ISSN 1476-1580

North West Geography

Volume 20, Number 1, 2020

Blowout Evolution Between 1999 and 2015 in Ainsdale Sand Dunes National Nature Reserve, England.

Thomas A.G. Smyth[1&2], Ella Thorpe[3] and Paul Rooney[3]

[1] Department of Biological and Geographical Sciences, School of Applied Sciences,
University of Huddersfield, Huddersfield, UK (t.ag.smyth@hud.ac.uk)

[2] Beach and Dune Systems (BEADS) Laboratory, School of the Environment,
Flinders University, Adelaide, Australia, 5041

[3]Liverpool Hope University, Department of Geography and Environmental Science,
Faculty of Science, Hope Park, Liverpool, UK.

Abstract

Mobile coastal sand dunes are an important habitat for a range of species that require warm substrates and a diversity of habitat structures. The extent of bare sand on coastal dunes in the UK has, however, dramatically declined since 1945. As a result, the removal of vegetation has become a management tool to re-create mobile and dynamic habitats that are typically associated with the earlier stages of dune succession. Blowouts, erosional hollows in dunes, act as important natural mechanisms for landscape disturbance by interrupting succession and providing a source of nutrient deficient sediment, via aeolian (wind) sediment erosion and subsequent deposition. This study investigates the evolution of three blowouts within Ainsdale Sand Dunes Natural Nature Reserve, North West England, in a dunescape that had been cleared of Corsican Pine approximately 25 years prior. Our results demonstrate that, contrary to previous studies of blowout evolution in highly vegetated dune systems, continued blowout expansion and growth has continued for at least 15 years (2005 to present). We anticipate these findings to be a starting point for deeper analysis of coastal dune mobility in the UK and northwest Europe, in order to better understand the environmental drivers maintaining dynamism in these environments.

Keywords

Sand dunes, aeolian, blowout, coast.

Introduction

Blowouts are erosional hollows that form on pre-existing sand deposits by the erosion and transport of sediment, primarily due to aeolian processes where dense vegetation cover is absent (Carter *et al.*, 1990; Hesp and Walker, 2012; Anderson and Walker, 2006). Blowouts are typically categorised into three categories: saucer, bowl or trough based on their morphology (Hesp and Smyth, 2019). Saucer blowouts are semi-circular, or circular shaped shallow depressions, whereas bowl blowouts are deeper circular hollows. In contrast to saucer and bowl blowouts, trough blowouts are elongated depressions, typically with a 'U' or 'V' shaped cross-sectional profile.

Geomorphic activity in blowouts is sustained by the erosion of sediment from the landform's deflation basin and erosional walls. Eroded sediment can be transported from the deflation basin and deposited downwind to form a depositional lobe. These dynamic processes can have an important role within dune system dynamics, as the erosion, transport and deposition of sediment disturbs ecological succession, potentially increasing local biodiversity (Gares and Nordstrom, 1991). Furthermore, the creation of bare sand and erosional hollows can form important habitats for a range plants (Rhind *et al.*, 2013), amphibians (Smith and Payne, 1980), reptiles (House and Spellerberg, 1983) and insects (Howe *et al.*, 2010).

For much of the 19th and 20th centuries coastal dune management in north west Europe focused on coastal defence and dune stabilisation (Provoost *et al.*, 2011), in turn reducing the extent of bare sand and blowouts. Dune stabilisation was achieved by the planting of vegetation, such as marram grass Ammophila arenaria (L.), in areas of bare and sparsely vegetated dune. These management techniques combined with an increase in growing season (Jackson and Cooper, 2011), reduction in grazing pressure

(Provoost *et al.*, 2011) and an increase in nitrogen deposition (Jones *et al.*, 2004) resulted in rapid increases in vegetation extent, therefore reducing the area of open bare sand (Jackson and Cooper, 2011; Pye *et al.*, 2014; Van der Biest *et al.*, 2017; Delgado-Fernandez *et al.*, 2019a; Jackson *et al.*, 2019;Moulton *et al.*, 2019).

Since the 1980s there has been an increased awareness in the ecological and coastal defence value of managing coastal dunes as a dynamic landscape (Van der Meulen and Wanders, 1984; Gares and Nordstrom, 1991; van Boxel *et al.*, 1997). Although there is debate about the sustainability of removing vegetation from dunes (Delgado-Fernandez *et al.*, 2019b; Rodgers *et al.*, 2019), many dune sites in north west Europe are actively grazed or stripped of turf to improve the conservation status of dune habitats and support essential ecosystem services, providing no other alternative is available (Arens *et al.*, 2020; Creer *et al.*, 2020; Pye and Blott, 2020). At several locations, vegetation has also been removed from blowouts and parabolic dunes to encourage aeolian sediment transport and provide opportunities for earlier successional stages. However, few studies (Arens *et al.*, 2004; Arens *et al.*, 2013) have examined blowout or parabolic dune dynamics following vegetation removal. The purpose of this study was to describe and analyse the morphological dynamics of three coastal dune blowouts (a saucer, bowl and trough) following the removal of a Coriscan Pine (*Pinus nigra ssp. Laricio*) plantation. The results of eight topographic surveys and five vertical aerial images over a 16-year period are discussed in the context of previous dune blowout studies.

Study Site

An area containing three blowouts within 100 m of each other in Ainsdale Sand Dunes National Nature Reserve on the Sefton Coast was investigated (Figures 1 and 2). The Sefton Coast, on the North West coast of England, has the

