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Abstract: High rates of coastal retreat characterise the weakly cemented Plio-Pleistocene rocks and sediments which form much of the cliffed coastline of East Anglia, southern North Sea. The accurate establishment of sediment losses from these cliffs has a regional significance as these sediments are important in maintaining beaches and nearshore bank systems and in feeding nearshore sediment transport pathways. However, the high spatial and temporal variability of cliff failure processes in such materials necessitates fine-scale integration of alongshore variations in cliff retreat over a series of well-established time periods to accurately define cliffline recession rates and sediment volume inputs to the nearshore system. This study applied the DSAS (Digital Shoreline Analysis System) within the GIS software package ArcMap to digitised, georeferenced positions of former shorelines, obtained from historic maps and aerial photographs (after 1992), for the sections of Benacre-Southwold and Dunwich-Minsmere on the Suffolk coast of East Anglia, UK; transects were cast every 10 m alongshore, producing very high spatial resolution upon which to assess shoreline retreat (over 1000 transects along 11 km of shoreline). Long-term (1883-2008) mean shoreline retreat rates varied between 2.3-3.5 m a-1 (Benacre-Southwold) and 0.9 m a-1 (Dunwich-Minsmere). For six cliffed subunits within these larger coastal sections, spatial variations in cliffline recession rates for shorter time intervals (at ca. 20-year intervals) within this longer (125 year) period were established. The combination of recession rates with photogrammetric methods of obtaining cliff top elevation at the same spatial resolution, available using aerial photographs and digital terrain models, along with cliff sediment composition, allowed the calculation of sediment volumetric inputs from cliff retreat in the period 1992-2008. Re-assessment of the magnitude and location of sediment inputs into the nearshore zone, their interaction with regional sediment transport and the growth of inshore bank systems, as well as the implications for contemporary and near-future coastal management strategies are discussed with reference to this section of the Suffolk coast.

Temporal and spatial variations in recession rates and sediment release from soft rock cliffs, Suffolk coast, UK

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Abstract

High rates of coastal retreat characterise the weakly cemented Plio-Pleistocene rocks and sediments which form much of the cliffed coastline of East Anglia, southern North Sea. The accurate establishment of sediment losses from these cliffs has a regional significance as these sediments are important in maintaining beaches and nearshore bank systems and in feeding nearshore sediment transport pathways. However, the high spatial and temporal variability of cliff failure processes in such materials necessitates fine-scale integration of alongshore variations in cliff retreat over a series of well-established time periods to accurately define cliffline recession rates and sediment volume inputs to the nearshore system. This study applied the DSAS (Digital Shoreline Analysis System) within the GIS software package ArcMap to digitised, georeferenced positions of former shorelines, obtained from historic maps and aerial photographs (after 1992), for the sections of Benacre-Southwold and Dunwich-Minsmere on the Suffolk coast of East Anglia, UK; transects were cast every 10 m alongshore, producing very high spatial resolution upon which to assess shoreline retreat (over 1000 transects along 11 km of shoreline). Long-term (1883-2008) mean shoreline retreat rates varied between 2.3-3.5 m a^{-1} (Benacre-Southwold) and 0.9 m a^{-1} (Dunwich-Minsmere). For six cliffed subunits within these larger coastal sections, spatial variations in cliffline recession rates for shorter time intervals (at ca. 20-year intervals) within this longer (125 year) period were established. The combination of recession rates with photogrammetric methods of obtaining cliff top elevation at the same spatial resolution, available using aerial photographs and digital terrain models, along with cliff sediment composition, allowed the calculation of sediment volumetric inputs from cliff retreat in the period 1992-2008. Re-assessment of the magnitude and location of sediment inputs into the nearshore zone, their interaction with regional sediment transport and the growth of inshore bank systems, as well as the implications for contemporary and near-future coastal management strategies are discussed with reference to this section of the Suffolk coast.

