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LETTER

Post-storm geomorphic recovery and resilience of a prograding coastal dune system

J E Bullard1 , D Ackerley1,2, J Millett1, J H Chandler1 and A-L Montreuil3

1 Geography and Environment, Loughborough University, Leicestershire, LE11 3TU United Kingdom
2 Department of Geography, University of Leicester, Leicestershire, LE1 7RH United Kingdom
3 School of Architecture, Building and Civil Engineering, Loughborough University, Leicestershire, LE11 3TU United Kingdom

E-mail: j.e.bullard@lboro.ac.uk

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Abstract

Geomorphic resilience is the capacity of a system to recover to pre-disturbance conditions following a perturbation. The 2013/14 Atlantic winter storm period had extensive geomorphological impacts and provides an opportunity to assess coastline resilience. This paper uses high spatio-temporal resolution data to quantify the beach-dune response and subsequent recovery of a prograding coastline following the 5 December 2013 North Sea storm surge. It demonstrates that despite the high water levels and destructive nature of the storm, the beach-dune system recovered sediment rapidly over the first post-storm year. Within four years the dune advance had exceeded the seawards position expected based on long-term coastal trends but had not yet recovered the pre-storm foredune profile. Cumulative evidence from numerous European locations suggests one of the stormiest periods on record triggered only a minor disturbance to what appear to be highly resilient beach-dune systems.

1. Introduction

The concept of geomorphic resilience in response to disturbance provides a framework for evaluating the impacts of natural and anthropogenic perturbations to geomorphic systems (Downes et al 2013, Phillips and Van Dyke 2016). It has resonances with landscape sensitivity and geomorphic effectiveness (Brunsden and Thornes 1979, Usher 2001) and strong links to ecological and biogeomorphic conceptual frameworks (Stallins and Corenblit 2018). Definitions of resilience all refer to the ability of a system to absorb the impact of, and recover from, a disturbance and return to its pre-impacted, or an alternative stable, state (Downes et al 2013). Geomorphic resilience reflects both the magnitude and frequency of disturbance, response time, relaxation time and recovery (Phillips and Van Dyke 2016). This framework has been applied to various systems and the focus here is on coastal response to storm events where the notion of resilience has gained considerable traction (e.g. Houser et al 2015, Walters and Kirwan 2016).

Climate change scenarios suggest changes to storminess and sea level may affect coastline susceptibility to erosion and flooding, and highlight the need to understand the implications of coastal resilience for geomorphology, habitat diversity, socio-economic impact and policy formulation (Lloyd et al 2013). The past 30 years have seen considerable improvements in both the quantity and spatio-temporal resolution of data available for evaluating coastal resilience (e.g. repeat aerial photography, beach profile monitoring, airborne and terrestrial Light Detection and Ranging - LiDAR) which allow the determination of the pre-storm state, and post-disturbance rate and nature of system response (e.g. Kandrot et al 2016, Pye and Blott 2016, Le Mauff et al 2018). Most studies of natural system resilience focus on local-scale sites over short-medium timescales. Downes et al (2013) argue that this focus limits consideration of wider scale processes even when broadly contextualised. However substantial variability in local response to the same disturbance event (Backstrom et al 2015, Masselink et al 2016, Crapoulet et al 2017) suggests sites exhibiting a range of representative antecedent conditions and/or

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response dynamics are needed as building blocks to support a framework for understanding both local geomorphic resilience and the potential for interactions between different geomorphic (sub-)systems.