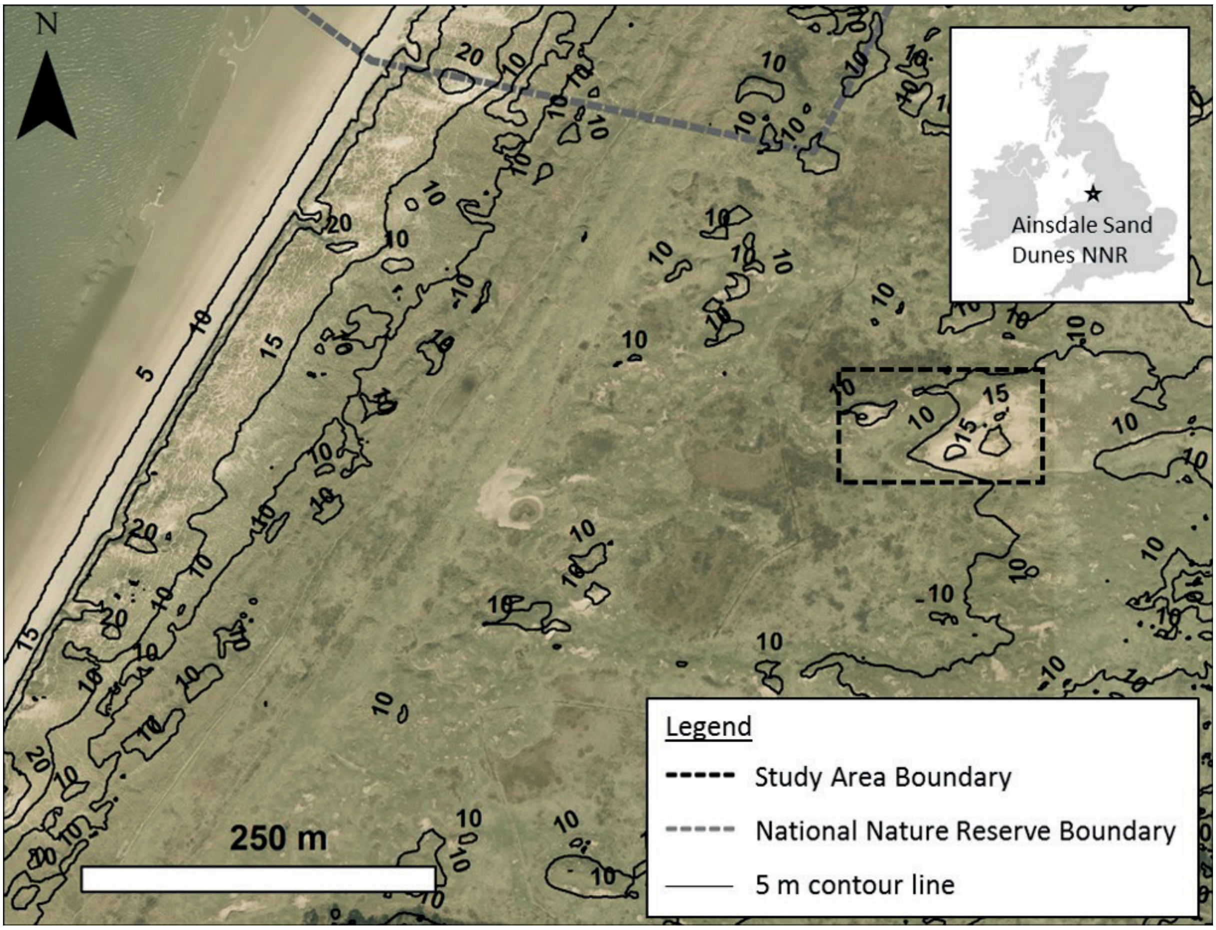

Figure 1. 2015 aerial image of the study site and surrounding dunes located within Ainsdale Sand Dunes National Nature reserve, approximately 20 km north of Liverpool in North West England (inset image). Contours are in metres and have been drawn in 5 m intervals based on 2014 LiDAR data (Table 1). The dashed box denotes the study site containing the three blowouts investigated in the study. (Image source: High Resolution (25cm) Vertical Aerial Imagery (2015) [JPG geospatial data], Scale 1:500, Tiles: sd2810,sd2811, Using: EDINA Aerial Digimap Service © Getmapping PLC.)

largest area of open dune landscapes in England (Doody, 1991) and includes a 30 km long frontal dune system, which varies between 2 and 4 km in width (Clarke and Ayutthaya, 2010; Delgado-Fernandez *et al.*, 2019a). The Sefton Coast dune system developed slowly over the Holocene, with the first generation of dunes becoming established by approximately 5600 BC (Pye and Neal, 1993).

The specific 10,800 m^2 area of dune investigated is located approximately 400 m inland from the foredune (Figure 1) and was a former Corsican Pine (*Pinus nigra ssp. laricio*) planation, established between 1900 and 1930 (Sturgess and Atkinson, 1993). The plantation was removed in the early 1990s as part of a dune restoration project and the area has been subsequently grazed by sheep and cattle (Smith and Lockwood, 2011). Following conservation management interventions to remove the pine plantations, the area is now largely comprised of fixed dunes with herbaceous vegetation (grey dunes). Vegetation predominantly consists of a short sward of grasses, herbaceous perennials and areas of scrub that are periodically cut and grazed. Marram grass (*Ammophila arenaria*) is present downwind of areas of active sediment transport (e.g. Figure 6a–c). In 2015, an active saucer, bowl and trough blowout were present within the study area (Figure 2).

Methods

Airborne LiDAR Surveys

The topography of the study area was measured using airborne LiDAR (Light Detection and Ranging) flown by The Environment Agency. Eight digital surface models of the area are available over a 15 year period 1999, 2000, 2001, 2002, 2008, 2010, 2013 and 2014 (Table 1). Airborne LiDAR is collected from a plane and uses pulses of light from an infrared laser to measure the variable distances between the Earth and the recording device (National Ocean Service, 2018). A digital surface model is an elevation model constructed from the highest LiDAR return and the model includes height of vegetation rather than 'bare earth', as is the case in a Digital Terrain Model. Despite the limitations of using a digital surface model for geomorphic change detection, the product was selected for this investigation due to its increased temporal resolution (five digital surface model datasets were available between 1999 and 2008, compared to two digital elevation models for the same period). The study sites were also dominated by bare sand and grasses (Figure 2), so changes in elevation due to vegetation are expected to be minimal. Each LiDAR scan was imported into ArcGIS 10.3 from which a 2 m x 2 m digital elevation model was created using the kriging spatial interpolation tool.

Figure 2: (a – c) The three blowouts examined (Photographs from 2018). (d) Annotated 2015 Google Earth aerial image of the study site.

Table 1: Details of LiDAR surveys and digital surface models used. All LiDAR data has a vertical accuracy of ±0.15 m root mean square error (RMSE).

Year	Survey month	Resolution (m)	Source
1999	March	2	England Lidar Digital Surface Model England (1999) [ASC geospatial data], Scale 1:4000, Tiles: D0003384, D0003399, Updated: 23 December 1999, Open Government Licence, Using: EDINA LIDAR Digimap Service.
2000	June	2	England Lidar Digital Surface Model England (2000) [ASC geospatial data], Scale 1:4000, Tiles: D0011386, D0011391, Updated: 18 December 2000, Open Government Licence, Using: EDINA LIDAR Digimap Service
2001	August	2	England Lidar Digital Surface Model England (2001) [ASC geospatial data], Scale 1:4000, Tiles: D0013430, D0017542, D0017545, Updated: 14 December 2001, Open Government Licence, Using: EDINA LIDAR Digimap Service
2002	September	2	England Lidar Digital Surface Model England (2002) [ASC geospatial data], Scale 1:4000, Tiles: D0023054, D0023057, Updated: 18 December 2002, Open Government Licence, Using: EDINA LIDAR Digimap Service
2008	March	0.25	England Lidar Digital Surface Model England (2008) [ASC geospatial data], Scale 1:4000, Tiles: D0098975, D0098976, D0098977, D0098994, D0098995, D0098996, D0099012, D0099013, D0099014, D0099031, D0099032, D0099033, D0099051, D0099052, Updated: 30 December 2008, Open Government Licence, Using: EDINA LIDAR Digimap Service
2010	March	1	England Lidar Digital Surface Model England (2010) [ASC geospatial data], Scale 1:4000, Tiles: D0131036, D0131043, Updated: 21 December 2010, Open Government Licence, Using: EDINA LIDAR Digimap Service
2013	October	1	England Lidar Digital Surface Model England (2013) [ASC geospatial data], Scale 1:4000, Tiles: D0165126, D0165137, Updated: 17 December 2013, Open Government Licence, Using: EDINA LIDAR Digimap Service
2014	May	2	England Lidar Digital Surface Model England (2014) [ASC geospatial data], Scale 1:4000, Tiles: D0170572, D0170580, Updated: 30 December 2014, Open Government Licence, Using: EDINA LIDAR Digimap Service

To analyse topographic change between LiDAR surveys, two transect lines were positioned on each blowout, one along the longitudinal axis of the blowout and the other along the lateral axis (Figure 3). Spatial and volumetric changes across an area including all three blowouts study site (120 m×90 m) were also calculated from the LiDAR data. This gave a quantitative measurement of the total erosion and deposition at the site between LiDAR surveys.