Keywords: Digital Shoreline Analysis System (DSAS), shoreline retreat, soft-rock cliffs, cliff elevation, NextMap, sediment release, ArcMap, coastal management, Suffolk

1. Introduction

'the rapid wearing back of the cliffs, especially at Covehithe, is a point of interest; and the measurements now given will be of service to future observers'

HW Bristow
Senior Director, Geological Survey Office
London, July 1887

Notice prefacing W. Whitaker's discussion of the 'waste of the coast' in the Memoir of the Geological Survey on the geology of coastal Suffolk, UK east coast (Whitaker, 1887).

The coastal zone performs important ecological, economic and societal functions, attracting settlements, industry and infrastructure and supporting natural habitats that provide valuable ecological services. It is also highly sensitive to changes in environmental forcing factors (Valiela, 2006). Sea level rise and the increasing frequency and magnitude of extreme weather events, consequent upon global environmental change, are likely to lead to more damaging rain and windstorm events, higher rainfall totals and greater wave energy and thus to accelerated erosion of beaches and coastal margins (Thorne et al., 2007). Such changes have profound implications for human communities whose resource base is at, or close to, the present coastline, raising problems that are likely to increase in importance as the global coastal population grows from 1.2 billion (1990) to 1.8-5.2 billion by the 2080s (Nicholls et al., 2007). Fast eroding, and thus retreating, soft cliff coasts are one coastal environment particularly vulnerable to environmental change and provide an environmental setting that raises serious issues as to appropriate management responses and coastal zone governance in the face of rapid coastline recession (Nicholson-Cole and O'Riordan, 2009).

Lateral retreat rates of coastal cliffs within the British Isles vary with rock type, ranging from less than 0.001 m a^{-1} in the most resistant rocks, through 0.01-1.0 m a^{-1} in less resistant chalks and sandstones, to over 10 m a^{-1} for easily eroded glacial tills (French, 2001). Some of the highest rates of cliff recession have been reported from the weakly cemented rocks and sediments of Pliocene and Pleistocene age which form much of the coastline of East Anglia, southern North Sea (HRWallingford, 2002) (Fig. 1). Accounts of lost towns and churches on this coast are 'partly fabulous but partly true' (Whitaker, 1907, 98) while 'exaggerated figures [of coastal land loss] are often quoted without authority, and it is a pity that so few precise measurements are available' (Steers, 1964, 385). Nevertheless, in 1907, the Director of the national mapping agency of the UK, the Ordnance Survey, used map evidence to argue before the Royal Commission on Coastal Erosion that Suffolk had the greatest loss of coastline of any county in England. Land loss of 148.5 ha took place between 1883 and 1903, with ca.

70% of this loss being in the vicinity of Southwold and Dunwich (Hellard, 1907, 46). Furthermore, the accurate establishment of sediment losses from these rapidly eroding cliffs has a regional significance that reaches well beyond this local loss of land. Particularly where the sediment input is predominantly of sand – as is the case of the Suffolk cliffs (James and Lewis, 1996) – cliff erosion both directly nourishes cliff-foot beaches and is implicated in sediment exchanges with the extensive systems of energy-dissipating nearshore sandbanks which lie immediately offshore. Thus the accurate measurement of cliff recession rates is of considerable importance at the regional scale (McCave, 1978; Vincent, 1979).

Many of the estimates of point-source sediment inputs from the cliff systems of the UK coastline of the southern North Sea and which remain widely-quoted in more recent reports (e.g. Southern North Sea Sediment Transport Study (HRWallingford, 2002)) were developed at a time when heavy reliance was placed upon the use of historic maps, sparse spot heights and interpolated contours for the derivation of sediment release statistics. In spite of subsequent developments in i) the provision of remotely sensed datasets; ii) the adoption, with the establishment of the UK National Rivers Authority / Environment Agency (EA), of standardized field and aerial photographic monitoring; and iii) the availability of analytical GIS platforms, these estimates from the 1970s and 1980s still largely form the basis for the discussion of sediment dynamics around the East Anglian coastline and underpin much of contemporary coastal management decision making. Since 1992, the EA (Anglian Region) has monitored biennial (winter and summer) cliff and beach profile change at 1 km intervals between the Humber and Thames estuaries. Results from these ground surveys provide useful ground control on interpretations of coastal retreat obtained from aerial photography. They have the disadvantage, however, of being widely-spaced at ca. 1 km intervals alongshore. This is a major difficulty in soft rock cliff systems which, as has long been known (e.g. see the evidence of Cooper, 1907; Whitaker, 1907; and Reid, 1907 to the UK Royal Commission on Coastal Erosion), exhibit considerable variability in erosion processes and retreat rates over a range of spatial (<1 km to >10 km) and temporal (<10 to >50 a) scales (e.g. Cambers, 1976; Pethick, 1996). This is because cliff recession involves both i) toe erosion by marine action which removes failure deposits allowing undercutting and steepening of the cliff base and ii) a range of mass movement processes, including rotational failures, slumps and spalling. There are often strong spatial variations in materials (both alongshore between sites and vertically within individual cliff profiles) in soft rock cliffs, temporal changes in pore water pressure, and seasonal and non-seasonal variations in basal conditions (including the impact of rare elevated water levels under storm surge conditions), as well as longer-term controls, including shifts in dominant weather patterns and changes in the rate of relative sea level rise. These controls interact in complex ways to influence the patterning of erosion and cliff retreat (e.g. Richards and Lorriman, 1987; Jones et al., 1993).