The Atlantic winter storm period of 2013/2014 was the most energetic since 1948 along the north west (NW) Europe coastline (Masselink et al. 2016) and the stormiest on record for the UK (Matthews et al. 2014). The storms had extensive geomorphological impacts including cliff retreat, beach rotation, dune scarping, washover of barrier islands (Castelle et al. 2015, Spencer et al. 2015, Masselink et al. 2016, Pye and Blott 2016) and provided the opportunity to determine coastline resilience following a major disturbance using detailed modern pre- and post-storm datasets. Most research on geomorphic response to the 2013/14 storm season—and previous stormy periods—has focused on eroding coasts, thus understanding of the processes associated with storm-induced coastal retreat and realignment is considerably more developed than current understanding of the storm response and recovery of prograding coasts (Moore et al. 2016, Ruggiero et al. 2016). This paper provides a counter-point to this by focusing on the 2013/14 post-storm recovery of a prograding dune system. This is important because both prograding and eroding coasts can exist within the same sediment cell and may respond differently to a single disturbance event. Existing research highlights the importance of the nearshore profile, which can substantially affect post-storm foredune recovery on all coastlines, acting as a buffer to wave action and a reservoir of dry sand for dune formation (McLean and Shen 2006, Maspatud et al. 2009, Hesp 2013). There is a marked asymmetry between the rapid storm erosion of dunes (typically hours) and relatively long time required to rebuild foredunes to their post-storm profile (volume, height; typically years) that means the sequencing, as well as magnitude, of storms has implications for dune stability and longevity (Thom and Hall 1991, McLean and Shen 2006, Hesp 2013, Castelle et al. 2017). This paper quantifies beach-dune response and recovery of a prograding coastline following the December 2013 North Sea storm surge. Data are used to classify and assess the disturbance impact and geomorphic resilience of the site within the context of the regional (NW Europe) response to the winter 2013/14 storm season.

2. Study region and methods

2.1. 2013/14 North Sea storm surge

The 5 December 2013 North Sea storm surge was caused by a deep low pressure that intensified to an extratropical cyclone tracking east across Scotland (UK Meteorological Office 2014) (figure 1). The storm caused coastal flooding on the west coasts of Wales, England and Scotland but the effect was strongest along North Sea coasts where the storm surge travelled south and was funneled between the European mainland and east coast of England. Maximum run-up levels varied from 5.02 to 5.83 m on the Lincolnshire coast and 5.64 to 6.37 m on the north Norfolk coast (Spencer et al. 2015). Brooks et al. (2016) identified 20 storm surges in the southern North Sea since 1883 but in the past 65 years, only two have been of comparable magnitude and impact (1953 c. 5.6 m; 1978 c. 4.7 m at Immingham). The 2013 storm surge caused cliff retreat up to 12 m, dune retreat of up to 19 m, washover of low dunes and breaching of gravel barriers on North Sea coastlines (Spencer et al. 2015). The winter of 2013/14 featured multiple identifiable storm events which impacted the western and southern coasts of the UK, however these had less geomorphic impact on the North Sea coastline due to more southerly storm tracks.

2.2. Lincolnshire coast

The area of interest (AOI) on the Lincolnshire coast (53°21′43″N 0°15′03″E) (figure 1(b)) comprises a dissipative macrotidal beach (mean spring tidal range 6 m) up to 3.5 km wide, backed by established dunes (>6 m Ordnance Datum Newlyn - ODN). Prevailing winds are offshore from the southwest; easterly onshore winds occur with less frequency but higher magnitude than offshore winds. Offshore sand banks protect the shore and are a source of sediment to the beach-dune system along with eroded sediments from the Holderness Cliffs to the north. There has been seawards progradation of the coastline of c.2 m yr⁻¹ over the past 120 years (Montreuil and Bullard 2012). Prior to the 2013 storm surge, the backshore was characterised by a semi-vegetated (10%–50% cover) hummocky incipient foredune. The site is within the Saltfleetby-Theddlethorpe Dunes National Nature Reserve and has no sea defences.

