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Understanding historical coastal spit evolution: A case study from Spurn, East Yorkshire, UK

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ABSTRACT: Globally sandy coastlines are threatened by erosion driven by climatic changes and increased storminess. Understanding how they have responded to past storms is key to help manage future coastal changes. Coastal spits around the world are particularly dynamic and therefore potentially vulnerable coastal features. Therefore, how they have evolved over the last few centuries is of great importance. To illustrate this, this study focuses on the historical evolution of a spit at Spurn on the east coast of the UK, which currently provides critical protection to settlements within the Humber estuary. Through the combination of digitized historical mapping and luminescence dating, this study shows that Spurn has been a consistent coastal feature over at least the past 440 years. No significant westward migration was observed for the last 200 years. Results show a long-term extension of the spit and a decrease in its overall area, particularly in the last 50 years. Breaches of the neck cause temporary sediment pathway changes enabling westward extension of the head. Use of digitized historical maps in GIS combined with OSL dating has allowed a more complete understanding of long-term spit evolution and sediment transport modes at Spurn. In doing so it helps inform future possible changes linked to pressures, such as increases in storm events and sea-level rise. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd

KEYWORDS: coastal erosion; spit; dunes; portable OSL; storms; centennial coastal evolution; historical maps

Introduction

Over the last 100 years it has been estimated that global sea levels have risen by ~20 cm (Church *et al.*, 2008) and in the North Sea region of Europe sea levels since 1800 have risen on average by 1.5 mm a^{-1} (Wahl *et al.*, 2013). Various authors have suggested that enhanced storminess has occurred in the North Atlantic and North Sea within the last 500 years (e.g. Wilson *et al.*, 2001; Clarke and Rendell, 2009; Sorrel *et al.*, 2012). On top of this, the incidence of storm-driven extreme sea levels with a 100-year return interval is predicted to increase by up to 20 cm in Northern Europe by 2100 (Vousdoukas *et al.*, 2018). As sea levels and the frequency of storms have risen, so coastlines have had to – and will continue to – evolve significantly (e.g. Masselink and Russell, 2013; Nicholls *et al.*, 2014). It has recently been predicted that 30–40% of beaches within Northern Europe will have retreated >100 m by 2100 under an RCP4.5 climate change scenario (Vousdoukas *et al.*, 2020). Understanding how coasts have evolved due to past changes may help inform coastal managers – to understand what is required to make coastlines more resilient to future change (Pethick, 2001; Gornish and Miller, 2010; Brooks *et al.*, 2016).

Many studies have researched historical (last 500 years) coastal changes: Thieler and Danforth (1994) in Puerto Rico; Kelley *et al.* (2005) in Maine, USA; Morton *et al.* (2005) in the Gulf of Mexico; Allard *et al.* (2009) in SW France; and Fruergaard and Kroon (2016) in Denmark. The benefits of such an approach for coastal managers is well exemplified by Kabuth *et al.* (2014), who successfully reconstructed multi-decadal shoreline changes along c. 7000 km of the Danish coastline between 1862 AD and 2005 AD. From this they were able to show, for example, barrier spit shore-facing erosion and distal accretion as well as saltmarshes and deltas accreting through time.

As shown by the spatial and temporal analysis of Haigh *et al.* (2016), the UK over the period 1915–2014 has experienced many extreme sea-level and storm-surge events. As sea levels in the north-east of England are rising and this rise is accelerating (average of 1.9±0.2 mm a^{-1} for 1800–2011 to 3.6±0.2 mm a^{-1} for 1993–2011; Wahl *et al.*, 2013), so the vulnerability of many parts of the UK to coastal flooding is increasing. One location in the UK where the risk of coastal flooding and erosion is particularly high is on the East Yorkshire coast, ~250 km north of London (Figure 1; Jorissen *et al.*, 2000; McRobie *et al.*, 2005; Skinner *et al.*, 2015). The orientation of the coast, particularly just north of where the River Humber enters the North Sea, leaves it particularly vulnerable to north-easterly North Sea storms and storm surges associated with them (e.g. Steers *et al.*, 1979; Lee, 2018). The effects of

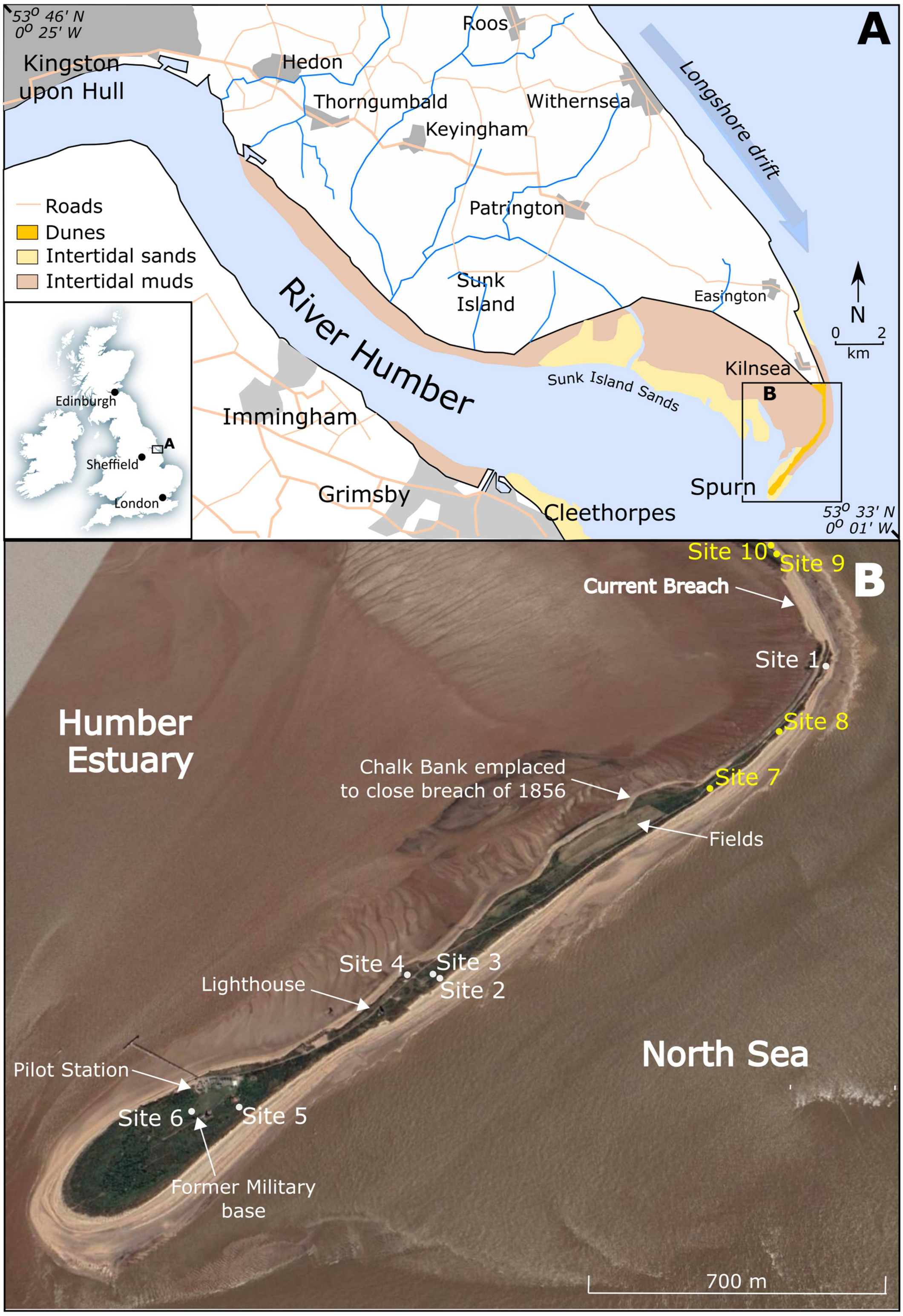

Figure 1. The coastal spit of Spurn Point. (A) Spurn and its relationship to the North Sea and River Humber. Also showing the important ports of Kingston upon Hull, Grimsby and Immingham. (B) Oblique view of Spurn and associated hinterland (CNES/Airbus image taken on 21 May 2019 from Google Earth) showing key points of reference and sampled sites. Vegetated areas unless otherwise stated are dunes. [Colour figure can be viewed at wileyonlinelibrary.com]

these are profound as the coast is low lying and comprises unconsolidated clay and sand-rich glacial diamict. As a consequence, the East Yorkshire coastal region experiences the highest coastal erosion rate in Europe, with cliff recession rates >4 m per year in places and an average over 1 m per year for the period 1852–2013 (Pye and Blott, 2015). Currently, the Humber estuary, and the settlements and docks at Immingham, Grimsby and Kingston upon Hull (Figure 1), are protected by a coastal spit at Spurn. Coastal spits, such as the one at Spurn, are particularly vulnerable to climatic change as they reply upon sediment supply to replenish eroded sediment (e.g. Kunte and Wagle, 1991; Mangor *et al.*, 2017). Spurn has been identified as one of the UK's most vulnerable coastal features (Kantamaneni, 2016). As shown by studies elsewhere, should Spurn erode away it could be expected that the tidal regimes along the estuary, wave action and water velocities would change, instigating higher levels of flooding, disruption to shipping, as well as changes in nutrient levels available for inland estuarine biota (van Heteren and van de Plassche, 1997; Boorman, 1999; Barbier *et al.*, 2011; Robins *et al.*, 2016).