Furthermore, as cliffs retreat they expose new cliff stratigraphies, change cliff elevations and establish new relations between the cliff face and the fronting beach. These changes also result in changes in alongshore extent. Over decadal time periods, clifflines can emerge (“switch on”) and disappear (“switch off”) entirely, with implications for sediment sources to the beach and nearshore zone. Hence sediment volume inputs exhibit high spatio-temporal variability in both quantity and location, thus ensuring that volumetric estimates need regular and detailed updating. Any attempt to fully characterise soft cliff behaviour and associated sediment budgets must properly identify and assess this spatio-temporal variability. At the meso-scale, the problem can be resolved by establishing well-constrained dates for the position of former clifflines and then sampling at a fine spatial interval alongshore. Such a methodology effectively integrates the smaller-scale alongshore variability in basal and cliff face processes, and their interaction with local sediment properties, between time markers of known date. However a methodology needs to be developed that allows rapid updating of sediment volume inputs at a high spatio-temporal density.

Fig. 1 about here

The primary aim of this paper is to show how modern analytical techniques can be used to derive improved and detailed quantification of the sediment volumes currently being released from a soft rock cliff system. The issue of including a high degree of spatio-temporal variability in cliff retreat can be addressed using the United States Geological Survey's Digital Shoreline Analysis System (DSAS; Thieler et al., 2005) which has been applied in different locations to assess historic shoreline retreat. The methodology is described in more detail below; it should be noted that it has not been used previously in assessment of sediment volumes from rapidly retreating cliffs. In order to provide such an assessment, detailed cliff elevation data are also required. Since 2002 'NextMap' elevation data have been available for the UK at a spatial resolution of 5 m, with elevation detail accurate to within 1 m (see below for further discussion). The ArcMap Surface Spot tool can be used to extract linear elevation data alongshore for any digitised shoreline position, and a combination of retreat rate and elevation can then be used to provide assessment of volumetric change in the retreating cliffs. Hence the combination of DSAS for accurate inclusion of the variable planform of the retreating shoreline, with NextMap elevation data enables detailed assessment of sediment volume inputs which can be readily and rapidly updated. This paper thus develops and applies a new methodology for the rapid and detailed estimation of sediment inputs. It does so with reference to two closely adjacent parts of the Suffolk coast which have been seen as two of the three major sources of sediment input along the East Anglian coastline (the other being the North Norfolk cliffs). The first area of interest is an 8 km long, southwesterly-trending shoreline between the settlements of Kessingland and Southwold and centred near the village of Covehithe. Further south, separated by the estuary of the River Blyth, the second area runs approximately north – south for 3km between the remains of the medieval town of Dunwich and the lagoons of the Minsmere Nature Reserve (Fig. 1). These two areas were chosen for detailed study for four reasons. Firstly, a wide range of data sources, ranging from archival material to contemporary modelling of nearshore processes, is available for this coast to inform the nature of soft cliff erosional dynamics. General rates of shoreline change have been established for the period since the sixteenth century, with more detailed measurements at particular cliffed sections, often associated with pioneering geological studies, from the mid-nineteenth century. Thus at Dunwich, Carr (1979) showed that the long-term pattern of shoreline recession, at 0.68-0.96 m a$^{-1,}$ has incorporated phases of both accelerated coastal retreat (e.g. 1753-1772: 3.48 m a^{-1}; 1863-1880 2.57 m a^{-1}1903-1919: 3.53 m a^{-1}) and periods of shoreline stasis (e.g. 1826-1823: 0.06 m a^{-1}; 1882/3-1903: 0.08 m a^{-1}). It is, however, difficult to see a clear pattern of change over space and time along this coast where erosion can be severe but intermittent (Halcrow, 2002). Secondly, because