Aerial Imagery

Aerial imagery of the study area was examined in Google Earth for the years 2000, 2005, 2010, 2012 and 2015 at an identical spatial scale. Investigation of the imagery revealed that the 2010 image appeared to be offset to the west by approximately 2 m compared to the other images. This inconsistency between images limited analysis to being predominantly qualitative in nature.

Results

Elevation Change

Over the 15-year period of observation, the elevation of the study area changed between every LiDAR survey (Figures 4 and 5). The topographic data collected in 1999 shows that there were no active blowouts present within the study area delineated in Figure 5. The LiDAR surveys between 1999 and 2000 demonstrate a basal lowering at all three 2015 blowout locations by approximately 0.5 m (Figure 5a) but the shape of the dunes profile remains largely unchanged despite the substantial change in elevation (Figure 4). This consistency in dune morphology but substantial change in dune elevation may be due to instrument error, as Pye and Blott (2016) noted that elevations of the 1999 LiDAR surveys of the Sefton Coast were approximately 20 cm too high.

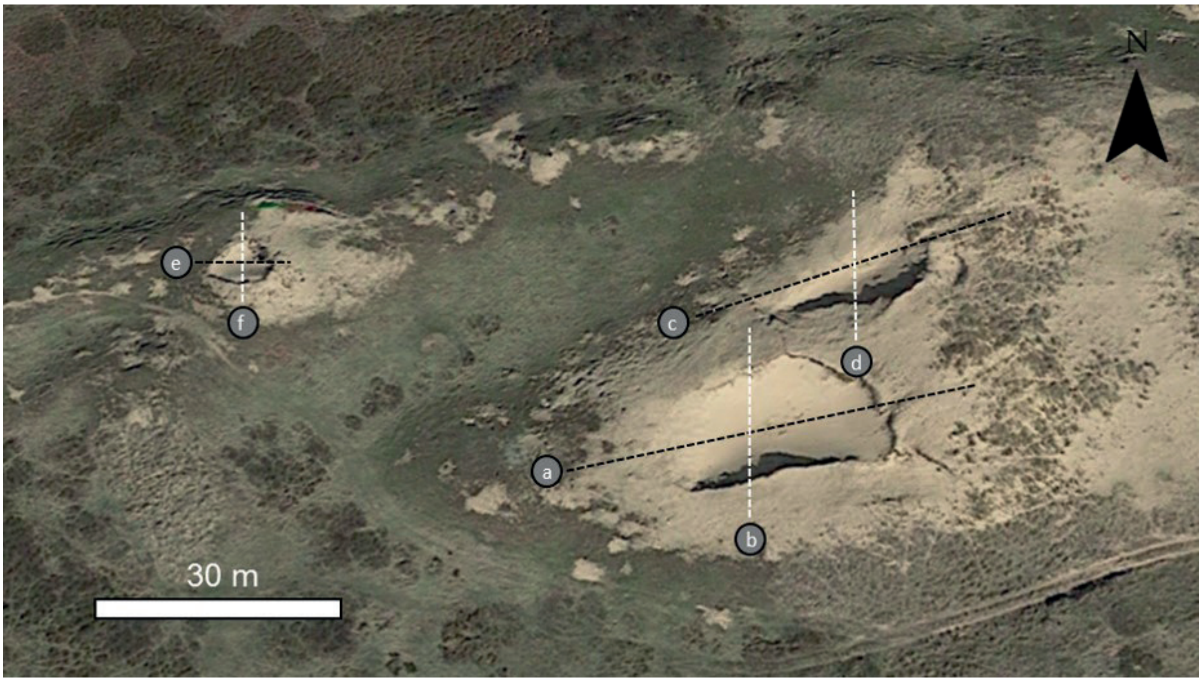

Figure 3: Location of longitudinal (a, c and e) and lateral transects (b, d and f) through the axis of the bowl (transects a and b), trough (transects c and d) and saucer (transects e and f) blowouts. (Image source: 2014 Google Earth).

Between 2000 and 2001, the elevation change data shows an overall depositional trend at the study site (Figure 5b). This depositional trend is also evident in the topographic transects (Figure 4), with elevation levels increasing between 2000 and 2001 along all six transects. Despite a substantial change in elevation at all six transect locations, the morphology of the each of the dune profiles remains similar to the previous year's survey.

Both the topographic transects (Figure 4) and surface elevation change map (Figure 5c) demonstrate that elevation change between 2001 and 2002 was minimal. Despite the minimal magnitude of topographic change, the morphology of the elevation transects does deviate compared to previous years. A small area of erosion is evident in the centre of the bowl blowout creating a small erosional hollow (Figure 4b) with a steepened longitudinal profile in the trough blowout. The period 2002 to 2008 demonstrates the greatest rate of erosion at all three blowouts. The bowl blowout expanded approximately 20 m in length and 2 m in depth (Figure 4a). The centre of the longitudinal profile of the trough blowout (Figure 4c) remained similar in shape to the profile measured in the 2002 survey, but decreased in elevation by approximately 1.5 m. Longitudinal and lateral elevation transects of the saucer blowout demonstrate dramatic (2 m in elevation) erosion of the dune slope and crest compared to that present in the 2002 survey. Clearly defined zones of sediment deposition to the south and east of all three blowouts are also evident in the 2002–2008 elevation change map (Figure 4d).

In comparison to the 2002–2008 elevation change analysis, relatively minor amounts of elevation change occurred between 2008 and 2010. The deflation basin of the saucer blowout becomes more uniform (Figures 4a, 4b and 5e) and the deflation basin of the trough blowout deepens by approximately 0.75 m (Figures 4c, 4d and 5e). The steep erosional walls that formed between the 2002 and 2008 surveys in the saucer blowout become more rounded and gently inclined. However, the elevation at the lowest point of the deflation basin remained unchanged between the 2008 and 2010 surveys (Figures 4e and 4f).

Between 2010 and 2013 the deflation basins of all three blowouts deepened. This is most evident in the lateral elevation transect of the bowl blowout (Figure 4b), which also demonstrates that the deflation basin expanded laterally by approximately 2.5 m during this period. The elevation change map for this period (Figure 5f) also demonstrates that some deposition occurred in the north and west of the bowl and trough deflation basins, while substantial erosion was present in the south and east of the bowl and trough deflation basins.