This study aimed to get insights into the long-term history of a coastal spit system and the changing sediment dynamics associated with it. Spurn was chosen as a case study for this with a view to, for the first time, quantifying changes in the Spurn area through time using digitized historical map data in conjunction with optically stimulated luminescence (OSL) dating of dunes found on the spit .

Region of Study

Spurn, on the East Yorkshire coast, is a 5.5 km sand, gravel and cobble barrier which extends from Kilnsea south-westwards across the mouth of the Humber estuary in shallow (<10 m) water (Figure 1). Spurn is of national and international importance, being a designated Site of Special Scientific Interest (SSSI), Area of Outstanding Natural Beauty, a National Nature Reserve and falling within the Ramsar Convention for Wetlands in the Humber. It is also an outstanding example of a dynamic spit system (May, 2003). The spit at Spurn consists of three geomorphically distinct parts (see Figure 4B later for boundaries). The head is the southernmost point, currently ~350 m wide and, where not built on, covered with dunes up to >10 m ordnance datum (OD). The neck is <50 m wide and attaches the head to the anchor point of the spit where it joins the mainland. It is partly covered in dunes with a maximum elevation of ~3 m OD. The neck also includes a stretch where, due to storm erosion in 2013, it is currently inundated during extreme high tides, effectively cutting off the head from the mainland (Spencer *et al.*, 2015; YWT, 2019). The anchor, underlain as it is by glacial diamict, has a thin sand covering only. Wave energy on the River Humber side of the spit is lower, which has allowed the development of inter-tidal mudflats and saltmarsh.

The East Yorkshire coast from Flamborough Head to the Humber estuary forms a single coastal sedimentary cell (Cell 2b of Motyka and Brampton, 1993) and is macrotidal with a mean spring tidal range of 5.7 m (HR Wallingford, 2003). The dominant wave direction is from the north-north-east and north-east and has a large swell component due to the large fetch (~900 km; ABPmer, 2009). Wave heights of 1.0–1.5 m are not uncommon, with storm heights reaching 4–8 m (Halcrow, 1988). In terms of sediment supply, this is moved to Spurn by erosion of the glacial diamict found along the East Yorkshire coast to the north (Ciavola, 1997). Whilst much of the eroded sandy material (94%) is transported off-shore, some is moved back on-shore (Ciavola, 1997). Southward movement of the sandy sediment takes place along the beach by long-shore drift within 2 km of the shore at a rate of 500 m a^{-1} (Ciavola, 1997; HR Wallingford, 2003). The form of the spit is strongly controlled by this wave-driven southwards coarse-sediment transport system and the Humber estuary's tidal flow, which intercepts the southerly sediment supply, moving the transport pathway off-shore (HR Wallingford, 2003). Wave refraction from the south-east allows sediment to round the head of the spit and for it to be transported northwards on the estuary side up its western shore (e.g. Ciavola, 1997).

Written records suggest that Spurn has existed at least since 600 AD (de Boer, 1964). Early maps confirm that Spurn's current form of a neck and a head have persisted for at least 300–400 years (e.g. de Boer, 1964; East Riding of Yorkshire Council, 2006). Evidence shows that there have been periodical inundations of Spurn by the sea, creating overwash plains on the neck, and breaching the spit. For example, in 1849 a breach 460 m in width and 4.9 m in depth (sufficient for a boat at high tide to sail through) was recorded (de Boer, 1964). In 1851 a second breach over 120 m in width occurred and in 1856 a third breach of >70 m in width and 4 m in depth happened (de Boer, 1964). These breaches had to be artificially closed with chalk to maintain access to the lifeboat and lighthouse stations on the head. In 2013, the most recent breach of Spurn caused the neck to become temporarily but not permanently inundated, with subsequent sedimentation allowing overwash only on the highest tides or during storms. Based on documented breaches, de Boer (1964) proposed that the whole of Spurn spit evolved in a cyclical pattern of breach and rebuild every 240–250 years. These cycles he proposed started in c. 1100, 1360 and 1610, with a final one starting in 1860. He also suggested that as the East Yorkshire coastline eroded back (westwards), the spit also moved westward into the Humber estuary, where it is partially protected from high-velocity winds and storm-wave conditions (de Boer, 1964, 1969, 1981). Recently, Lee and Pethick (2018), based on visual examination of maps, failed to recognize the cycles of de Boer, including the 1610 breaching event, but did find evidence of some limited westward movement of the neck since 1684. The inconsistencies between these studies cause ambiguity when considering the future of Spurn and its management.

Methods

Historical mapping

The use of historical maps to understand past changes in coastlines is not new. For example, Kelley *et al.* (2005) successfully used historical maps to give a longer-term perspective on coastal sediment movement for the Saco Bay area, Maine, USA. Likewise, Lee and Pethick (2018) also used observations from historical maps to try and understand the historical evolution of Spurn. Whilst such approaches are useful to highlight some changes, quantification of these and other less obvious changes were not able to be undertaken in either study. GIS is widely used to relate changes in attributes and space at local and global scales but the analysis of the relationships between space, attribute and time has been more problematic (Gregory, 2005). Historical GIS (HGIS) is a relatively recent approach, which, through geo-referencing, allows historical and contemporary data sets to be overlaid for direct spatial comparison and analysis (Knowles, 2014). As an approach to monitoring long-term (decadal and longer) changes in geomorphic features, it has been successfully applied to historical coastline changes – for example in the US Gulf of Mexico, SW France, Puerto Rico and Denmark (Thieler and Danforth, 1994; Morton *et al.*, 2005; Allard *et al.*, 2009; Kabuth *et al.*, 2014).

In order to apply the HGIS approach to Spurn, historical maps and aerial images were acquired from DigiMap, Spurn Discovery Centre, East Ridings Archives (Treasure Centre) and the Hull History Centre. From the acquired map collection, a total of 24 maps were used spanning from 1577 to 2018. As the exact date of mapping is not always given for older maps, so maps are referred to by their publication date which may have been some years later. Maps were converted and digitally uploaded into ArcMap software (see online Supporting Information for more details). These were then overlain onto the 2013 (10 m resolution) raster image downloaded from DigiMap. The type of map utilized dictated how many geo-referencing points could be used. Ordinance Survey (OS) maps contained grid references, allowing good geo-referencing. For older maps, geo-referencing relied on features such as road networks, land divide lines and buildings, which were consistent between multiple maps. In these cases, a minimum of three widely spaced points were used to minimize distortion errors. Where maps contained less than three accurate geo-referencing points, they could only be scaled using the scale bar, preventing their direct comparison with geo-referenced maps. Maps which fell into this category dated to 1797, 1774, 1768 and 1734.

Once digitized, outlines were produced for all selected maps using the 'change polygon' approach of Smith and Cromley (2012) – although given the relatively small area of interest, an automated methodology was not employed. Instead, polygons were visually created following either the high-tide line or, where this was not available on earlier maps, the land outline. The high-tide line was used as it is the *average* high-tide line, consistent in being mapped on most maps (important for a comparative study). Any lateral changes in the high-tide line position would have been relatively small (estimated at <1.5 m in the last 200 years) due to the steep beach profiles created by the destructive waves on this coastline.

Errors from surveying, annotation, map distortion and geo-referencing are acknowledged but are hard to quantify (e.g. Tucci and Giordano, 2011). Quik and Wallinga (2018), whilst studying historic river meander changes in the Netherlands, quantified geospatial uncertainties of 27 to >100 m. We suggest that such levels of uncertainty are probably applicable to the pre-1818 mapping and difficulties associated with scaling these earlier maps but are lower for the post-1818 geo-referenced maps. Whereas historical mapping of coastlines may often have been from sketches rather than triangulated surveys, this may be less of an issue for Spurn. From at least the 17th century, Spurn was of great significance for shipping-based trade associated with the major ports of Immingham, Grimsby and Hull, offering both shelter in storms and a hazard to be avoided. Its military significance was recognized since the beginning of the 19th century, when gunnery bases were established on it. Accurate mapping of this feature and the surrounding waters was therefore of much greater importance commercially, militarily and in terms of navigation than would generally have been the case for most coastlines. It therefore benefitted from triangulation points at Kilnsea, Spurn Point, Spurn Lighthouse and off-shore on Humber Fort. We argue that the mapping errors therefore should be low. The systematic quantification of geospatial errors used by Quik and Wallinga (2018) relied on multi-point ground control points ($n = 8$–35). This is suitable for a intensively developed area but less applicable for Spurn, with its limited occupation and relative remoteness, so was not adopted. We estimate therefore that for the geo-referenced maps from 1818 onwards, uncertainties are in the order of ±11 m as derived for a regional (7000 km of coastline) study by Kabuth *et al*. (2014).

For geo-referenced maps from 1818 onwards, Spurn was also divided into the anchor, neck and head sections to allow for both whole and more detailed comparisons of area change (Figure S3). The anchor boundary was defined as the boundary between glacial diamict and sand, as mapped by the British Geological Survey. The neck was defined as south of this, until the land broadened to >150 m wide. The head was defined as all land south of the neck. Area was calculated for all the map outlines, allowing for general patterns of change to be analysed, as well as more localized changes.

Luminescence dating

In coastal spit contexts, dating dune initiation gives a minimum age of the spit. Phases of dune building/erosion may also indicate net sediment supply and impacts of storms (Bateman *et al*., 2018). Storms can also cause enhanced sediment movement into the near-shore and beach environment which, after a lag period, could lead to invigorated dune building. As part of this study, luminescence dating methods were employed in order to establish the age of different parts of the spit. Such an approach was taken by Fruergaard and Kroon (2016), who investigated the impact of the 1634 storm in Denmark using both OSL and historic maps.

