, *No. 64*, (58 pp.).

Mitsch, W. J., & Gosselink, J. G. (2007). *Wetlands*. New York: John Wiley & Sons, Inc (582 pp.).

Mountney, N. P., & Russel, A. J. (2009). Aeolian dune-field development in a water table-controlled system: Skeidara rsandur, Southern Iceland. *Sedimentology*, *56*, 2107–2131.

Mozas-Calvache, A. T., Pérez-García, J. L., Cardenal-Escarcena, F. J., Mata-Castro, E., & Delgado-García, J. (2012). Method for photogrammetric surveying of archaeological sites with light aerial platforms. *Journal of Archaeological Science*, *39*(2), 521–530.

Neal, A. (2004). Ground-penetrating radar and its use in sedimentology: Principles, problems and progress. *Earth-Science Reviews*, *66*, 261–330.

Niethammer, U., James, M. R., Rothmund, S., Travelletti, J., & Joswig, M. (2012). UAV-based remote sensing of the Super-Sauze landslide: Evaluation and results. *Engineering Geology*, *128*, 2–11.

O'Sullivan, D., & Young, R. (1995). *Book of Lindisfarne Holy Island*. London: Batsford Ltd, 128.

Olivier, M. J., & Garland, G. G. (2003). Short-term monitoring of foredune formation on the east coast of South Africa. *Earth Surface Processes and Landforms*, *28*, 1143–1155.

Orford, J. D., Wilson, P., Wintle, A. G., Knight, J., & Braley, S. (2000). Holocene coastal dune initiation in Northumberland and Norfolk, eastern UK: Climate and sea level changes as possible forcing agents for dune initiation. In I.Shennan, & J.Andrews (Eds.), Holocene Land–Ocean Interaction and Environmental Change Around the North Sea. *Geological Society, London, Special Publications*, *166*, 197–217.

Plater, A. J., & Shennan, I. (1992). Evidence of Holocene sea-level change from the Northumberland coast, eastern England. *Proceedings of the Geologists' Association*, *103*, 201–216.

Psuty, N. P. (2008). The coastal foredune: A morphological basis for regional coastal dune development. *Ecological Studies*, *171*, 11–27.

Pye, K., & Blott, S. J. (2008). Decadal-scale variation in dune erosion and accretion rates: An investigation of the significance of changing storm tide frequency and magnitude on the Sefton coast, UK. *Geomorphology*, *102*, 652–666.

Pye, K., & Neal, A. (1994). Coastal dune erosion at Formby Point, north Merseyside, England: Causes and mechanisms. *Marine Geology*, *119*, 39–56.

Raistrick, A., & Blackburn, K. B. (1932). The late-glacial and post-glacial periods in the North Pennines. Part III—The post-glacial peats. *Transactions of the Northern Naturalists Union*, *1*, 79–103.

Ramsar Convention Secretariat (2006). *The Ramsar Convention Manual: A guide to the Convention on Wetlands (Ramsar, Iran, 1971)* (4th ed.). Gland, Switzerland: Ramsar Convention Secretariat (114 pp.).

Richter, A., Faust, D., & Maas, H. -G. (2013). Dune cliff erosion and beach width change at the northern and southern spits of Sylt detected with multi-temporal Lidar. *Catena*, *103*, 103–111.

Ritchie, W. (2001). Coastal dunes: resultant dynamic position as a conservational managerial objective. In J. Houston, P. J. Rooney, & S. E. Edmondson (Eds.), *Coastal Dune Management: Shared experience of European Conservation Practice. European symposium on coastal dunes of the Atlantic biogeographical region*. (pp. 1–14). Liverpool: Liverpool University Press.

Romankevich, E. A., Vetrov, A. A., & Peresypkin, V. I. (2009). Organic matter of the World Ocean. *Russian Geology and Geophysics*, *50*, 299–307.

Saye, S. E., Pye, K., & Clemmensen, L. B. (2006). Development of a cliff-top dune indicated by particle size and geochemical characteristics: Rubjerg Knude, Denmark. *Sedimentology*, *53*, 1–21.