Unlike any other time during the study period, between 2013 and 2014 large amounts of sediment were deposited into the deflation basin of the blowouts rather than eroded from them (Figure 4g). Although erosion still

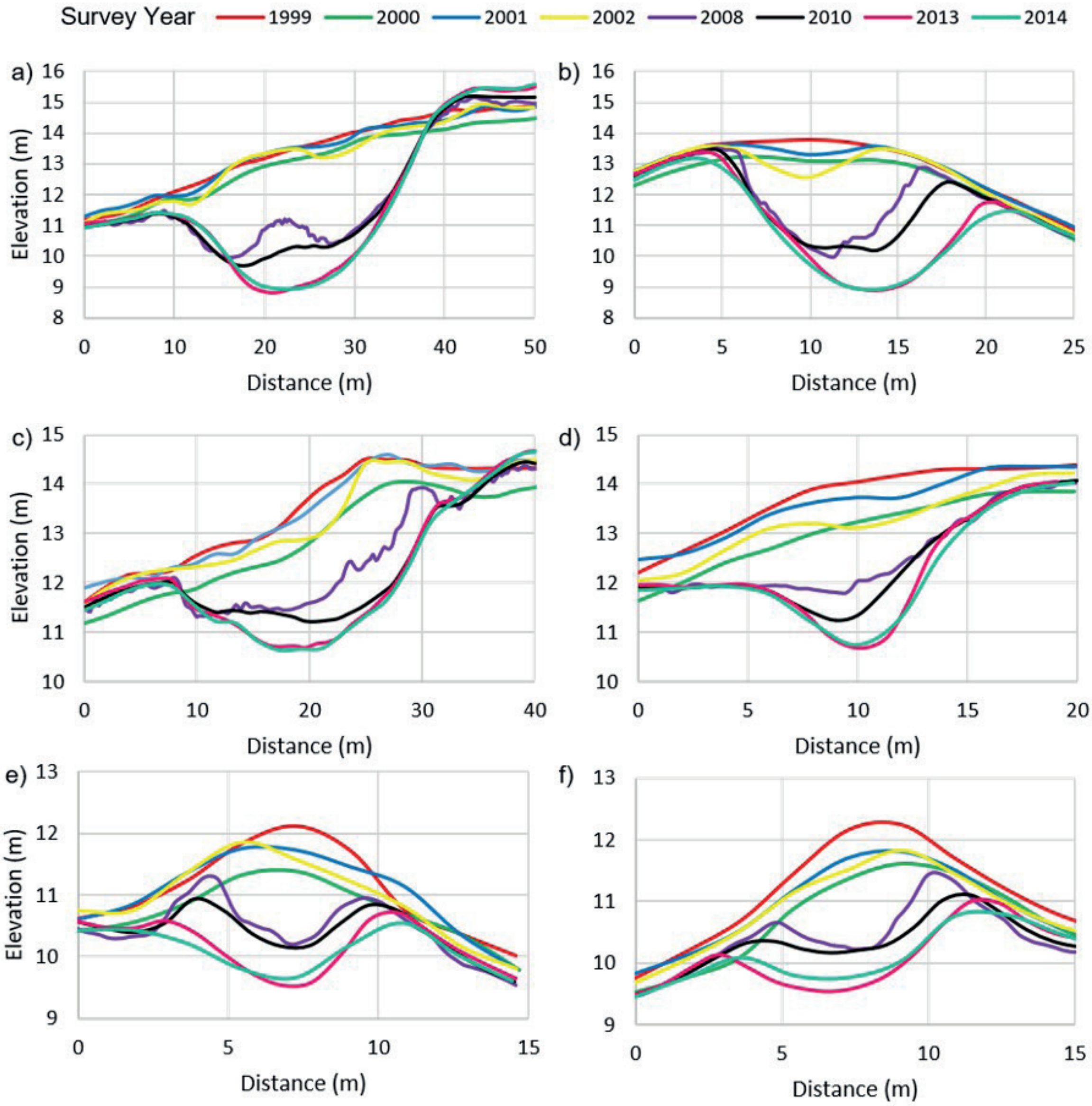

Figure 4: Topographic transect lines of topographic surveys from 1999 to 2014 through the: a) longitudinal axis of the bowl blowout; b) lateral axis of the bowl blowout; c) longitudinal axis of the trough blowout; d) lateral transect through the trough blowout; e) longitudinal axis of the saucer blowout; f) lateral axis of the saucer blowout. A plan view of all transects in relation to the landforms is visible in Figure 3. Topographic data summarised from digital surface models detailed in Table 1.

occurred at the northern edge of the bowl blowout and slightly in the centre of the trough blowout, deposition occurred on the southern and south-easterly sectors of all three blowouts. Figure 4g also records zones of deposition occurring between the blowouts. The transect data supports the evidence from the elevation maps indicating that overall elevation increased slightly from the 2013 height for all three blowouts, but most notably in the saucer blowout.

Aerial Imagery

Topographic change was identified using five Google Earth images between 2000 and 2015 (Figure 6).

In 2000 (Figure 6a) evidence of any clearly defined blowouts is absent. At that time the dune complex is largely covered in vegetation with minimal amounts of bare sand visible. In 2005 (Figure 6b) the formation of all three blowouts had begun with some erosional hollows visible. Figure 6b also shows that in 2005 approximately 50% of the study area appears to be covered in bare sand, with the south and east of the study area particularly un-vegetated. The 2010 image of the blowouts (Figure 6c) records a reduction in bare sand area and an increase in vegetation cover compared to the 2005 image; however, the blowouts were well defined by 2010 with clearly defined patches of bare sand around the