A total of six sites on Spurn were selected for dating purposes (Figure 1B). At all sites, cores were drilled into the dunes using a Dormer Engineering sand auger system. Site 1 was selected from prominent dunes facing the North Sea at the narrowest mid-part of the neck and an OSL sample retrieved from 1.8 m below the surface (Figure 2). Sites 2 and 3 were from North Sea-facing shore-parallel dunes and the interdune, respectively on the southern end of the neck. Site 2 was located in a dune whose crest was 6.7 m above sea level, from which a 6.0 m core down to the current high-tide level was obtained. From this an OSL sample was obtained from 80 cm above the base (Figure 2). Site 3 was cored down to 2 m from the surface, at which point impenetrable clastic material was encountered which was interpreted as relating to a former beach deposit. An OSL sample was collected 30 cm above the beach deposit. Site 4 was located nearby at 6.7 m above sea level in a large dune near the site of the former lifeboat Inn on the estuary side of the spit (Figure 1B). Here, coring drilled through 4.5 m of sand before hitting impenetrable clastic material which was interpreted as relating to a former storm beach. An OSL sample was collected from 1.4 m above the beach sediments. Site 5 was located on the North Sea-facing side of the head. Here, a core of 6.7 m was drilled to an OSL sample from 30 cm above the beach material. Site 6 was located in the centre of the head of the spit and an OSL sample obtained 3.5 m from the surface to avoid any sediment affected by World War II disturbance (Crowther, 2006).

For the luminescence ages, quartz grains were extracted and cleaned as per Bateman and Catt (1996). The palaeodoses were measured at the single aliquot level (9.6 mm diameter) using OSL within a Risø DA-18 luminescence reader using the single aliquot regeneration (SAR) protocol as per Murray and Wintle (2003). Dose rates for the luminescence ages were based (where available) on field gamma spectrometry measurement or inductively coupled plasma mass spectrometry measurements and were attenuated for grain size and present-day moisture contents (Table I). Ages are quoted in years in the Common Era (CE) with one sigma uncertainties (see online Supporting Information for more details).

Results

Historical mapping

Eight historical maps spanning 1577–1797 could only be scaled not geo-referenced (Figure S2). These showed huge variability in shape and size of Spurn over short time periods, ranging from the spit occupying 10.9 km^2 in 1610 to only 0.7 km^2 in 1768. Differences also look large between the most recent scaled map of 1797, which showed the spit area to be 5.5 km^2, and the first geo-referenced map, from 1818, which showed it to be 1.5 km^2 in area. This variability may reflect the accuracy of the original mapping and/or difficulties associated with scaling these earlier maps. As such, maps prior to 1818 were not included in more detailed analysis.

Fifteen maps spanning the period 1818–2018 were geo-referenced (Figure S3). One of the most striking things apparent from the new digitized mapping is the overall

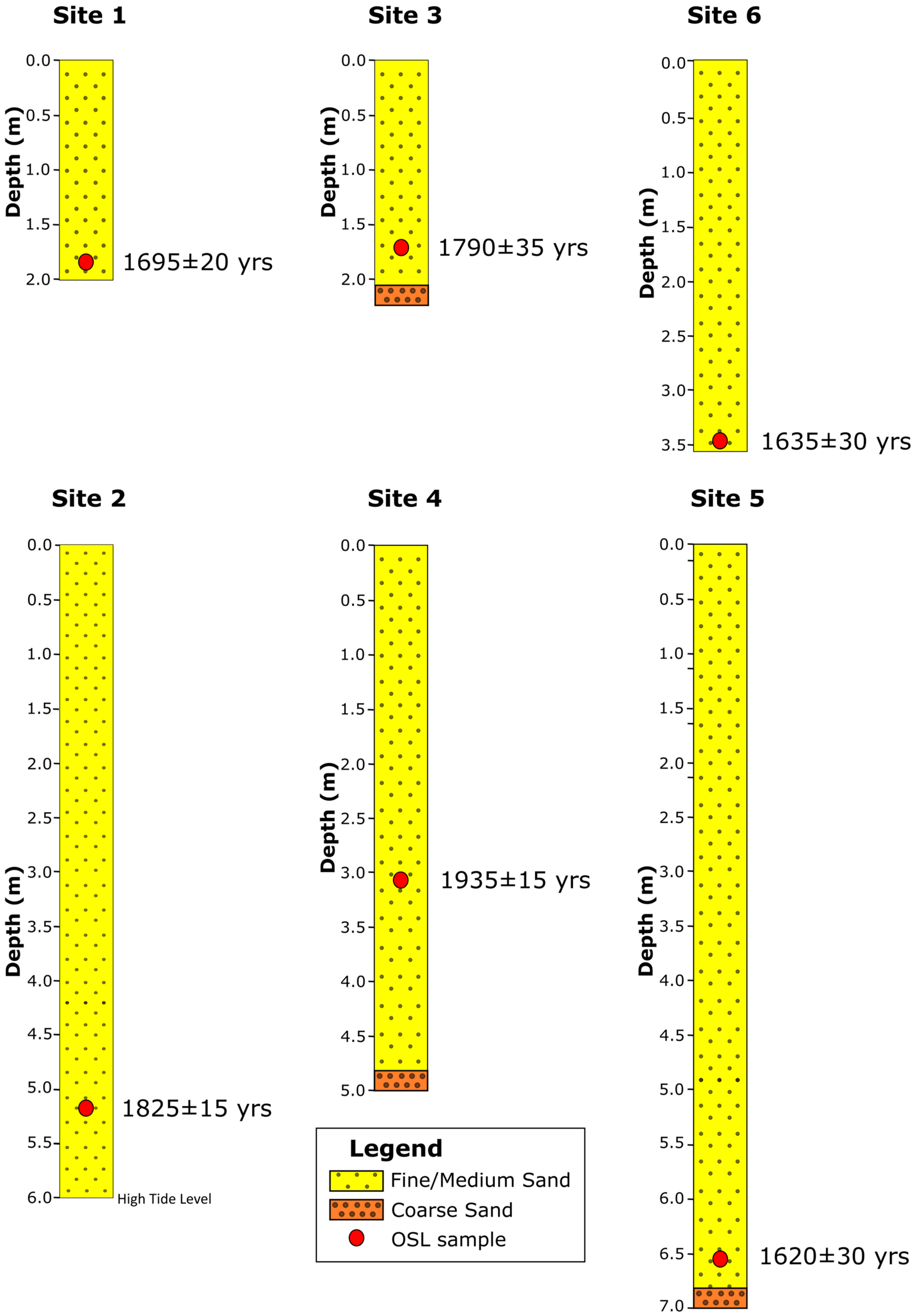

Figure 2. Cored and sampled dune stratigraphy from Spurn. Also shown are basal OSL ages (shown in years CE). [Colour figure can be viewed at wileyonlinelibrary.com]

consistency of the position and alignment of the spit. Figure 3 shows the Spurn digitized map outlines overlain on one another to track spit evolution through time. This shows that Spurn has also extended south-westerly since the 1860s, but not continuously. The speed of this extension has varied, being rapid in the periods 1864–1885 (when it extended ~160 m), 1947–1960 (when it extended ~100 m) and 1980–1991 (when it extended ~75 m). Between these periods, spit extension was minimal or in the case of 1928–1947 and 1973–1980, reversed. A net extension south-westwards of ~330 m has taken place since 1864. The final element shown in Figure 3 is that both the neck and head of the spit were more variable in the period 1818–1910. Whilst the neck remained fairly variable in plan form during the period 1910–1970, except for the spit extending, the form of the head appears to have stabilized. In contrast, the mapping clearly indicates the ongoing coastal erosion of the North Sea side of the anchor, which between 1818 and 1910 was continual (Figure 4C). Of note is the period 1910–1973, in which coastal erosion reduced before it increased again.

Of the 200 years spanned by the new geo-rectified data, spit breaching has only been captured in 1855 and 1864, conforming to documentary evidence. Other overwash events or short-lived (minor) breaches may have been missed by the approach taken to compile this data. This is exemplified by the recent overwash event in January 2013, which does not appear on the 2018 map. By 2018, spit upper beach regrowth has been sufficient for the overwash throat to have infilled and for the mean high-tide mark (used for polygon mapping in this study) to re-establish itself, even though overwashing

Table I. OSL-related data for basal samples from Spurn dunes

Sample site	Sample code	Depth from surface (m)	Water content (%)	K (%)	U (ppm)	Th (ppm)	Cosmic dose rate (Gy a^{-1})	Total dose rate (Gy a^{-1})	D_e (Gy)	Age (years CE)
Site 1	Shfd05117	1.8	3.8	0.45	0.88	2.9	0.19±0.01	0.99±0.04	0.30±0.03	1695±20
Site 2	Shfd13026	5.2	2.6	0.4	1.21	2.9	0.11±0.01	0.98±0.04	0.19±0.02	1825±15
Site 3	Shfd12028	1.7	6.3	0.5	0.88	2.3	0.17±0.01	0.97±0.04	0.22±0.03	1790±35
Site 4	Shfd12024	3.1	1.9	0.5	1.39	2.1	0.14±0.01	1.10±0.04	0.09±0.01	1935±15
Site 5	Shfd19042	6.4	3.2	0.4	0.60	1.7	0.09±0.01	0.74±0.03	0.30±0.02	1620±30
Site 6	Shfd05119	3.5	4.2	0.45	0.88	2.9	0.13±0.01	0.95±0.04	0.36±0.03	1635±30

during storms still takes place. Future work could utilize the more frequent production of maps, newspaper articles and imagery over the last 30 years to provide more detailed recording of overwash events and impacts of individual major storm events.