the cliffs most probably fail by a more-or-less instantaneous failure response to removal of beach or basal cliff material (Lee and Clark, 2002), this coastline is characterised by phases of extremely high rates of shoreline recession (as detailed by the Futurecoast (Halcrow, 2002) analysis of the Shoreline Behaviour Unit between Lowestoft and the Blyth estuary). These erosion rates have given cause for serious public concern, as detailed in the 2010 draft Shoreline Management Plan for this region (Suffolk Coastal District Council, 2010). Thirdly, one of the difficulties in assessing soft rock cliff dynamics on the East Anglian coastline is that the majority of the cliff sections have been modified by human activities, either directly through cliff face stabilisation programmes or, and more frequently, indirectly by the alteration of beach volume changes through the construction of shore-parallel seawalls and revetments and/or the emplacement of shore-normal groyne fields (e.g. Clayton, 1989). The cliffs on this coast have not been subject to such interventions (except for very recently (post-2002) at Easton Bavents and, in a more limited fashion, near the village of Dunwich) and thus provide a clear picture of natural fluctuations in cliff retreat rates over time. Fourthly, the Covehithe- Eastern Bavents and Dunwich-Minsmere cliffs have traditionally been identified as one of the major source areas for sediment input into the regional sediment circulation system; thus the correct specification of sediment inputs at these locations is not just of local interest but of regional significance and importance. These inputs have a key role to play in decisions on coastal policy options in this area, as laid out in Shoreline Management Plans (Suffolk Coastal District Council, 2010) and Coastal Habitat Management Plans (Guthrie and Cottle, 2002). Overall, therefore, this coast offers a demonstration site for emerging research methodologies concerned with the interactions between sea level rise; sediment supply and transport; and different types of management intervention (Hanson et al., 2007).

2. Location

The solid geology of coastal East Anglia consists of basin marginal, largely marine Pliocene and Early to Middle Pleistocene strata (shallowing sequence of Crag Group and associated deposits) resting on an eroded Palaeogene and Cretaceous basement (Hamblin et al., 1997; Gibbard and Zalasiewicz , 1988; Gibbard et al., 1998). Calcarenites (Coralline Crag, late Early – Middle Pliocene), which lie offshore in the study region (Balson et al., 1993), and iron-stained, coarse-grained shelly sands (Red Crag, latest Pliocene-early Pleistocene), present below -5 m O.D.N. (Ordnance Datum Newlyn, which approximates to mean sea level) in boreholes between Aldeburgh and Orford (Zalasiewicz et al., 1988), are unconformably overlain by the sands and clays of the Norwich Crag Formation. Importantly, differences in Plio-Pleistocene stratigraphy alongshore are reflected in the likely proportion of different sediment types input into the nearshore zone as a result of cliff retreat (Table 1). In addition, the configuration and character of the deposits is likely to exert a strong control on cliff hydrology and failure mechanisms (as discussed by Gray (1988) to the south of this study region, at the Naze cliffs, Essex), particularly where the cliff base coincides with a transition from silty clay to sands and gravels. At Easton Cliffs, the Crag deposits include an overlying pale grey silty clay stratum with laminae of fine-grained sand, burrowed by worms, small Crustacea and bivalves, indicative of an intertidal mudflat environment (West et al., 1980; Mottram, 1989). Whereas the underlying Crag arenite is thought to represent the warm Antian Stage (Tiglian C1-3 warm stage, Marine Isotope Stage 77 (Gibbard et al., 2007a)), the overlying clays have been correlated with the cold stage Baventian / pre-Pastonian (Tiglian C4c cold stage, Marine Isotope Stage 70 (Gibbard et al., 2007a)) of the pre-glacial Early Pleistocene (Funnell and West, 1962; Zalasiewicz et al., 1988). Crag is also exposed at Easton

Wood (Mottram, 1989) and at the southern end of the Covehithe cliffs (Long, 1974); here overlying clays dip northwards for ca. 1000 m and are in turn overlain by sand and gravel deposits of the Westleton Beds, with thin, laminated tidal silts (West, 1980). Representative images from each of the main study locations are shown in Fig. 2.