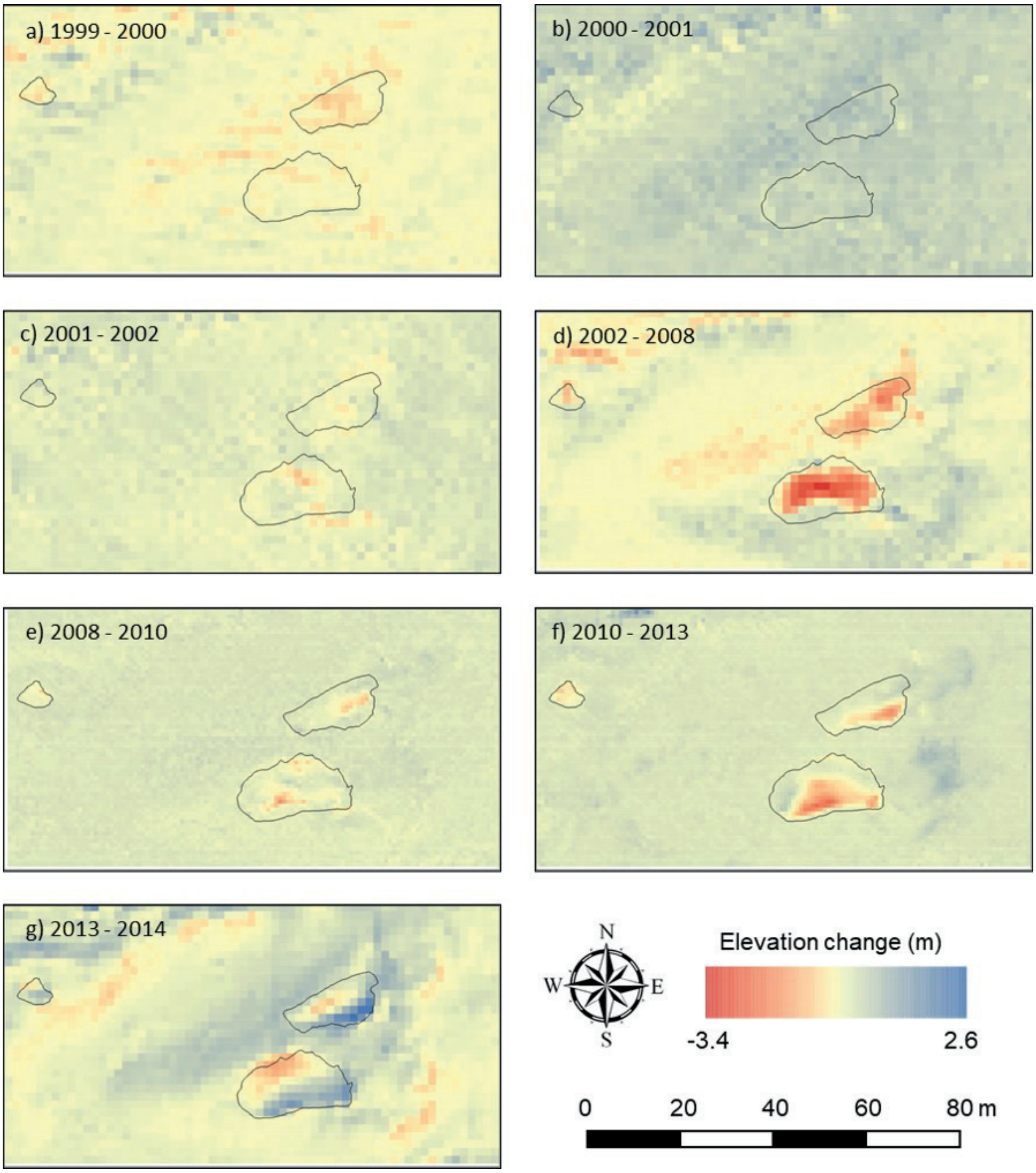

Figure 5: Topographic change maps of the eight surveys between 1999 and 2014. The black outline on frames a – g refers to the blowouts rim in 2015, as digitised from aerial imagery. Topographic change data has been calculated from the digital surface models detailed in Table 1.

immediate rims of the blowouts. The 2012 image (Figure 6d) displays little change from 2010.

Discussion

This study provides an important insight into spatial and temporal variations within three blowouts and their immediate surrounds over a prolonged period. Previous studies using aerial photography alone were unable to calculate volumetric and topographic changes within blowouts (Jungerius and van der Meulen, 1989; Abhar *et al.*, 2015) and erosion pin studies have suffered from a relatively limited spatial resolution (Harris, 1974; Jungerius *et al.*, 1981; Pluis, 1992; Bitton and Byrne, 2002). Although previous ground-based LiDAR studies have been able to resolve topographic change to a much higher resolution than the airborne LiDAR used by this study (Smith *et al.*, 2017; Delgado-Fernandez *et al.*, 2018; Smyth *et al.*, 2019), the duration of survey periods was substantially shorter in comparison to this study (maximum of 3 years in Smith *et al.* (2017) compared to 15 in this study).

Aerial photography from 2000 (Figure 6a) demonstrates that very little bare sand was exposed at the start

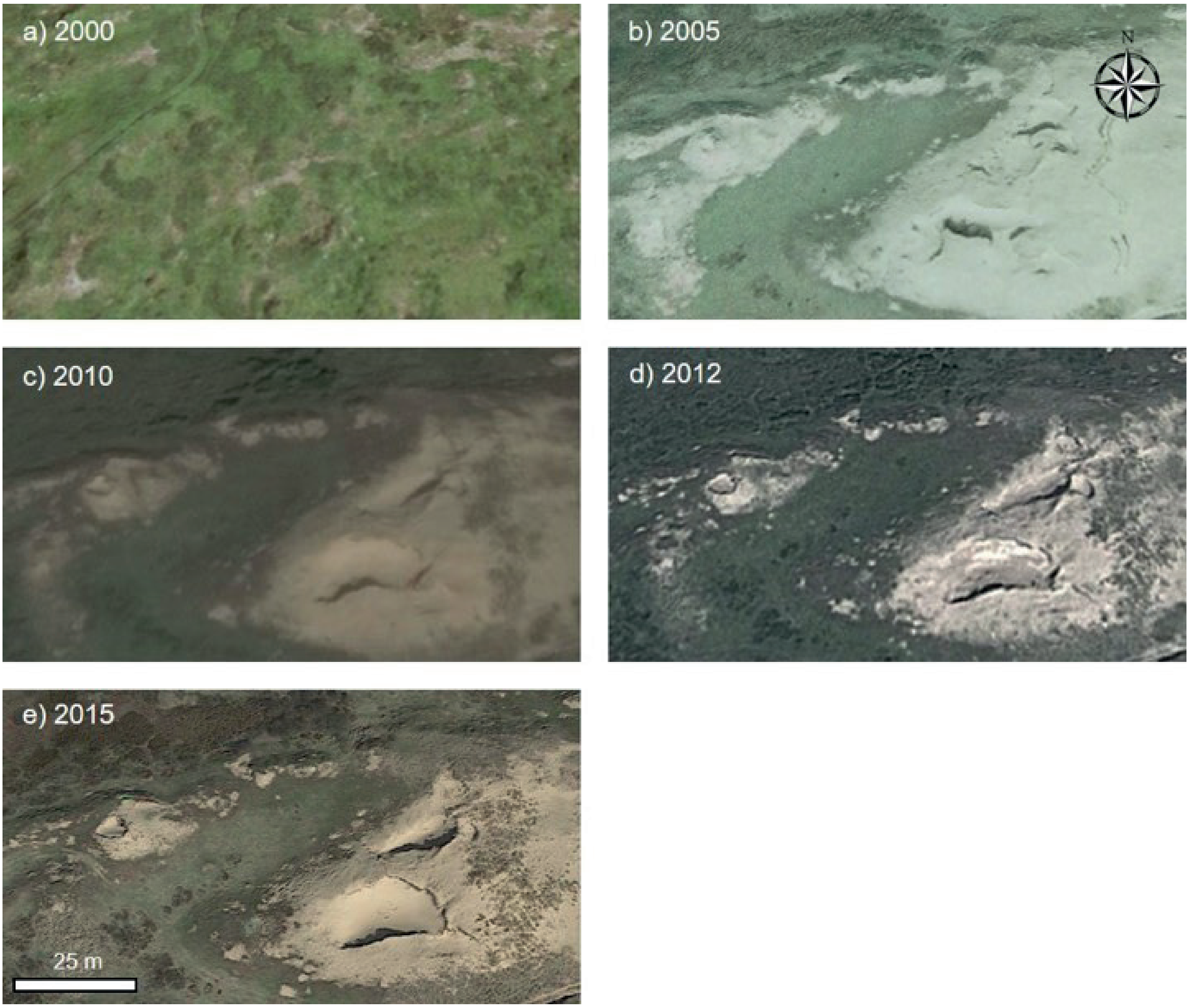

Figure 6: Google Earth imagery of the study area for (a) 2000; (b) 2005; (c) 2010; (d) 2012; (e) 2015.

of the study period. The extensive vegetation coverage in 2000 also correlates with an absence of blowouts between 1999 and 2002 as evidenced by the LiDAR data (Figures 4 and 5). Evidence from the LiDAR surveys and aerial imagery suggest that a sudden change, both in the extent of vegetation cover and in the topography, occurred between 2002 and 2005. Personal communication with land managers and a rigorous search of the literature has revealed that no vegetation removal or geomorphological interventions were performed by the land manager in the study area at this time. Furthermore, an increase in bare sand is visible throughout the surrounding dunes (Figure 7), which suggests that the changes between 2002 and 2008 were not solely due to conservation land management interventions or to recreational pressures. It may be significant that 2003 was an exceptionally hot and dry year with much of Europe experiencing drought, which negatively affected the growth of vegetation throughout the continent (Gobron *et al.*, 2005). Research by Wolfe *et al.* (1995) in the Great Sand Hills region of southwestern Saskatchewan suggests that even relatively short-lived drought can result in rapid changes in dune activity and bare sand extent over a 3-year period. Research on the hydrological conditions Ainsdale Sand Dunes NNR (Abesser *et al.*, 2017) also demonstrates that between 2003 and 2005 water table levels were consistently between 0.5 m and 1.0 m below ground level, indicating that any deflation hollows formed during the period were not flooded and therefore aeolian sediment transport could occur.