Luminescence dating

The OSL age obtained from the base of the dune at site 1, on the neck of the spit, returned an age of 1695 ± 20 years CE. On first appearance this is surprisingly old given the variability of the neck as shown by the historical mapping (Figure 3). However, when all the historical maps are overlain, as per Figure 4A, it becomes apparent that the sampled dune at site 1 is part of a small area which appears on all maps back to 1818. This area is probably the last vestige of the neck which previously was curved eastward of it before 1734 and subsequently has been eroded.

At site 2, from a dune on the North Sea side of the neck, the OSL age obtained was 1825 ± 15 years CE. As the underlying beach was not encountered here and the sample is 80 cm above the current high-tide line, emergence of the spit here may have been considerably earlier. Such an interpretation is supported by site 3, located just inland from site 2, from which an age of 1790 ± 35 years CE was obtained just above the beach material. Site 4, from a dune on the Humber estuary side of the neck of Spurn, shows a very different and younger record with a basal age of 1935 ± 15 years CE.

At sites 5 and 6 on the head of Spurn, the basal dune dates obtained were 1620 ± 30 and 1635 ± 30 years CE. Their antiquity fits with the long-term stability of these sites, as shown from the historical map data (Figure 4D). As the cores in both cases bottomed out at beach material, these ages indicate the establishment of the head of the spit at these localities just prior to 1620.

Discussion

Historical mapping

The early scaled maps show that part of the head, as well as the anchor, have existed from at least 1577. They also show the variability of the neck. This was initially aligned to the East Yorkshire coast and then extended slightly eastward of the coastline. By 1734 it had taken on the more south-western alignment that it still has today. Of possible note is the thinness of the depicted neck in 1768, which may indicate that severe erosion led to overwashing or a breach at some point just prior to this time (but after 1736). A severe gale causing coastal flooding was reported for a storm hitting the east coast of England on 19th January 1734 (Figure 5; Kington, 2010). This was followed 2 years later by a storm which caused a tidal surge, breached sea walls and made thousands homeless between Lincolnshire and Kent (Harland and Harland, 1980). Such closely spaced storms would have caused spit erosion and given that there would have been a lag between mapping and the publication of the map, the effects of these storms may be what is represented in the map of 1768.

One of the most striking things apparent from the new digitized mapping from 1818 onwards is the overall consistency of the position and alignment of the spit. De Boer (1964), without map digitization, rescaling or geo-referencing, identified ~1.25 km of westward migration of Spurn between 1350 and 1850. Lee and Pethick (2018) proposed a much smaller 500 m westward migration of the spit between the late 1600s and

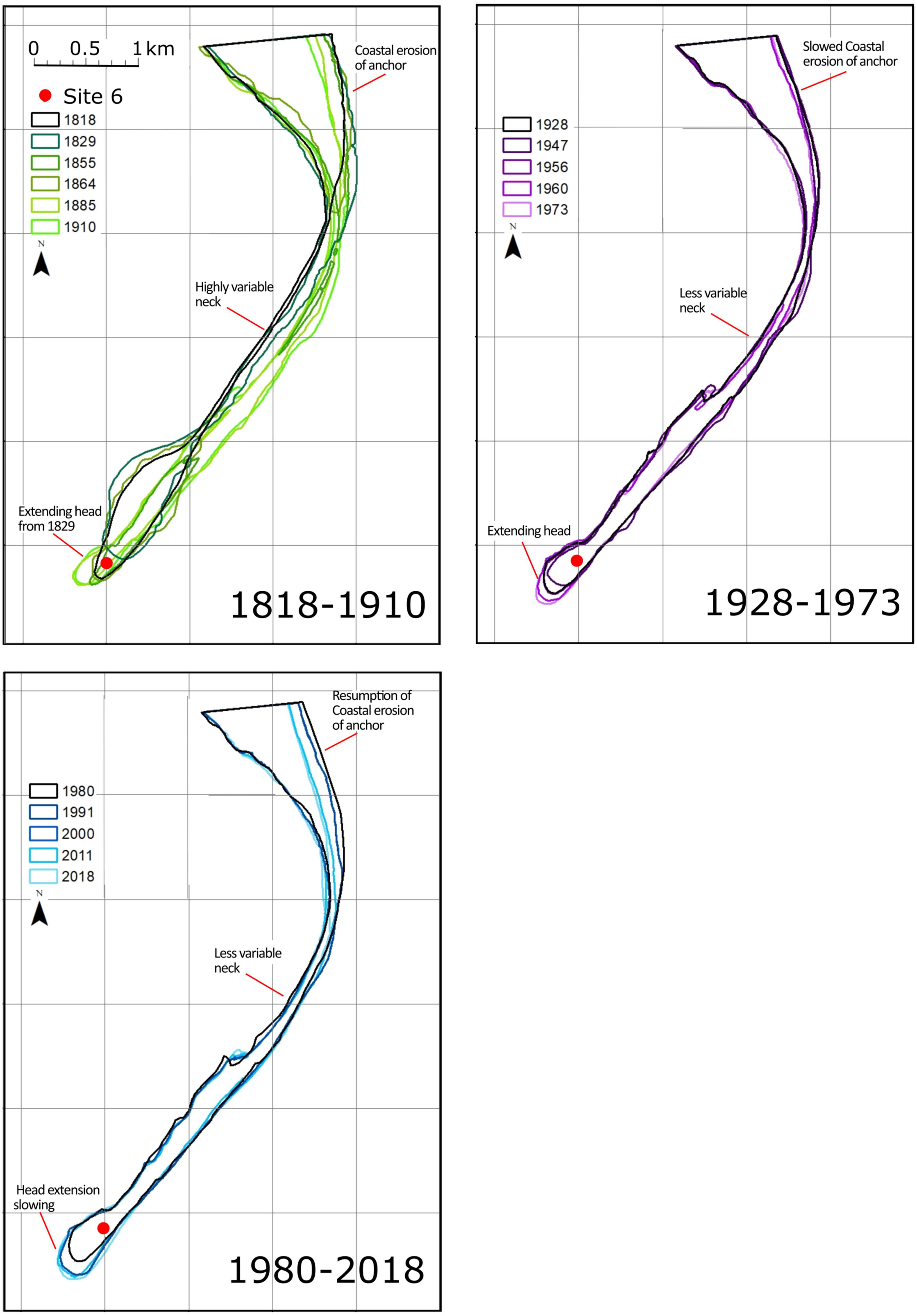

Figure 3. Overlays of long-term evolution of Spurn based on historical mapping and aerial imagery. Clearly depicted is the long-term coastal erosion on the North Sea side of the anchor. Also shown is the extension south-westwards of the head over the last 100 years. [Colour figure can be viewed at wileyonlinelibrary.com]

the mid-1800s. They related this migration to the extensive land reclamation schemes (covering 65 km^2) which took place in the Humber estuary in the early 1600s and late 1700s (Figure 5). These closed the Humber North channel around Sunk island just west of Spurn and forced the Humber tidal flood system southward, allowing more sediment accommodation space around Spurn. The new digitized and geo-referenced maps for the period 1818–1856 show that both the anchor and the head, whilst changing in plan form, held overall position throughout this period. Any small-scale westward migration therefore must have taken place prior to 1818.

That the new mapping shows an overall consistency of the position and alignment of the spit from 1818 onwards may reflect anthropogenic impacts as well as natural processes