2.3. Beach profiles, surveys and environmental data

Pre- and post-storm cross-shore topographic profiles made using RTK-GPS (UK Environment Agency - EA) were used to assess biannual changes of the beach-dune from January 2013 to January 2018 and analysed using the SANDS v8.1.1 Asset Management System. To quantify three-dimensional post-storm recovery a terrestrial LiDAR system (Leica ScanStation 2; ScanStation P20 - TLS) was used to survey a 40 × 50 m AOI of the beach-dune system incorporating the scarped dune face, incipient foredune and upper beach approximately once per month for 12 months from January 2014 with an additional survey in April 2015 (figure 2). The tripod-mounted LiDAR instrument was deployed at a minimum of three viewpoints with one scanning location always sited...
above the foredune scarp, to reduce areas of potential shadowing and ensure the density of point measurements (1 ppcm$^2$) was consistent across the AOI (Soudarissanane et al. 2011). The separate point cloud datasets were registered into a single, locally-defined coordinate system using four high-definition survey (HDS) targets. This local registration process utilised a 3D bundle adjustment algorithm, implemented in Leica Geosystems’ Cyclone software, which yielded a mean absolute error (MAE) of <4 mm for the survey series. The locations of the HDS targets were determined using a Trimble R6 survey-grade differential GPS (dGPS) system. In post-processing, the OS grid coordinates were transformed to a local OS-related system to improve the accuracy of referencing (≤6 mm MAE between the TLS and local OS grid coordinate systems; Ackerley et al. 2016). The point cloud datasets were georeferenced to a local plane grid and scaled with reference to the British National Grid OSGB36/ODN. Following the manual and automated removal of redundant points, the LiDAR datasets were clipped to the 40 × 50 m areal extent of the AOI.

Vegetation-induced errors from TLS surveys are common in coastal environments and can exceed other survey-related errors (Coveney and Fotheringham 2011). Vegetative material was present in all surveys and rooted vegetation increased in cover and height during the study. To focus on the morphological recovery of the beach–dune system, a moving window approach was employed to segment the point cloud into ‘ground’ and

Figure 1. (a) Synoptic chart 5 December 2013 (UK Met Office 2014); (b) Study location; (c) Post-storm scarp at AOI (scarp height is c.2 m), photograph taken 15/11/13 looking north; (d) AOI looking south along former scarp line taken 18/10/17; (e) EA beach profiles.
‘vegetation’ components (Fan et al 2014). The optimal size of this local filter was determined using sensitivity analysis performed for over 100 dGPS-derived control points (Guarnieri et al 2009, Wang et al 2009). From this analysis a 0.05 × 0.05 m neighbourhood was found to provide the best compromise between the resolution and accuracy of surfaces produced from filtered data (mean absolute difference: 0.0218 m; Ackerley et al 2016). The lowest elevations within the moving window were interpolated to produce digital terrain models (DTM S1, DTM S2, … DTM S12). Significant changes in elevation between DTMs were identified as those exceeding the minimum level of detection (LoD), a sum of registration and georeferencing MAE (Brasington et al 2003), and included in DTMs of difference (DoDs). A local window calculating standard deviation over a 3-by-3 cell neighbourhood was additionally applied over the DTMs to generate maps of local surface roughness (roughness DTM S1, roughness DTM S2, … roughness DTM S12) which provided qualitative information on morphological form (Nield et al 2011). The areal extent of the standard deviation moving window was determined subjectively. Despite the filtering processes, landward of the scarp face vegetation cover was too dense to have confidence that changes were due to morphological, rather than vegetation, dynamics and is excluded from calculations of volume changes. Contours corresponding to the foredune scarp face (6 m ODN), highest astronomical tide (HAT 4.09 m ODN) and boundary between the primary foredune and upper beach active aeolian sub-units (3.5 m ODN) were overlain to the DTMs and DoDs. Changes in elevation above the 3.5 m contour line are interpreted as primarily aeolian-driven (dune unit) whereas changes below 3.5 m ODN are primarily marine-driven (beach unit).

Two key determinants of post-storm dune recovery are the frequency and direction of sand-transporting winds and water level. Hourly mean wind speed and direction measured at the nearest meteorological station, Donna Nook, were obtained from the British Meteorological Data Centre for December 2013 to April 2015. Wind data from the WainFleet No.2 station were adjusted to the same height as the Donna Nook station and substituted for the period 10/03/14 to 03/07/14 for which data from Donna Nook are not available. The occurrence of onshore (0° to <150°), alongshore (>170° to 330°, 330°–350°) and offshore (>170° to 330°) winds ≥8 m s⁻¹ (i.e. potential sand-transporting winds) was calculated for each survey period. Water level records are from Immingham (British Oceanographic Data Centre) and used to determine the frequency of events with water level ≥3.5 m ODN and ≥4.09 m ODN occurring between successive surveys (Montreuil et al 2013).
3. Results