Fig 2 about here

The clay/sand and gravel contact rises to ca. +5.0 m O.D.N. in the northern Covehithe cliffs. Here, and at Easton Cliffs, the overlying deposits include gravel lenses assigned to the Westleton Beds Member by Hey (1967). At Covehithe, these deposits are thought to represent gravel-lined nearshore rip channels cut into beachface sands (Mathers and Zalasiewicz, 1996) whereas further south, at Dunwich and at Minsmere, larger-scale gravel channel fills are regarded as marking the position of tidal inlets between barrier islands (Mottram, 1997). The Westleton Bed gravels are overlain at Covehithe by thin, iron-stained sand and the quartz and quartizite-rich gravels of the Kesgrave Formation (Hey, 1967). These gravels are in turn followed in the cliff face by the Corton Sands, sands with chalk grains and occasional concretions, representing the glacial outwash from the Middle Pleistocene Anglian Glaciation (Ehlers and Gibbard, 1991; Lee et al., 2006; Gibbard et al., 2007b), and finally, below the topsoil, by the decalcified Lowestoft Formation (Anglian) till (Marine Isotope Stage 12, Gibbard et al., 2007b)) which is also present at Dunwich-Minsmere (Mottram, 1989).

Sea level reached close to its present level at ca. 4 ka BP but then oscillated in the period up to the seventeenth century when it again approached its current position (Carr, 1969). The trend of regional sea level rise over the period 1956-2006, as recorded at the Lowestoft tidegauge, has been 2.47±0.23 to 2.57±0.33 mm a^{-1}, depending on the method of analysis used (Shennan and Horton, 2002; Woodworth et al., 2009). Halcrow (1991), combining geological subsidence with a rate of sea level rise based on a medium emissions scenario, suggest a rate of relative sea level rise of 5-6 mm a^{-1} in the near-future.

The regional tidal regime is semi-diurnal in character, with a mean spring tidal range at Lowestoft of 1.9m; the clifflines within the study area experience a slightly higher mean spring tidal range. However, on this part of the East Anglian coastline water levels associated with storm surges (e.g. Pugh, 1987; HRWallingford, 2002) can exceed the tidal range. Thus, for example, whilst Highest Astronomical Tide has been established at 1.4 m O.D.N. at Lowestoft, the surges of 31 January-1 February 1953 and 9 November 2007 reached 4.6 m and 4.1 m O.D.N. respectively at this location (Muir-Wood et al., 2005; Horsbaugh et al., 2008). Surge impacts on cliff recession rates are considered in more detail below. Storms causing significant land loss at Dunwich were recorded in AD 1286, 1328, 1347, 1560, 1570 and 1740 (Bacon and Bacon, 1988).

In general, wave energy is low to moderate, with annual average wave heights ranging from 0.4 to 0.5 m (Fortnum and Hardcastle, 1979). The largest (> 2.2 m high) waves come from the northeast, reflecting the extended fetch in this direction (Pye and Blott, 2006; Marine Aggregate Levy Sustainability Fund, 2009).

Fig. 3 about here

The 8 km long shoreline between Benacre Ness and the town of Southwold comprises five cliffed sub-units, each up to 1 km in length. From north to south these are: Benacre, Covehithe, Easton Wood, Northend Warren and Easton Cliffs (Fig. 3A), reaching elevations of 9 m, 15 m, 12 m, 9 m and 14 m O.D.N. respectively. The cliffed sections are separated by near-sea level valley bottom lagoons, or Broads. From north to south, these are Benacre Broad, Covehithe Broad and Easton Broad (northern and southern limbs). The Broads contain open water and marginal freshwater marshes and are separated from the backshore by narrow ridges of gravel and coarse sand. These ridges are vulnerable to breaching and saltwater flooding under storm surge conditions (Whitaker, 1907; Steers, 1953; Pye and Blott, 2009).