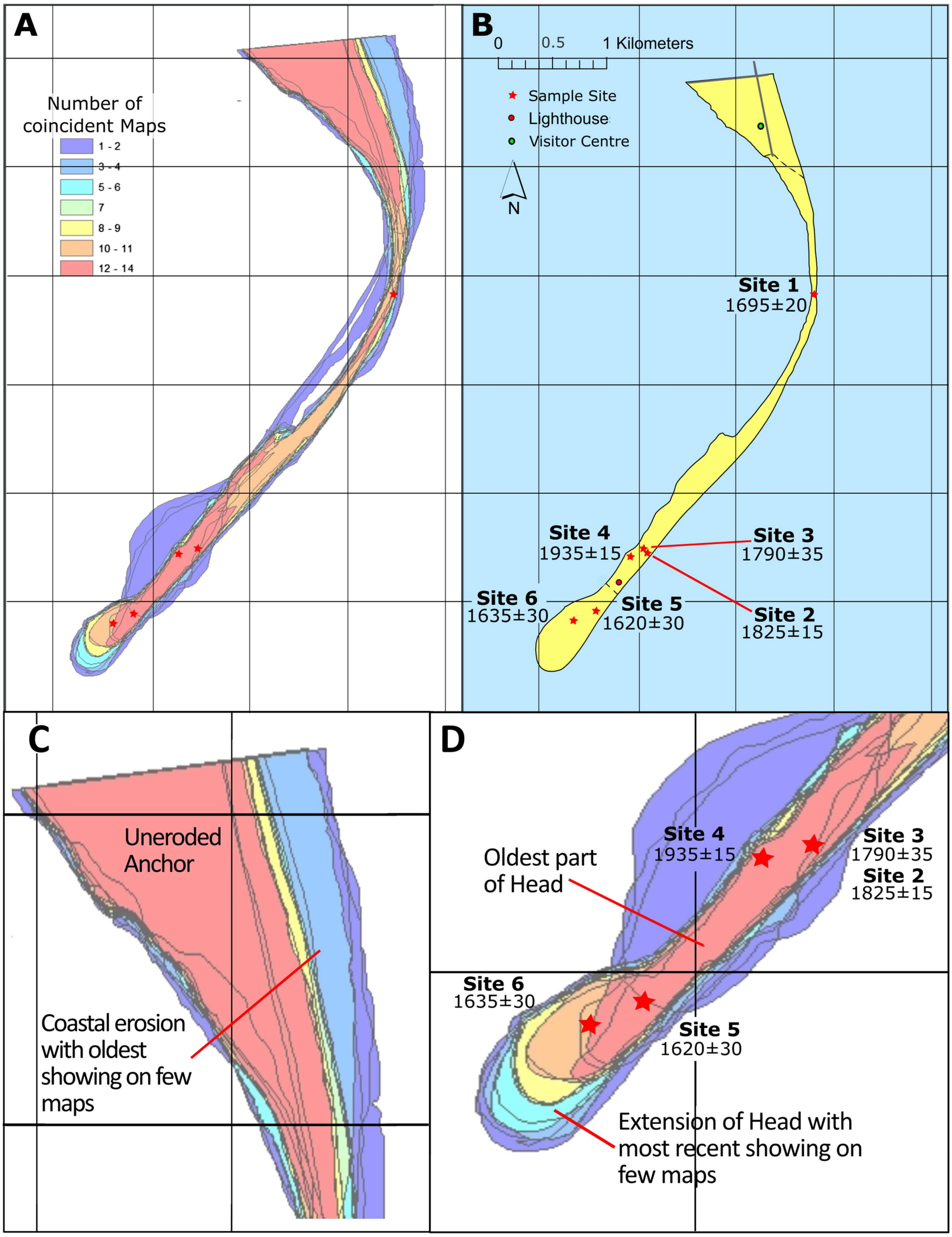

Figure 4. Evidence of long-term stability of parts of Spurn. (A) Map overlays between 1818 and 2018 with stable parts of the spit indicated by higher coincidence of maps (yellow–red) and areas of erosion, recent accretion or more variability indicated with lower frequency of appearance on maps (purple–green). (B) Results of the OSL dating programme with ages shown in years CE. (C) Inset of anchor showing stable uneroded part in red and the effects of ongoing coastal erosion reflected in increasingly fewer maps overlapping. (D) Inset of head showing oldest part in red and ongoing spit extension reflected in increasingly fewer maps. [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 5). Documents show that significant anthropogenic efforts were made to stabilize the spit after the breach events of 1849–1856. Gravel extraction from the spit was banned in 1854 although it continued in a reduced form until the early 20th century (Lee and Pethick, 2018). Breaches were filled with (less erodible) chalk blocks on the estuary side (de Boer, 1981). From 1853, revetments and groynes were constructed until, by 1926, there were groynes along the length of the spit on the North Sea side of the neck and head (Trinity House, 1940; Crowther, 1997). Finally, sand trapping behind installed wattle fences led to the creation of more dunes which were artificially planted with marram to stabilize them. By 1878 the groynes and dune creation efforts had led to a wide (~90 m) beach on the North Sea side and established dunes ~50 m in width extending over 3 km along the neck (Pickwell, 1878 cited in Lee and Pethick, 2018). Groynes and revetment structures have not been maintained and have failed during the latter half of the 1900s. This appears to have caused more variability in sediment accretion and erosion, particularly in the neck, for the period 1980–2018.

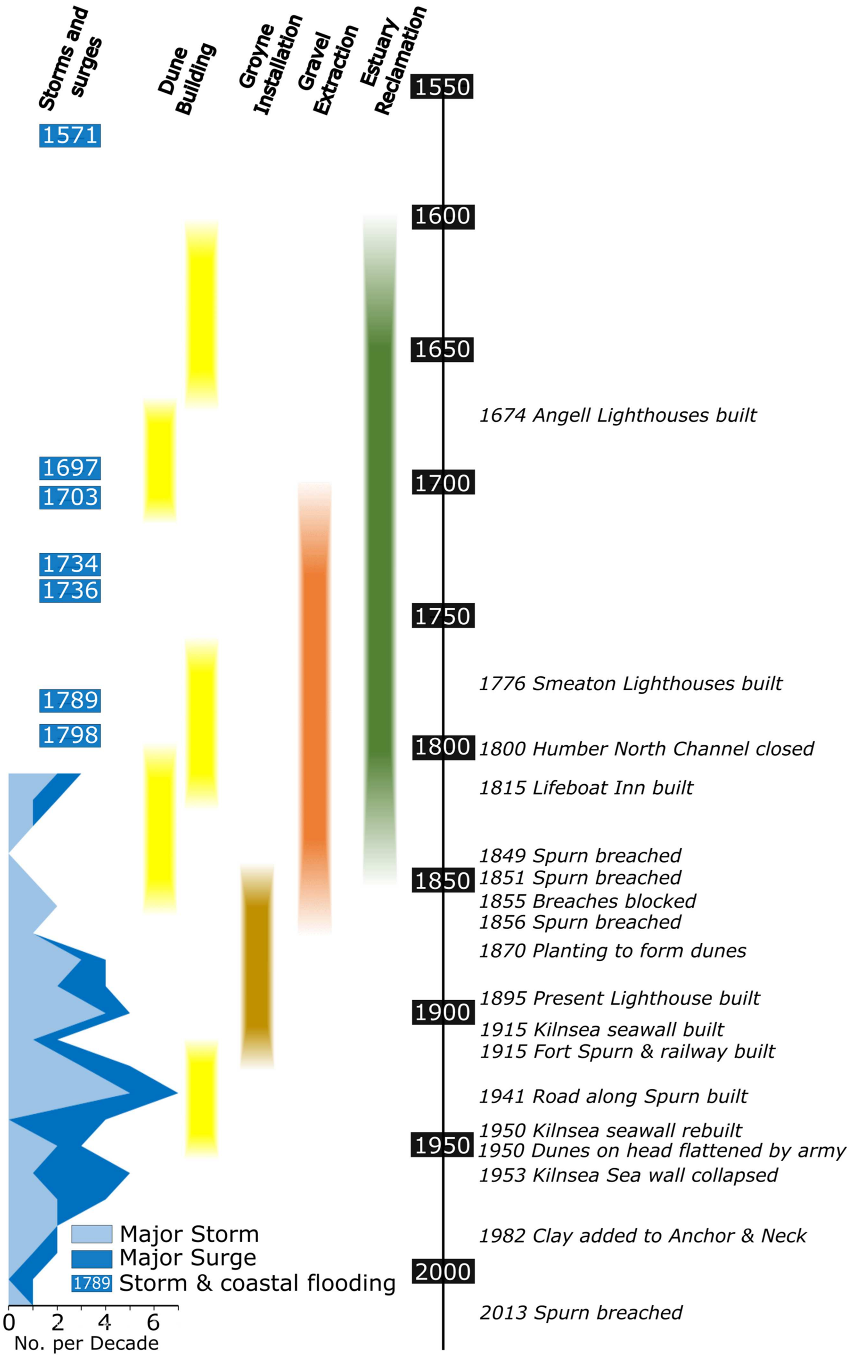

Figure 5. Summary of key events which have influenced the evolution of Spurn over the last 500 years and referred to in text. Storms and surge data from Steers *et al.* (1979), Harland and Harland (1980), Kington (2010) and Lee (2018). Dune building based on OSL dating in this study. Groyne construction, gravel extraction and estuary reclamation taken from Crowther (2006). [Colour figure can be viewed at wileyonlinelibrary.com]

Lee and Pethick (2018) proposed that the dominant trend for Spurn since the 1680s has been south-westerly lengthening with progressive accretion across the nearshore zone. The earlier scaled maps presented here do support an extension of Spurn in the late 1700s when marsh reclamation was happening. The geo-referenced maps show that the speed of this extension has varied through time, with a net extension south-westwards of ~330m since 1864 (Figure 3). The period of rapid extension between 1947 and 1960 is supported by the remains of military bunkers and search lights built in the Second World War, which would have overlooked the River Humber and are now inland surrounded by dunes (Figure 1B).

The lull between 1910 and 1973 in the ongoing coastal erosion of the North Sea side of the anchor (Figure 3) is attributed to the construction in 1915 of the Godwin Battery at Kilnsea with a 275m-long sea wall protecting the erodible cliffs (Figure 5; Lee, 2018). It would appear that once a replacement wall built in 1950–1952 was badly damaged in a storm surge in 1953 (Crowther, 1997; Lee, 2018), coastal erosion once again increased.

Luminescence ages

Sites 1, 5 and 6 all showed dune initiation at ~1620. As coarser beach material was found at the base of the cores at sites 5 and 6, this dune-building phase may have formed just after the creation of the head/neck as the spit extended. Just prior to this was the 5th October 1571 storm, which is documented to have caused extensive coastal flooding from Dover to the River Humber (Figure 5; Harland and Harland, 1980). This storm would also have caused significant coastal erosion from which a newly emergent spit could have formed when sediment was moved down the coast and back on-shore.