3.1. Geomorphological impact of the 5 december 2013 storm

Figure 1 shows the difference between the pre-storm profiles (January and June 2013) and the immediate post-storm profile (January 2014). The c.1 m high incipient foredunes at 15–20 m were eroded during the storm and the established foredune retreated 10 m. A scarp face developed at c.10 m and from the base of the scarp to 3.5 m ODN beach level increased due to redistribution of the upper beach sediments. The backshore was left devoid of rooted vegetation and vegetative matter removed during the scarping was strewn across the beach as wrackline debris (figure 1(c)).

3.2. Post-storm geomorphological recovery

Following the storm surge, from January to December 2014 within the AOI there was a net loss from the beach of −2.61 m³ and accumulation of +180.1 m³ in the dunes (figure 3). From December 2014 to April 2015 the beach gained +41.67 m³ and the dunes lost −59.83 m³ of sediment.

During the first 4 post-storm months strong offshore winds dominated (table 1) and several low magnitude storms occurred (up to 1.45% of water levels >3.5 m). The volume of sediment above 3.5 m in the DEM decreased in March and April losing a cumulative −59.71 m³ but the spatial pattern of sediment loss varies for each time period (figure 4). From 17/01/14 to 18/02/14 the DoD shows gains immediately seawards of the scarp line but erosion further seawards which may be due to further offshore redistribution of sediment due to high water levels (reaching up to 3.97 ODN).

The dunes had a net sediment gain of 63.69 m³ in the spring (mid-April to mid-June) during which the frequency of water level >3.5 m was the lowest for the survey period. This also included the first survey period when onshore winds were more frequent than offshore winds (S5–S6). Discrete nebkha accumulated between the HAT line and the scarp base. There was little change in sediment volume from June to July and then from July to December 2014 the dunes rapidly gain sediment. Relatively low wind speeds and a low percentage of winds >8 m s⁻¹ suggests this sediment gain was caused by sand-trapping vegetation which recovered over the summer and captured wind-blown sediment in an incipient foredune. This is particularly clear in August 2014 where discrete nebkha form and develop, merging to form a larger near-continuous incipient foredune about...
Table 1. Summary of the meteorological and marine conditions, and surface changes experienced over the data collection period.

| Event frequency | Wind speed (m s\(^{-1}\)) | Water level | Volume change (m\(^3\)) |
|-----------------|---------------------------|-------------|-------------------------|
|                 | Offshore | Onshore | Along-shore | Min | Mean | Max | \(\geq 3.5\) | \(\geq 4.09\) | Beach | Dunes |
| 13 December 2013–30 January 2014 | 30.76 | 0.95 | 10.57 | 1.54 | 7.79 | 18.52 | 1.31 | 0.17 | n/a | n/a |
| 30 January [S1] – 18 February 2014 | 21.74 | 12.89 | 8.20 | 0.51 | 7.81 | 20.06 | 0.46 | 0.00 | -18.90 | 2.30 |
| 18 February [S2] – 18 March 2014 | 25.34 | 2.58 | 6.37 | 0.51 | 6.48 | 14.40 | 1.12 | 0.00 | 5.95 | -37.63 |
| 18 March [S3] – 16 April 2014 | 27.06 | 11.29 | 0.43 | 0.62 | 7.02 | 16.85 | 1.45 | 0.00 | -7.38 | -22.08 |
| 16 April [S4] – 15 May 2014 | 18.52 | 12.01 | 2.89 | 0.62 | 6.70 | 16.22 | 0.18 | 0.00 | 15.02 | 50.64 |
| 15 May [S5] – 17 June 2014 | 5.06 | 11.72 | 1.07 | 0.62 | 5.50 | 12.48 | 0.00 | 0.00 | -1.62 | 35.12 |
| 17 June [S6] – 16 July 2014 | 6.25 | 3.63 | 4.36 | 0.62 | 5.14 | 13.89 | 0.93 | 0.00 | -3.38 | -4.15 |
| 16 July [S7] – 21 August 2014 | 7.05 | 5.35 | 2.79 | 0.51 | 5.39 | 15.95 | 1.30 | 0.00 | -2.00 | 68.46 |
| 21 August [S8] – 1 October 2014 | 1.89 | 4.11 | 2.42 | 0.51 | 4.82 | 15.43 | 0.56 | 0.03 | -3.98 | 14.39 |
| 1 October [S9] – 13 November 2014 | 10.37 | 7.78 | 4.09 | 0.51 | 6.22 | 17.49 | 1.65 | 0.00 | 1.29 | 12.61 |
| 13 November [S10] – 9 December 2014 | 2.61 | 12.40 | 3.10 | 0.51 | 5.54 | 17.49 | 1.52 | 0.00 | 12.39 | 60.22 |
| 9 December [S11] – 20 April 2015 [S12] | 23.03 | 2.66 | 2.44 | 0.51 | 6.43 | 18.00 | 2.67 | 0.45 | 41.67 | -59.83 |
0.5 m high by December 2014. Early winter conditions were atypical with strong onshore winds dominant. A comparison of December 2014 with April 2015 indicates a small loss of sediment particularly between the HAT and 3.5 m contours.