Saye, S., van der Wal, D., Pye, K., & Blott, S. (2005). Beach–dune morphological relationships and erosion/accretion: An investigation at five sites in England and Wales using Lidar data. *Geomorphology*, *72*, 128–155.

Schuur, E. A. G., Vogel, J. G., Crummer, K. G., Lee, H., Sickman, O., & Osterkamp, T. E. (2009). The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature*, *459*, 556–559.

Semiletov, I. P., Pipko, I. I., Shakhova, N. E., Dudarev, O. V., Pugach, S. P., Charkin, A. N., et al. (2011). Carbon transport by the Lena River from its headwaters to the Arctic Ocean, with emphasis on fluvial input of terrestrial particulate organic carbon vs. carbon transport by coastal erosion. *Biogeosciences*, *8*(9), 2407–2426.

Shennan, I., & Horton, B. (2002). Holocene land- and sea-level changes in Great Britain. *Journal of Quaternary Science*, *17*(5–6), 511–526.

Shennan, I., Milne, G., & Bradley, S. (2009). *Late Holocene relative land- and sea-level changes: Providing information for stakeholders. GSA Today*, *19(9)*. (pp. 52–53). The Geological Society of America, 52–53.

Short, A. D., & Hesp, P. A. (1982). Wave, beach and dune interactions in southeast Australia. *Marine Geology*, *48*, 259–284.

Suanez, S., Cariolet, J. -M., Cancouët, R., Ardhuin, F., & Delacourt, C. (2012). Dune recovery after storm erosion on a high-energy beach: Vougot Beach, Brittany (France). *Geomorphology*, *139–140*, 16–33.

Splinter, K. D., & Palmsten, M. L. (2012). Modeling dune response to an East Coast Low. *Marine Geology*, *329–331*, 46–57.

Taffs, K. H., Logan, B., Parr, J. F., & Jacobsen, G. E. (2012). The evolution of a coastal peatland at Byron Bay, Australia: Multi-proxy evidence from the microfossil record. In S. G. Haberle, & B. David (Eds.), *Terra Australis 34: peopled landscapes: archaeological and biogeographic approaches to landscapes* (pp. 429–442). Canberra, Australia: ANU E-Press9781921862724.

Turcotte, D. L. (1999). Self-organized criticality. *Reports on Progress in Physics*, *62*, 1377–1429.

Whinam, J., Hope, G. S., Clarkson, B. R., Buxton, B. P., Alspach, P. A., & Ada, P. (2003). Sphagnum in peatlands of Australasia: Their distribution, utilisation and management. *Wetlands Ecology and Management*, *11*(1–2), 37–49.

Williams, A. T., Alveirinho-Dias, J., Garcia Novo, F., Garcia-Mora, M. R., Curr, R., & Pereira, A. (2001). Integrated coastal dune management: checklists. *Continental Shelf Research*, *21*, 1937–1960.

Wilson, P., & Braley, S. M. (1997). Development and age structure of Holocene coastal sand dunes at Horn Head, near Dunfanaghy, Co. Donegal, Ireland. *The Holocene*, *7*, 187–197.

Wilson, P., Orford, J. D., Knight, J., Braley, S. M., & Wintle, A. G. (2001). Late-Holocene (post-4000 years BP) coastal dune development in Northumberland, northeast England. *The Holocene*, *11*(2), 215–229.

Worrall, F., Reed, M., Warburton, J., & Burt, T. (2003). Carbon budget for a British upland peat catchment. *Science of the Total Environment*, *312*(1–3), 133–146.

Zarnetske, P. L., Seabloom, E. W., & Hacker, S. D. (2010). Non-target effects of invasive species management: Beachgrass, birds, and bulldozers in coastal dunes. *Ecosphere*, *1*(5), 1–20.

Zhang, K., Whitman, D., Leatherman, S., & Robertson, W. (2005). Quantification of beach changes caused by Hurricane Floyd along Florida's Atlantic Coast using airborne laser surveys. *Journal of Coastal Research*, *21*, 123–134.

Please cite this article as: Lim, M., et al., Quantification and implications of change in organic carbon bearing coastal dune cliffs: A multiscale analysis from the Northumber..., *Remote Sensing of Environment* (2015), http://dx.doi.org/10.1016/j.rse.2015.01.034