Elsewhere on the neck, site 4 had an age of ~1935, site 3 an age of ~1790 and nearby site 2, which is closer to the sea, an age of ~1825. Emergence of the spit at this point only just prior to 1790 (the OSL age from site 3 was 30 cm above beach material) appears unlikely given older ages from the head and on the neck to the north (site 1), the stability of this spit as shown in the mapping (Figure 3D) and these sites' proximity to the former Lifeboat Inn which was built in 1819 (Figure S3). Site 4 was proximal to the route of the former Spurn and Kilnsea military railway (built in 1915) and may be too young due to it having been excavated out during its construction (Crowther, 2006). Its basal age probably reflects that by the 1930s sediment transport, which had been slowed by the installation of the inter-tidal groynes in the 1850s–1920s, was once again able to make its way round the head of Spurn for on-shore south-westerly winds to move and form dunes. Sites 2 and 3 may reflect localized erosion of the spit that followed dune regrowth. Between the ages of the two sites it is noted that five documented major storms and two tidal surges occurred (Figure 5; Steers *et al.*, 1979). Dune regrowth at site 2 could reflect sediment released during the storms and then transported down-coast and moved on-shore.

In summary, the basal dune OSL ages suggest Spurn in its current form appears to have initially formed in the early 17th century. This fits with Pye *et al.* (2007), who reported (based on documentary evidence) that extensive marram-covered dunes had formed along the entire length of the spit by the late 18th century.

Accretion and erosion around Spurn

Digitization of the historical map record allowed an examination of where along the spit erosion and accretion was occurring through time. This was undertaken by comparison of time-adjacent map pairs. Areas in the first of the paired maps showing as sea but mapped as spit in the second map were classified as accretion. Areas in the first map mapped as spit but showing in the second map as sea were marked as erosion (Figure 6). GIS tools were used to measure both accretion and erosion in terms of area (Table II). As the time span covered between map pairs varied, in order to calculate area change data between mapped periods, changes were calculated as a 10-year average (the average remapping frequency after 1885) to make comparisons possible. Given that the anchor, neck and head appear to respond differently through time (Figure 3), rather than taking a chronological approach, each of these parts of the spit are discussed in turn before trends between them are considered. It should be noted that whilst the anchor–neck boundary is fixed through time as the boundary between diamict and sand, the neck–head boundary depends on the width of the spit exceeding 150 m. Some co-variance between the size of the neck and head should be expected due to this.

As expected, the anchor part of the spit shows slow but steady long-term erosion with a net loss of 0.38 km^2 between 1818 and 2018. Decadal changes (in both accretion and erosion) are mostly less than 0.05 km^2 (Figures 6 and 7, Table II). The long-term erosion trend was interrupted only in the period 1818–1829 by modest accretion (the only decade when the whole spit appears to have grown) and in 1973–1980 (Figure 7).

The neck shows a net accretion of 0.38 km^2 between 1818 and 2018 but much larger variability decade on decade (Table II, Figures 6 and 7). The neck appears to have attained its largest areal extent in 1885–1910, after which it reduced. Erosion of the neck in the 1850s is the only time the whole spit was eroded and is coincident with major storms between 1849 and 1856 which caused the spit to be breached (Figure 6; Trinity House, 1940). Significant accretion on the neck between 1864 and 1910 coincides with human intervention and the installation of coastal groynes and artificial dune creation (Figure 6). Erosion between maps published in 1947 and 1960 probably reflects the erosion that took place from the 1942 and 1953 storms. The 1942 storm surge is documented to have caused severe erosion on the eastern shoreline (de Boer, 1981). The 1953 storm, whilst failing to breach Spurn, did cause extensive damage to the Kilnsea sea wall and erosion of the dunes (Crowther, 2006). Whilst sediment moved on-shore in 1960–1980 allowing the spit to grow again, since that time it has been steadily declining in size.

The head shows large decade-on-decade variability and, despite its stability in terms of position and its extension to the southwest, a slight net erosion of 0.16 km^2 over the period 1818–2018 (Figures 6 and 7; Table II). The head shows significant erosion in the period 1828–1855 (as elsewhere on the spit) associated with the breaching event and cut-off of sediment supply. Growth was slow in the period 1855–1928 as sediment was intercepted on the neck by the newly installed groynes. Significant accretion occurred in the period 1956–1960 and significant erosion in the period 1960–1980. The 1960s saw four major storm surges (Steers *et al.*, 1979) followed by a major storm surge in 1978 (Lee and Pethick, 2018). These may account for the erosion of the head in this period (Figure 7).

Initially, the timing of the erosion and accretion of the head appears at odds with that occurring on the neck. This is probably partly an artefact of the neck–head boundary moving through time, as combined the neck and head show a net accretion of 0.23 km^2. However, the head is at the effective end of the sediment transport pathway and largely driven by what happens further up-current. With a long-shore drift rate of 500 m a^{-1}, sediment eroded at the north end of the neck could be at the southerly tip of the neck within 8 years. Erosion from the head does not look like it is followed with significant movement of sediment back on-shore leading to accretion, presumably because the near-shore zone shelves more steeply here and tidal currents are high enough to sweep sediment away. This loss drives the overall size of the spit. The map data also show that most of the time erosion and release of sediment from the East Yorkshire coastline and the anchor leads to a sediment influx to the North Sea side of the neck (Figure 8A). This then passes through to the head where it is either moved off-shore or more permanently accretes at the end of the Humber estuary side of the spit, allowing for spit extension (Figure 8A). However, the data also show that during breach events this sediment transport switches as sediment is able to move to the Humber estuary side of the spit when crossing the breach zone (Figure 8B). This leads to a significant accretion of sediment on the Humber estuary side of the head. However, once the breach is filled, this newly accreted sediment appears not to last as it is rapidly eroded away or blown inland as dunes.

Increasing sea levels of 0.64 ± 0.38 mm a^{-1} between 1960 and 2006 at nearby Immingham (Woodworth *et al.*, 2008) might have been expected to cause more spit erosion. There is some evidence for this, with the spit area showing a small decrease in size over the last 200 years of 0.160 km^2 (Table III) and this may be accelerating. Whilst within errors, the average decadal change for the 200-year period is 0.01 ± 0.18 km^2 compared to -0.02 ± 0.12 km^2 for the last 100 years, and -0.04 ± 0.15 km^2 for the last 50 years. This warrants further, more intensive monitoring to verify. As well as erosion and accretion of

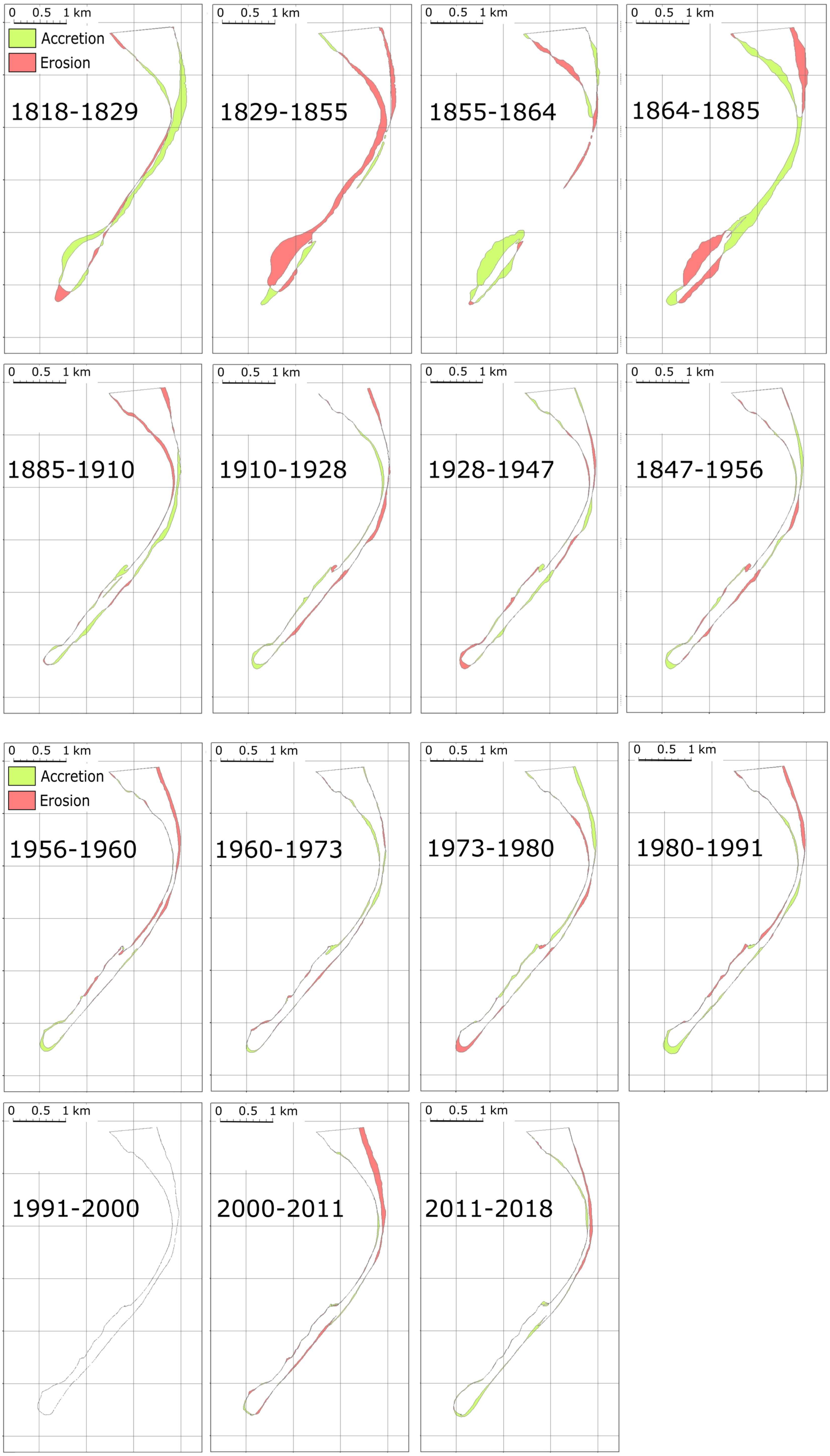

Figure 6. Are as of accretion and erosion on Spurn from 1818 to 2018 based on paired historical maps and more recently, aerial imagery. [Colour figure can be viewed at wileyonlinelibrary.com]