Once initiated, all three blowouts within the study area migrated and extended predominantly in an easterly

Figure 7: Google Earth images of the study site and surrounding dunes from (a) 2000 and (b) 2005. These images illustrate the substantial change in the overall extent of bare sand between 2000 and 2005.

direction, i.e. downwind in relation to the site's prevailing westerly winds (Figures 5 and 6; Pye and Blott, 2010). This expansion of the erosional features in a downwind direction is similar to the spatial-temporal evolution of blowouts at Cape Cod, USA, whose extension direction broadly correlated with incident wind conditions (Abhar *et al.*, 2015; Smith *et al.*, 2017). In contrast, Jungerius *et al.* (1992) noted that in the Meijendel dunes, Netherlands, most blowouts grew in an upwind direction i.e. toward the prevailing wind direction, and in some cases relatively rapidly (approximately 25 m in 10 years). Jungerius *et al.* (1992) attributed upwind blowout growth to the decrease in erosivity of near-surface winds as they become loaded with sand, thus erosivity is greatest at the location where wind enters the blowout. The downwind migration of the three blowouts recorded in this study may be due to the formation of their relatively tall and steep downwind erosional walls (Figure 4a, 4c and 4e). As near surface wind flow encounters these steep walls, instead of declining in erosivity as hypothesised by Jungerius *et al.* (1992), streamlines compress and wind speed not only increases but also has a strong upward vertical component as it moves over the surface of the dune (Smyth *et al.*, 2012; Smith *et al.*, 2017; Smyth *et al.*, 2019). As a result, sediment is eroded from the upper slopes of the erosional wall and the rim of the blowout is displaced downwind (Smith *et al.*, 2017; Smyth *et al.*, 2019). This hypothesis for topographic change is supported by the overall (1999 – 2014) topographic change map for the study site (Figure 8) as the areas of topographic accretion (sediment deposition) are primarily situated to the east of the blowouts, downwind of the blowouts relative to incident wind conditions.

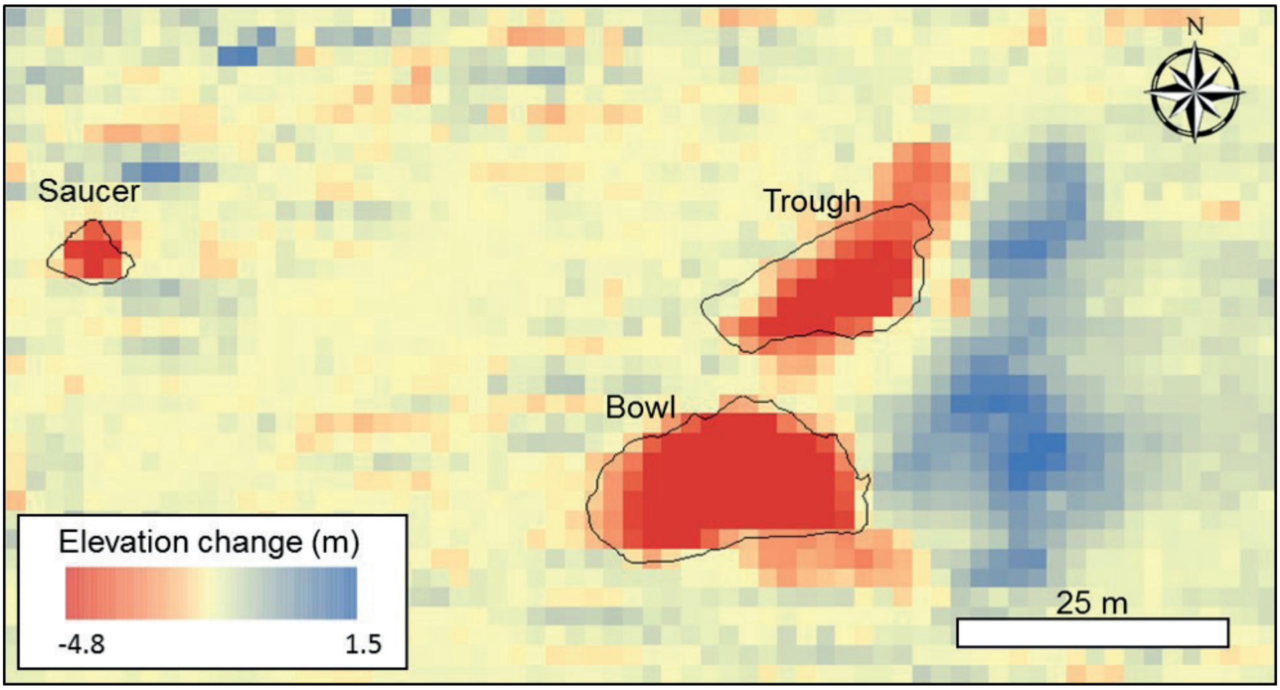

Figure 8: Overall topographic change between 1999 and 2014 at the study site. Black outlines refer to the 2015 location of each of the blowouts.

Figure 6 also demonstrates that the shape of the three blowouts became simpler and more circular over the study period. This morphological evolution is particularly notable for the bowl blowout in the south of the study site. Jungerius *et al.* (1992) and Abhar *et al.* (2015) noted that a similar process occurred during blowout expansion. The increased simplicity of the bowl blowout in this investigation appears partly due to the amalgamation and unification of several erosional hollows. This is particularly evident in the aerial imagery of the bowl blowout between 2005 (Figure 6b) and 2010 (Figure 6c). Due to ongoing expansion of the blowouts at the site, the amalgamation of the bowl and trough blowouts is a distinct possibility. The joining of these two relatively large landforms could have complex morphological and ecological implications for the site, due to the substantial changes in local wind flow and the release of a substantial amount of sediment that would be distributed and deposited downwind (Smith *et al.*, 2017).

Implications for Coastal Dune Management

The evidence from the LiDAR surveys and aerial imagery implies that all three blowouts have been continually expanding/migrating for approximately 15 years and display no indications of stabilising any time soon. Compared to blowout creation/restoration projects in other coastal dune systems that are unconnected to the beach and foredunes, the sustained mobility of these landforms is remarkable. Van Boxel *et al.* (1997), Arens and Geelen (2006) and Arens *et al.* (2013) have all noted that reactivation interventions have been less successful than expected, with the bare sand coverage in some 'restored' blowouts decreasing by over 8% per year from their inception. The sustained presence of bare sand at this site is also contrary to the decline in bare sand measured on the Sefton Coast since 1945 (Delgado-Fernandez *et al.*, 2019b).