The summer and winter profiles show removal of the pre-storm incipient foredune and scarping of the established foredune forming a flat beach (January 2014; figure 1(e)). The summer 2014 profile highlights the initiation of an incipient foredune c. 5 m wide just above the HAT at c. 25 m from the scarp. By winter 2014 the incipient dune has extended to 20 m wide (15–35 m from scarp) with a height of 0.75 m and continues to grow reaching c. 1.5 m by January 2018. There is limited deposition/infilling at the base of the scarp and a trough persists between this and the developing foredune. The foredune toe is located 15 m further seawards in January 2018 compared to the pre-storm position.

Figure 4. DoDs for each successive survey. Arrow width is proportionate to the frequency of onshore (green) or offshore (blue) winds ≥8 m s⁻¹ (table 1).
4. Discussion

4.1. Foredune recovery on a prograding coast

The December 2013 storm surge caused considerable dune scarping along the Lincolnshire coast. Within the AOI, dunes retreated 15–20 m which sets the dune-line back around ten years of advancement based on Montreuil and Bullard’s (2012) long-term estimate (1891–2010) of annual shoreline accretion of 2 m yr⁻¹ or up to twenty years based on recent accretion rates (c. 1 m yr⁻¹; 2005–2010). This accords with 13.59 m of coastline retreat at Donna Nook, 12 km to the north, following the December 2013 storm, where long term progradation rates of 0.21 to 1.1 m yr⁻¹ also indicate erosion equivalent to at least ten years of advancement (Spencer et al 2015). By January 2018 the incipient foredune toe was c. 15 m seawards of the pre-storm position which suggests rapid recovery and progradation beyond the pre-storm position, and seawards of the expected position assuming resumption of the long-term 1–2 m yr⁻¹ rate of advance. Accretion along this coast is associated with retreat of the up-drift Holderness cliffs to the north so this rapid progradation may be associated with up-drift storm erosion during 2013/14 (Montreuil and Bullard 2012).

Recent research provides insight into the processes contributing to the observed morphological changes. Dune recovery comprised initial accumulation at the base of the scarp through slumping but also lee side deposition due to flow separation of offshore winds initiated by scarp development (Lynch et al 2010). Within 3 months a beach ridge had developed between the HAT and 3.5 m (dune-beach) contours and persisted throughout the survey period. After 3–6 months, post-storm discontinuous echo dunes formed parallel to, and c. 0.5–1 m from, the scarp base. These formed during offshore winds from a combination of sand transport from the landward dunes deposited downstream from the scarp base, and possible flow reversal transporting sediment from the upper beach to the seaward dune face, with the separation between dune and scarp likely maintained by topographically-steered winds (Bauer et al 2015) (figure 1(d)). These echo dunes persisted and grew during the year responding to summer onshore sand transport (Hesp et al 2009). Within 4 months of the storm discrete nebkha or shadow dunes are visible from the DoDs (figure 4) and form around debris and vegetation on the backshore. In the first 6 months these features are dynamic, changing in extent and orientation in relation to wind regime (figure 3(d)) and then coalesce to form a continuous incipient partially-vegetated foredune (Goldstein et al 2017). Sediment incorporated into these dunes may be from offshore winds depositing sand on the backshore or by trapping sand blown onshore from the beach (Bauer et al 2012, 2015). During the first year of recovery the nebkha and incipient dunes form in a similar position relative to ODN to the pre-storm dunes (just above HAT), but are located further seawards (20–35 m from the scarp) than their predecessors (15–25 m from scarp) (figure 1). During the subsequent 3 years the position of the incipient dune is unchanged but the breadth and height both increase. These stages of recovery add detail to Hesp’s (2002) suggested post-storm geomorphic response of a prograding dune system.