The 3 km long Dunwich-Minsmere cliffs, which form a sixth cliffed subunit (Fig. 3B), rise steeply at both their northern and southern margin to attain elevations of up to 17 m O.D.N..

The mesotidal range and the availability of gravel-sized sediments, most probably relict (Halcrow, 2002) gives rise to narrow, steep cliff-fronting beaches which show considerable seasonal fluctuations in elevation and width. Using the EA shore profile record, Lee (2008) has shown that the 'beach wedge' area that fronts cliffs in this area varies between 5 m^2 (when the underlying geological basement of Baventian clay is revealed) and 50 m^2 in extent. He has argued that this wedge exerts a strong control on cliff recession rate. To the north of the study area, near Kessingland, the coastline is characterised by a series of sand and shingle ridges which form the low coastal protuberance of Benacre Ness. These ridges front an old, low cliffline which is being re-activated with the northerly migration of the Ness at an average (1766-1992) rate of ca. 23 m a^{-1}. Considerable fluctuations in beach volumes have also been reported at Dunwich, although with a general maintenance of beach widths of ca. 45 m and gradients of 6-7 º, partly as a result of human interventions (Pontee, 2005).

Contrasts in offshore water depths between the two locations are potentially significant for wave energy levels at the shoreline. At Benacre, water depths typically increase to 10 m at around 1.5 km offshore. However, offshore from the Dunwich-Minsmere cliffs water depths only attain 10 m at 3 km offshore and the immediate nearshore region is occupied by the Sizewell - Dunwich Bank (Pye and Blott, 2009). Hence subtidal gradients are greater in the region of Benacre to Southwold compared to the offshore profile to the south. In the Benacre – Southwold section, shoreline protection from predominant north easterly waves is, however, gained by a change in coastline orientation to a more north – south alignment and by the presence of the southernmost extent of the Lowestoft Bank system (Carr, 1981; Reeve and Fleming, 1997; Horillo-Caraballo and Reeve, 2008). However, it should be noted that both the Lowestoft Bank system in the north of the study region, and the Dunwich – Sizewell bank system in the south, are continuously shifting in extent, height and overall volume, with much-debated consequences for the wave climate at the shore (e.g. Fortnum and Hardcastle, 1979; Robinson, 1980; Pye and Blott, 2006).

3. Methods

The analytical approach employed in this study comprised a two stage process: firstly, the obtaining of reliable estimates of historic shoreline change for different time periods over the past 125 years and, secondly, using the recession of the cliff top edge and associated variations in cliff top elevations in this area to calculate the volume of sediment released from the cliffs over the most recent time periods. Reconstructions of coastal recession on the Suffolk coast of East Anglia have been established since the sixteenth century, particularly through the use of the surveys of Radulphus Agas and Thomas Gardner in 1585 and 1754 respectively (Robinson, 1980; Chant, 1986; Pye and Blott, 2009). However, the analysis reported here is restricted to the period from the appearance in the 1840s of the six-inch survey by the Ordnance Survey (OS), the UK national mapping agency (for history see Seymour, 1980). After this time error terms in the fixing of shoreline positions can be more confidently determined (Carr, 1962; Oliver, 1996).

3.1. Determination of shoreline retreat rates and areal land loss

3.1.1. Determining alongshore shoreline change, 1883-2008

The errors and issues relating to digitising shorelines from historic maps and aerial photographs have been outlined by Moore (2000). The main technical challenge is to define a consistent, time-independent boundary for the shoreline. Many studies comparing shorelines of different age have used the mapped position of mean high water springs (MHWS). Such an approach is, however, problematic as with long historical studies the definition and location of high water changes over time. Fortunately, the positions of clifftop and cliff base are also marked on historic maps. The cliff top or cliff base provides a more consistent marker of the shoreline as they result from field surveys that are neither time-constrained by tidal variation (often the case when mapping high and, especially, low water position) nor are they open to some degree of subjectivity in defining exactly where MHWS is located (Harley, 1972; Oliver, 1996). For many cliffed coastlines, MHWS and the cliff base are coincident and one approach to defining shoreline position takes a combination of MHWS (where there is no cliffline) and cliff base (Cambers, 1975). This approach was also taken here in an initial assessment which looked at the continuous record of alongshore change, between 1883 and 2008, encompassing both the cliffed sections and the Broads between them as shown in Figs 3A and 3B.