A number of factors may be important in the sustained mobility of the blowouts within the study site. Firstly, all three blowouts are located on the upwind slopes of local topographic highs (Figure 1), with low-lying land immediately to the west and south west. Due to the lack of relief upwind of them and their relative topographic prominence in the landscape, these locations are subject to streamline compression and wind flow acceleration, increasing the erosivity of the sites compared to the surrounding landscape. Secondly, the site's elevated location also positions it away from the water table, limiting any flooding of the deflation basins and thus maximising the number of days in which aeolian sediment transport is possible. Thirdly, observations during frequent visits to the site between 2016 and 2019 also indicate that the local area supports a relatively high rabbit population. This has been evidenced by frequent burrowing on the erosional walls, intense grazing of young pioneer vegetation within the deflation basins, and large rabbit latrines in and around the blowouts.

An implication of the continued mobility of these dunes for land managers wishing to maintain a dynamic dune system is that, despite the trend of global 'greening' in coastal sand dunes (Jackson *et al.*, 2019), where certain environmental conditions exist, sand dune mobility can be maintained without mechanical intervention. The results also indicate that where the aim is to increase open conditions or a diversity of habitat structures, relatively small interventions in specific locations may be successful in generating areas of bare sand that will be sustainable without frequent and resource-expensive management interventions. However, further research is required over a larger area and with a greater number of sites to definitively identify what the environmental drivers of bare sand are in contemporary coastal dunes in north west Europe.

Conclusion

This study documents the evolution of three blowouts at Ainsdale Sand Dunes National Nature Reserve, North West England, over a 16-year period. In contrast to other blowouts and large parabolic dunes that have formed or been created in previously vegetated coastal dune landscapes (Arens and Geelen, 2006; Arens *et al.*, 2013), all three blowouts in this study are continuing to expand and generate substantial areas of bare sand ~15 years after their initiation. This continued mobility may be due to several local factors, such as a local increase in erosivity by topographically accelerated wind flow, a lack of interaction with the water table, and grazing of stabilising vegetation. Further research is therefore required to identify common environmental factors associated with bare sand patches globally.

Acknowledgements

We thank David Mercer and the staff at Ainsdale National Nature Reserve (Natural England), for information about and access to the study site. We are grateful to the participants of first 'Coastal dune dynamics and evolution: natural vs. artificial drivers' workshop (February 2019) hosted by the Coastal Studies Lab at Edge Hill University for feedback on the initial results. We also thank Professor Irene Delgado-Fernandez for reviewing the article and Dr Cathy Delaney for valuable feedback.

References

Abesser, C., Clarke, D., Hughes, A.G., Robins, N.S, 2017. Modelling small groundwater systems: experiences from the Braunton Burrows and Ainsdale coastal dune systems, UK. *Journal of Coastal Conservation* 21(5), 595-614.

Abhar, K.C., Walker, I.J., Hesp, P.A., Gares, P.A., 2015. Spatial–temporal evolution of aeolian blowout dunes at Cape Cod. *Geomorphology* 236, 148-162.

Anderson, J.L., Walker, I.J., 2006. Airflow and sand transport variations within a backshore–parabolic dune plain complex: N.E. Graham Island, British Columbia, Canada. *Geomorphology* 77(1-2), 17-34.

Arens, S.M., Geelen, L.H.W.T., 2006. Dune landscape rejuvenation by intended destabilisation in the Amsterdam water supply dunes. *Journal of Coastal Research* 22(5), 1094-1107.

Arens, S.M., Slings, Q., De Vries, C.N., 2004. Mobility of a remobilised parabolic dune in Kennemerland, The Netherlands. *Geomorphology* 59(1-4), 175-188.

Arens, S.M., Slings, Q.L., Geelen, L.H., Van der Hagen, H.G., 2013. Restoration of dune mobility in the Netherlands. In: Martinez, L.M., Gallego-Fernández, J.B., Hesp, P.A. (eds.), *Restoration of Coastal Dunes*. Springer-Verlag, Berlin, pp. 107-124.

Arens, S.M., De Vries, S., Geelen, L.H., Ruessink, G., van der Hagen, H.G., Groenendijk, D., 2020. Comment on 'Is 're-mobilisation' nature restoration or nature destruction? A commentary', by I. Delgado-Fernandez, R.G.D. Davidson-Arnott & P.A. Hesp. *Journal of Coastal Conservation* 24(2), 1-4.

Bitton, M.C., Byrne, M.L., 2002. A volumetric analysis of coastal dune blowout morphology change, Pinery Provincial Park. In: *Proceedings of the Parks Research Forum of Ontario (PRFO) Annual Meeting*, pp. 221-230.

Carter, R.W.G., Hesp, P.A., Nordstrom, K.F.,1990. Erosional landforms in coastal dunes. In: Nordstrom, K.F., Psuty, N.P., Carter, R.W.G. (Eds.) *Coastal Dunes: Form and Process*. Wiley, London, pp. 217-249.

Clarke, D., Ayutthaya, S.S.N., 2010. Predicted effects of climate change vegetation and tree cover on dune slack habitats at Ainsdale on the Sefton Coast, UK. *Journal of Coastal Conservation* 14(2), 115-125.

Creer, J., Litt, E., Ratcliffe, J., Rees, S., Thomas, N., Smith, P., 2020. A comment on some of the conclusions made by Delgado-Fernandez et al.(2019), "Is 're-mobilisation' nature conservation or nature destruction? A commentary". *Journal of Coastal Conservation* 24(3), 29.

Delgado-Fernandez, I., Smyth, T.A.G., Jackson, D.W.T., Smith, A.B., Davidson-Arnott, R.G.D., 2018. Event-scale dynamics of a parabolic dune and its relevance for mesoscale evolution. *Journal of Geophysical Research – Earth Surface* 123(11), 3084-3100.

Delgado-Fernandez, I., Davidson-Arnott, R.G., Hesp, P.A., 2019a. Is 're-mobilisation' nature restoration or nature destruction? A commentary. *Journal of Coastal Conservation* 23(6), 1093-1103.

Delgado-Fernandez, I., O'Keeffe, N., Davidson-Arnott, R.G., 2019b. Natural and human controls on dune vegetation cover and disturbance. *Science of the Total Environment* 672, 643-656.

Doody, J.P., (Ed.), 1991. *Sand Dune Inventory of Europe*. Peterborough: Joint Nature Conservation Committee/European Union for Coastal Conservation.

Gares, P.A., Nordstrom, K., 1991. Coastal dune blowouts. Dynamics and management implications In: *Proceedings of the 7th Symposium on Coastal and Ocean Management Part 4 (of 4)*. A.S.C.E., pp. 2851-2862.

Gobron, N., Pinty, B., Mélin, F., Taberner, M., Verstraete, M.M., Belward, A., Lavergne, T., Widlowski, J.L., 2005. The state of vegetation in Europe following the 2003 drought. *International Journal of Remote Sensing* 26(9), 2013-2020.