Table II. Incremental net area change from 1810 to 2020 subdivided by geomorphic parts of spit. Changes >10 m^2 are highlighted with increases in green (accretion) and decreases in red (erosion). Dark shading indicates greater than 1 standard deviation from the average for that geomorphic part. Area has been calculated from geo-rectified historical maps and imagery. Changes have been adjusted to per decade to account for the different number of years between maps

Mapped period (years CE)	Anchor (km^2)		Neck (km^2)		Head (km^2)	
	Area	Change per decade	Area	Change per decade	Area	Change per decade
2011–2018	0.45	−0.01	0.64	−0.03	0.28	0.10
2000–2011	0.46	−0.10	0.66	−0.09	0.21	0.00
1991–2000	0.57	0.00	0.76	0.00	0.21	0.00
1980–1991	0.57	−0.06	0.76	−0.01	0.21	0.06
1973–1980	0.63	0.09	0.78	0.05	0.14	−0.07
1960–1973	0.57	0.00	0.74	0.33	0.19	−0.29
1956–1960	0.56	−0.15	0.31	−1.15	0.57	1.00
1947–1956	0.63	0.00	0.77	−0.06	0.17	0.07
1928–1947	0.62	0.01	0.83	0.02	0.11	−0.02
1910–1928	0.61	−0.02	0.80	−0.02	0.15	0.03
1885–1910	0.64	−0.03	0.84	0.04	0.10	0.02
1864–1885		−0.04		0.30		0.03
1855–1864	0.71	−0.03	0.75	−0.09	0.07	0.07
1829–1855	0.82	−0.01	0.20	−0.15	0.21	−0.15
1818–1829	0.89	0.05	0.52	0.24	0.53	0.08
1818	0.83	–	0.26	–	0.44	–
Total change	**−0.38**		**0.38**		**−0.16**	

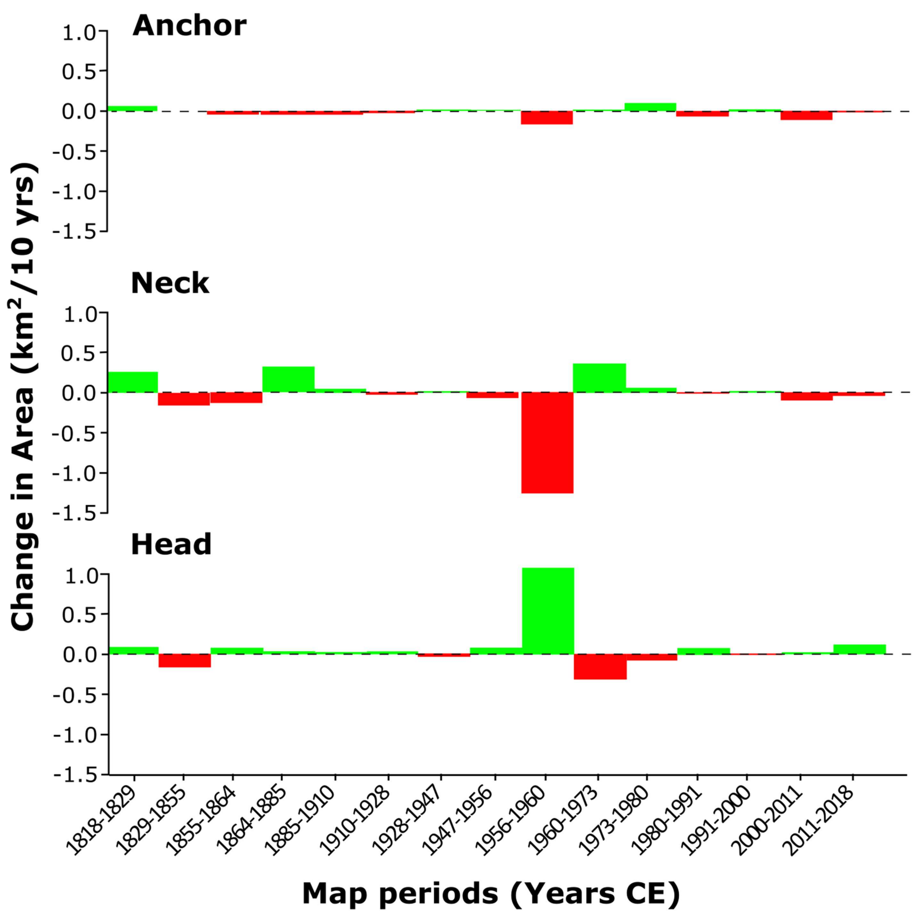

Figure 7. Summary of net changes per map period in terms of erosion (red) and accretion (green) by different geomorphic parts of Spurn. As the period between maps varies, the values have been adjusted to per decade to allow comparison. [Colour figure can be viewed at wileyonlinelibrary.com]

the neck and head being inter-related, there may also be underlying cyclicity to the size of Spurn. Following a decade of net erosion (as indicated in red in the right-hand column of Table III), the spit recovers by slowly accreting for 20–30 years (as indicated in green in the right-hand column of Table III) before another period of erosion. For example, net erosion took place in the 1950s followed by net accretion in the 1960s and 1970s. Only three 30–40-year cycles have taken place in the

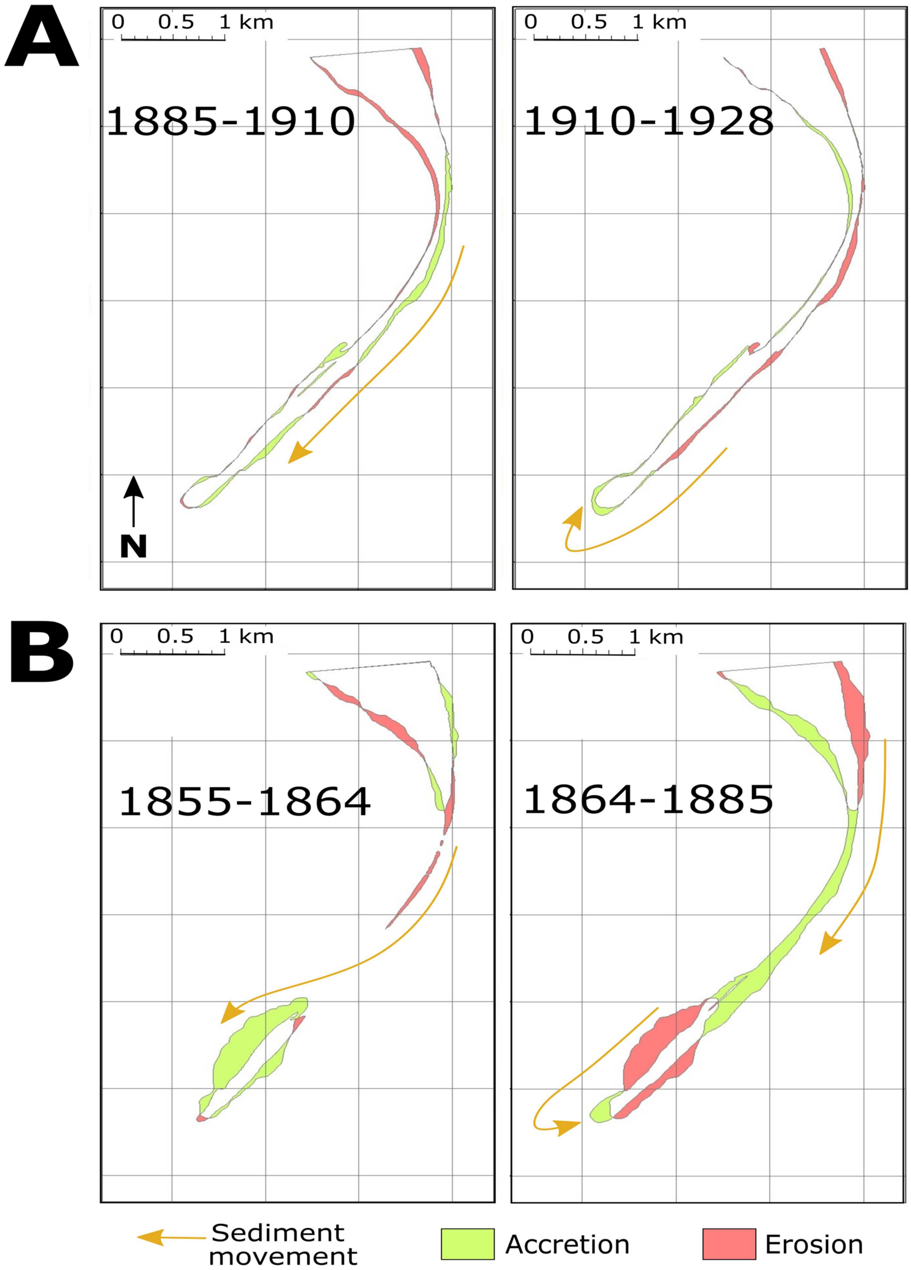

Figure 8. Proposed sediment transport modes for Spurn. (A) 'Normal' mode with sediment eroded from East Yorkshire glacial diamicts transported by long-shore drift along the spit and preferentially being deposited at the head where a proportion of sediment becomes stabilized as dunes. (B) 'Breach' mode with sediment eroded from East Yorkshire glacial diamicts moved through the breach and initially deposited on the Humber estuary side of the spit. This sediment is subsequently moved southward to the head, where a proportion of sediment becomes stabilized as dunes due to dominant south-westerly winds. Long-shore drift of sediment from the north helps close the breach so that the 'normal' mode resumes. [Colour figure can be viewed at wileyonlinelibrary.com]