Foredune development and post-storm recovery has been linked to nearshore characteristics, particularly along coastlines characterised by dynamic dry bars and saturated troughs (ridge and runnel topography) which can segment the dry fetch length and limit onshore aeolian transport to the dunes (Vanhée et al 2002, Aagaard et al 2004, Anthony et al 2008). Anthony et al (2008) model of cross-shore fetch segmentation on a macrotidal beach suggests sediment delivery from beach to dunes is most likely when strong cross-shore or oblique onshore winds coincide with neap tides, and most restricted when the upper beach trough is close to the foredune. The Lincolnshire coast features multiple dynamic intertidal bars that migrate cross-shore in response to tidal cycles (Van Houwelingen et al 2008) and longshore to the south at rates of up to 30 m per month (van Houwelingen et al 2006). The biannual EA profiles for the site (which extend to c. 450 m and −3 m ODN) suggest the storm caused flattening of the bar-trough topography on the upper beach (cf van Houwelingen et al 2008) but little change in topography below 0 m ODN. The bars on the upper beach re-established before January 2015. Given the known longshore dynamics of the bars it is not possible to link the monthly records of bar migration to foredune recovery for this site.

4.2. Coastal resilience to the 2013/14 North Atlantic winter storms

Evaluating geomorphic resilience requires understanding of the pre-disturbance conditions to which the system might return. Phillips and Van Dyke (2016) argue that for coastal systems meaningful indicators of pre-disturbance conditions are long-term stability, accretion or erosion, and a state transition would require a shift from one to another of these states rather than merely an alteration to the rate of change. They describe five classes of disturbance based on system response:

(1) ‘minor disturbance’ where pre-disturbance and post-disturbance states are the same;

(2) ‘transitional disturbance’ where the post-disturbance condition is a new state but one previously occupied by the system;
(3) 'clock-resetting event' where disturbance returns the system to its original incipient state

(4) 'state space expansion event' which results in a system condition or configuration that has never previously existed;

(5) 'extinction event' that completely obliterates the system.

From other studies of geomorphic recovery following the 2013/14 storms, most suggest that coastal system states have remained unchanged or show clear signs of rapidly returning to the pre-storm state. Pye and Blott (2016) concluded that despite 2013/14 being the stormiest period for 143 years, the geomorphic effects on the Sefton coast, England were 'virtually insignificant' within the long-term context from late 18th century to present. Significant beach–dune recovery occurred within 1 year of the storms and long-term trends had not changed. Similarly at Truc Vert, SW France, post-storm recovery was very rapid during the summer 2010, and determined that although the response to the 2013 storm surge represents a large-scale disturbance event amplified by spring tides, its effects were mitigated ('filtered' - Phillips and Van Dyke 2016) by offshore winds up to 95 km hr$^{-1}$. Rebuilding of the incipient foredunes was instigated rapidly after the storm and within 12 months recovery was substantial with 180.1 m$^3$ of sediment added to dunes in the AOI. By normalising for survey area and time between surveys (Young and Asford 2006), previous seasonal sediment budget changes determined for 'embryo' dunes (described by Montreuil et al 2013) 0.6 km to the north can be compared to changes in the AOI. Rates of volume change for the embryo dunes in winter (2009/10) were $-0.000 \, 49 \, m^3 \, m^2 \, day^{-1}$ and $+0.000 \, 77 \, m^3 \, m^2 \, day^{-1}$ in summer 2010 (Montreuil et al 2013). By comparison, winter 2014 changes on the incipient foredunes following the 2013 storm were $-0.000 \, 30 \, m^3 \, m^2 \, day^{-1}$, summer 2014 showed a gain of $+0.000 \, 51 \, m^3 \, m^2 \, day^{-1}$ and winter 2014/15 was $-0.000 \, 023 \, m^3 \, m^2 \, day^{-1}$. The order of magnitude and trend of sediment budget changes immediately following the 2013 storm is comparable with pre-disturbance conditions, although winter 2014/15 shows a sediment loss likely due to erosion associated with high water levels immediately prior to the April 2015 survey (5.57 m ODN 07/04/15). The EA profiles indicate that by January 2018 the incipient dunes incorporated 73.25 m$^3$ m$^{-1}$ of sediment, considerably more than the pre-storm incipient dunes (51.13 m$^3$ m$^{-1}$). This suggests behaviour similar to that identified by Morton et al (1994) where once post-storm recovery has started, a prograding system can undergo continuous gains that exceed the volume eroded by the storm.