Harris, C., 1974. Wind speed and sand movement in a coastal dune environment. *Area* 6(4), 243-249.

Hesp, P.A., Smyth, T.A., 2019. Anchored Dunes. In: Livingstone, I., Warren A. (Eds.), *Aeolian Geomorphology: A New Introduction*. Wiley-Blackwell, Chichester, U.K., pp. 157-178.

Hesp, P.A., Walker, I.J., 2012. Three-dimensional aeolian dynamics within a bowl blowout during offshore winds, Greenwich Dunes, Prince Edwards Island, Canada. *Aeolian Research* 3(4), 389-399.

House, S.M., Spellerberg, I.F., 1983. Ecology and conservation of the sand lizard (Lacerta agilis L.) habitat in southern England. *Journal of Applied Ecology* 20, 417-437.

Howe, M.A., Knight, G.T., Clee, C., 2010. The importance of coastal sand dunes for terrestrial invertebrates in Wales and the UK, with particular reference to aculeate Hymenoptera (bees, wasps & ants). *Journal of Coastal Conservation* 14(2), 91-102.

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

Jackson, D.W.T., Costas, S. González-Villanueva, R. and Cooper, J.A.G., 2019. A global 'greening' of coastal dunes: An integrated consequence of climate change? *Global and Planetary Change* 182, 103026.

Jones, M.L.M., Wallace, H.L., Norris, D., Brittain, S., Haria, S., Jones, R.E., Rhind, P., Reynolds, B.R., Emmett, B.A., 2004. Changes in vegetation and soil characteristics in coastal sand dunes along a gradient of atmospheric nitrogen deposition. *Plant Biology* 6(05), 598-605.

Jungerius, P.D., Van der Meulen, F., 1989. The development of dune blowouts as measured with erosion pins and sequential air photos. *Catena* 16(4-5), 369-376.

Jungerius, P.D., Van Der Meulen, F., Loedeman, J.H., Stuiver, J., 1992. A geometrical approach to monitoring blowout development from aerial photographs using a Geographical Information System (GIS). In: Curtis, T.G.F., Sheehy-Skeffington, M.J., Carter, R.W.G. (Eds.) *Coastal Dunes: geomorphology, ecology and management for conservation*. Balkema, Rotterdam, pp. 129-138.

Jungerius, P.D., Verheggen, A.J.T., Wiggers, A.J., 1981. The development of blowouts in 'De Blink', a coastal dune area near Noordwijkerhout, The Netherlands. *Earth Surface Processes and Landforms* 6(3-4), 375-396.

Moulton, M.A., Hesp, P.A., Miot da Silva, G., Bouchez, C., Lavy, M., Fernandez, G.B., 2019. Changes in vegetation cover on the Younghusband Peninsula transgressive dunefields (Australia), 1949–2017. *Earth Surface Processes and Landforms* 44(2), 459-470.

National Ocean Service, 2018. *What is LIDAR?* https://oceanservice noaa gov/facts/lidar.html.

Pluis, J.L.A., 1992. Relationships between deflation and near surface wind velocity in a coastal dune blowout. *Earth Surface Processes and Landforms* 17(7), 663-673.

Provoost, S., Jones, M.L.M., Edmondson, S.E., 2011. Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. *Journal of Coastal Conservation* 15(1), 207-226.

Pye, K., Blott, S.J., 2010. Geomorphology of the Sefton Coast sand dunes. In: Worsley, A., Lybery, G., Holden, V., Newton, M. (Eds.), *Sefton's Dynamic Coast: Proceedings of the Conference on Coastal Geomorphology, Biogeography and Management*. Coastal Defence Sefton MBC Technical Services Department, pp. 131-160.

Pye, K., Blott, S.J., 2016. Assessment of beach and dune erosion and accretion using LiDAR: Impact of the stormy 2013–14 winter and longer term trends on the Sefton Coast, UK. *Geomorphology* 266, 146-167.

Pye, K., Blott, S.J., 2020. Is 're-mobilisation' nature restoration or nature destruction? A commentary. Discussion. *Journal of Coastal Conservation* 24(1), 10.

Pye, K., Neal, A., 1993. Late Holocene dune formation on the Sefton coast, northwest England. *Geological Society London, Special Publication* 72(1), 201-217.

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

Rhind, P., Jones, R., Jones, L., 2013. The impact of dune stabilization on the conservation status of sand dune systems in Wales. In: Martinez, L.M., Gallego-Fernández, J.B., Hesp, P.A. (eds.), *Restoration of Coastal Dunes*. Springer-Verlag, Berlin, pp. 125-143.

Rodgers, S., O'Keeffe, N., Delgado-Fernandez, I., 2019. Factors affecting dune mobility in Newborough, Wales. In: Durán, R., Guillén, J., Simarro, G. (Eds.) *Proceedings of the X Jornadas de Geomorfología Litoral, Castelldefels, Barcelona, 4-6th September 2019*. p. 129.

Smith, A., Gares, P.A., Wasklewicz, T., Hesp, P.A., Walker, I.J., 2017. Three years of morphologic changes at a bowl blowout, Cape Cod, USA. *Geomorphology* 295, 452-466.

Smith, P.H., Lockwood, P.A., 2011. Grazing is the key to the conservation of *Gentianella campestris* (L.) Börner (*Gentianaceae*): evidence from the north Merseyside sand-dunes. *New Journal of Botany* 1(2), 127-136.

Smith, P.H., Payne, K.R., 1980. A survey of natterjack toad (*Bufo calamita*) distribution and breeding success in the north Merseyside sand-dune system, England. *Biological Conservation* 19(1), 27-39.

Smyth, T.A.G., Hesp, P.A., Walker, I.J., Wasklewicz, T., Gares, P.A., Smith, A.B., 2019. Topographic change and numerically modelled near surface wind flow in a bowl blowout. *Earth Surface Processes and Landforms* 44, 1988-1999.

Smyth, T.A., Jackson, D.W., Cooper, J.A.G., 2012. High resolution measured and modelled three-dimensional airflow over a coastal bowl blowout. *Geomorphology* 177, 62-73.

Sturgess, P., Atkinson, D., 1993. The clear-felling of sand-dune plantations: soil and vegetational processes in habitat restoration. *Biological Conservation* 66(3), 171-183.

Van Boxel, J.H., Jungerius, P.D., Kieffer, N., Hampele, N., 1997. Ecological effects of reactivation of artificially stabilized blowouts in coastal dunes. *Journal of Coastal Conservation* 3(1), 57-62.

Van der Biest, K., De Nocker, L., Provoost, S., Boerema, A., Staes, J., Meire, P., 2017. Dune dynamics safeguard ecosystem services. *Ocean and Coastal Management* 149, 148-158.

Van Der Meulen, F., Wanders, E.A.J., 1984. Moving sand dunes: aspects of nature conservation and dune management in coastal dunes of Meijendel, The Netherlands. *De Levende Natuur* 84(1), 18-23.

Wolfe, S.A., Huntley, D.J., Ollerhead, J., 1995. Recent and late Holocene sand dune activity in southwestern Saskatchewan. In: *Current Research 1995-B Geological Survey of Canada*, pp. 131-140.