last 190 years, and since 1980 shorter periods of recovery have happened before net erosion has taken place again. Whilst increases in net decadal erosion are evident and cycles of erosion and accretion are speeding up, these changes are small. This may at least partly reflect that spit formation is a balance between sediment supply and direct erosion. Increasing sea levels may be driving enhanced erosion of the spit, but this may be being partly offset by the same erosion releasing more sediment from the up-current East Yorkshire coast (Balson and Philpott, 2004; Lee, 2011). However, considerable elevational change has been observed along the spit, especially the neck. The dunes in the 1950s on the neck were recorded as being over 9 m OD (Phillips, 1962) and are now a maximum of around 3 m OD. Furthermore, hard engineering coastal protection schemes at various places along the East Yorkshire coast have been constructed over the last 30 years, potentially reducing the sediment supply to Spurn. Whilst increasing erosion might be a function of increasing sea levels, it should also be noted that there has been a change in Spit management practice since Yorkshire Wildlife Trust took over Spurn in 1959. Since that time coastal defence maintenance has declined, allowing the spit to respond to changes more freely.

Implications for future spit management

Future spit management will depend on embracing, and where appropriate adapting to, change in the system of which this paper provides a detailed analysis and historical context. The new data presented above show the form and position of Spurn, particularly the neck, as far more dynamic pre-1900s (Figure 3). Since the 1850s, the Spurn has been partially held

Table III. Spurn area change through time subdivided by area eroding and area accreting. Data based on geo-referenced historical maps. As time span between maps varies, the net changes per decade are also shown. Net erosion per decade is highlighted in red and net accretion in green, showing a 30–40-yearcycle

Time period	Total erosion (km^2)	Total accretion (km^2)	Total net change (km^2)	Net change per decade (km^2)
2011–2018	0.09	0.13	0.04	0.09
2000–2011	0.27	0.05	−0.22	−0.17
1991–2000	0.00	0.01	0.01	0.00
1980–1991	0.16	0.16	0.00	−0.01
1973–1980	0.13	0.17	0.04	0.09
1960–1973	0.07	0.12	0.05	0.04
1956–1960	0.20	0.08	−0.12	−0.31
1947–1956	0.13	0.14	0.01	0.01
1928–1947	0.14	0.15	0.01	0.00
1910–1928	0.16	0.14	−0.02	−0.01
1885–1910	0.17	0.23	0.05	0.02
1864–1885	0.55	0.58	0.03	0.02
1855–1864	0.18	0.45	0.27	0.30
1829–1855	0.85	0.13	−0.72	−0.28
1818–1829	0.16	0.57	0.41	0.37
Total change			**−0.16**	

in place artificially through hard engineering and with management working against rather than with the processes that shape the feature (Figure 5). A recent policy shift is now managing the spit to work with natural processes. It is postulated that Spurn will revert to a geomorphological system functioning more similarly to that documented before the 1850s.

Going forward, the spit will increasingly experience waves propagating closer to dune toes driven by increases in relative sea level (RSL) (Woodworth, 2017) unless this can be offset by increased sediment supply. As the new data show, maintaining sediment supply to the neck and head from the anchor and further up-current on the East Yorkshire coast is key to the long-term resilience of the spit, allowing it to continue dune building. Increased erosion of source material along the East Yorkshire coast and accelerated long-shore transport will aid future spit resilience. However, curtailing the yield of sediment from the East Yorkshire coastline through artificial cliff stabilization and/or groynes could make the spit less resilient in the future unless sediment nourishment is adopted – an approach which has proven useful elsewhere in the world (e.g. Armstrong and Lazarus, 2019). Ultimately, with the approach taken here, for changes to be recorded they have to manifest themselves in a change in area of the spit. A precursor to major erosive changes may well be the erosion of dunes, leading to their reduced height along the spit, thereby making the landform more vulnerable to storm surges and/or high tides. Establishment of a long-term high-resolution digital elevation model using LiDAR would enable better future monitoring of spit evolution and its relationship to storms and surges.

Additional to RSL increases, extreme events and the return period of such events are predicted to increase in the UK, thereby changing the in-shore wave climate (Chini *et al.*, 2010; Haigh *et al.*, 2016). Clustering of high-magnitude storms, as identified in this paper, has had a profound effect on the morphological development of Spurn in the past and may become more important in the future. Whilst RSL scenarios are well researched, the magnitude and directionality of storms is less so, but this is critical for vulnerable features such as spits. Given the likelihood of return periods increasing, the 'breach mode' (Figure 8B) may become more common as a result of storm clustering, with Spurn experiencing prolonged phases of overwashing sediment across the whole of its length. Within a management context, this broadening of the barrier may be beneficial as narrow steep and high dune ridges are more vulnerable to breach compared to lower and wider barriers (Obhrai *et al.*, 2009).

Ongoing and future coastal zone management of the Humber estuary, particularly in relation to accommodation space, will have an effect on the relationship of tidal prism to cross-sectional area at the mouth, and hence the stability of Spurn (Townend, 2005; Townend *et al.*, 2007). To counter this, the Environment Agency – the government agency responsible for managing shoreline and estuary flooding, is now undertaking managed realignment within the Humber estuary as part of an integrated coastal zone management approach to offset losses associated with estuarine coastal squeeze, as well as direct impacts of port development (Hemingway *et al.*, 2008).

Looking beyond the case study of the spit at Spurn, use of digitized historical maps in GIS combined with OSL dating allows a more complete understanding of long-term spit evolution and sediment transport modes. In doing so, it can help recognize the variability surrounding phases of future change linked to pressures such as increases in storm events and sea-level rise. As these coastal pressures are not confined to Spurn or the UK, such an approach could be of great benefit to coastal managers in a variety of settings where there is an extended history of map making and/or coastal dune systems to serve as sediment archives.

Conclusions

- Historic mapping shows the spit at Spurn to have been in existence from at least 1577 CE.
- Luminescence ages suggest Spurn in its current form initially was established in the early 17th century, perhaps after the severe storm of 1571 CE.
- No evidence was found for westward spit migration since 1818 CE.
- The dominant trend has been for south-westerly spit lengthening, which has extended the spit by around 330 m since 1818.
- Whilst net coastal erosion of the anchor has been relentless, the areas of both the neck and head of the spit have been more variable.
- Analysis of accretion and erosion since 1818 shows a 0.160 km^2 decrease in overall size of Spurn over the last 200 years,

with the rate of erosion potentially increasing over the last 50 years.
- Over the last 200 years, erosion and accretion may have followed a 30–40-year cycle with a decade of erosion followed by slow accretion for 20–30 years. Since 1980, shorter periods of recovery have happened before net erosion has taken place again.
- Sediment transport modes switch during breach events. Instead of the sediment influx moving down the North Sea side of the neck to the head where it forms dunes and extends the spit, it is deflected into the Humber estuary side where it temporarily extends the head before itself being eroded.
- Use of digitized historical maps in GIS, combined with OSL dating, has allowed a more complete understanding of long-term spit evolution and sediment transport modes at Spurn.
- This case study of the spit at Spurn illustrates the historical dynamics of this type of coastal feature and how such studies, irrespective of where in the world they are, can inform future possible changes in coastal spits linked to pressures such as increases in storm events and sea-level rise.

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Conflict of Interest

No conflicts of interest are declared.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Figure S1. Example radial plots of OSL palaeodoses (D_e) for the samples collected from Spurn spit.
Table S1. The decades covered using contemporary and historical mapping of Spurn during this study. For each map, the source location and original data type are displayed (i.e. if it was sourced as hardcopy or a digital file). Where a map is labelled 'overlaid', this indicates that outlines created were done using geo-referencing techniques and so can be overlaid with other maps for direct comparison. Where years are labelled 'scaled' it was not possible to accurately geo-reference the map and so the map was stretched to the correct scale and the outline was created individually.
Figure S2. Early maps of Spurn for which geo-referencing was not possible. These maps show much higher levels of variance between time periods, either reflecting mapping inaccuracies or a far more mobile spit at Spurn prior to the 19th century.
Figure S3. Evolution of Spurn as found on geo-referenced historical maps and aerial imagery from 1818 through to 2018. Red dashed line indicates boundary between anchor, neck and head.

Figure S4. Early postcard (date unknown) of the Lifeboat Inn on Spurn as taken from the top of the present lighthouse, which was built in 1895. Annotated is the approximate position of site 4 and the route of the former Spurn and Kilnsea military railway whose building might have led to sand removal at site 4.

Figure S5. Rapid rate of coastal erosion marked at former Blue Bell Inn, Kilnsea, 488 m from the sea in 1847, 174 m from the sea in 1994 and estimated (from Google Earth) at 124 m in 2017. Over the last 170 years, coastal retreat at this point has been on average 2.1 m per year.

Figure S6. Sampling sites on Spurn Point. (A) Dune cored at site 5 on estuary side of neck of spit. (B) Dune cored on head part of spit at site 6. Also shown is the Dormer Engineering corer used to collect OSL samples from depth. (C) Dune cored at site 3 on North Sea side of neck of spit. (D) Deflation of sediment from beach on Spurn spit after a major storm. (E) Input of sand to back of beach and dunes on Spurn spit after a major storm.