Recovery of coastal foredunes is widely reported to take considerably longer than that of the adjacent beach following a storm, and this recovery period can be extended by the impact of subsequent storms (Houser et al 2015). Typically the time period is several years, occasionally extending to decades (Mathew et al 2010, McLean and Shen 2006) but evidence from this paper and elsewhere (e.g. Morton et al 1994) indicates recovery may occur more rapidly on prograding coastlines (<3 years). In cases where dune volume recovers rapidly, as reported here, by Morton et al (1994) and Castelle et al (2017), the post-storm geomorphic profile of the redeveloped incipient foredunes is different to the pre-storm profile and may undergo further change before reaching an equilibrium state.

4.3. Concluding remarks

Geomorphic resilience depends on the primary controlling factors of the system state, and the magnitude, frequency and intensity of disturbance. Where long-term coastline trends are controlled by strong morphological preconditioning, including local bathymetry, geomorphology and sediment supply, even high magnitude storm events cause only a minor disturbance to the system (Chaverot et al 2008, Pye and Blott 2016, Phillips et al 2017) which can be described as highly resilient. In other cases the occurrence of storm events themselves may be a primary control on coastal geomorphology due to their frequency, and resilience may hinge on the clustering of storms (Kish and Donoghue 2013, Houser and Hamilton 2009). Downes et al (2013)
highlight the importance of research on resilience being evidence-based and the need to apply methodologies that allow comparison of studies across time and space. Including this paper, recent studies focusing on coastal resilience in response to stormy periods have used repeat LiDAR surveys to determine changes in beach-dune sediment budget and the evolution and recovery of geomorphological features (Telling et al 2017). Insights into to the rapidity and persistence of geomorphological recovery are dependent on the time between surveys where closely-spaced surveys enable the detection of geomorphological change in response to specific forcing factors, whilst longer time periods between surveys (e.g. 6 months-years) indicate net changes and longer-term trends in coastline dynamics. Results reported here suggests that, as with the west coasts of England, Ireland and France, one of the stormiest periods on record triggered only a minor disturbance to the prograding beach-dune system on England’s east coast.

The impact of changing climate on the magnitude and frequency of storms in NW Europe is difficult to predict. There is a consensus that storm tracks will shift poleward with concomitant changes to regional impacts, but it remains unclear whether storminess will intensify (Zappa et al 2013, Mölter et al 2016, Rasmijn et al 2016). This paper has focused on the post-storm response of a prograding coastal dune system and demonstrated the ability of that system to recover rapidly from the impacts of a high magnitude storm. It highlights geomorphological response to seasonal forcing factors and the importance of both offshore and onshore winds for incipient foredune recovery. Within four years dune advance has exceeded the position expected based on longer term coastal trends. One implication of this is that coastal protection offered by prograding coasts is likely to endure irrespective of future changes to storminess.

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ORCID iDs

J E Bullard © https://orcid.org/0000-0002-2030-0188

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