Historic OS maps surveyed in 1882 - 1883 (plotted as 1883), 1903, 1921 – 1928 (plotted as 1925), 1947 (1941 at Dunwich – Minsmere), and 1981 (1974 at Easton Cliffs), and published at a scale of 1:10 560 (available digitally at www.edina.ac.uk/digimap/), were selected for the initial analysis of shoreline change over time. Analyses of this kind can suffer from the delay between field survey dates and the publication dates of particular Ordnance Survey map editions and it is not always clear from the published maps when surveys were undertaken. For this research, the authors have been fortunate in having access to the collections of a legal deposit library, the Map Library of the University of Cambridge, which holds not only published map sources but also copies of provisional, unpublished maps from the Ordnance Survey. By comparing both published and unpublished maps sources it has been possible to better define map survey dates along the Suffolk coast.

These maps were then supplemented with information on shoreline position (MHWS / base of cliffs) from vertical aerial photographs taken as part of the UK Environment Agency (EA) (Anglian Region) Sea Defence Management Study (SDMS) monitoring programme; eight 1 x 1 km photographs covered the coastline between Benacre and Southwold and three 1 x 1 km photographs covered the cliffs between Dunwich and Minsmere. Photographs from the years

1992 and 2008 were used in this analysis, thus extending the map-based analysis beyond 1981. These were supplied in a georeferenced format via the Shoreline Management Group of the EA (Anglian Region).

Initially all maps and aerial photographs were individually registered against the 2008 Environment Agency aerial photograph, using the software package ArcMap 9.2 (www.esri.com), using the British National Grid (OSGB36) co-ordinate system. This initial registration was based upon six ground control points located at road junctions, field boundaries and buildings that have been evident on all maps and photographs since 1883. Each feature was selected on the basis of it being likely to have remained stable since the earliest surveys and having close proximity to the coast. This georeferencing generated a RMSE below 10 in every case. Further independent error estimates were then carried out for every map and aerial photograph used in this study by measuring distances between seven additional ground control points (including St Andrews Church, Covehithe; Porter's Farm, Covehithe Broad; Greyfriars Monastery, Dunwich; and Coastguard Cottages, Minsmere), on every map and photograph used in the study and the same features on the 2008 aerial photograph. For the 1883 map the average distance of the seven points from the locations on the 2008 aerial photograph was 6.46 m. Assuming a rate of shoreline retreat of 3 m a^{-1}, the error compared to the retreat over the period 1883-2008 is 1.7%. The average difference for the seven control points for the 1905, 1928, 1957, 1983, 1992 and 2001 sources (maps and aerial photographs) are 9.01 m, 8.70 m, 4.5 m, 2.0 m, <1 m and <1 m respectively. These differences generate an error relative to total retreat over the respective period of 2.88% (1903-2008), 3.24% (1925-2008), 1.20% (1947-2008), 3.57% (1981-2008), 2.08% (1992-2008) and <4.76% (2001-2008). Pye and Blott (2006) estimated that the errors associated with georeferencing maps over similar time periods for the coast around Dunwich-Minsmere, based upon similar criteria for the ground control points, to be within ± 4 m, while Vincent (1979) estimated the accuracy to which coastal cliff retreat might be measured from historic maps to be in general within 5% of the true value. The figures generated here are broadly consistent and suggest shoreline change can be estimated to an accuracy ranging between 1 - 5%, even using a relatively conservative rate of shoreline change.

Shorelines were then digitised from each map and aerial photograph. Where possible the cliff base was used as an unambiguous marker of shoreline position and a surrogate for mean high water springs (MHWS). In between the cliffed sections digitising was problematic due to the effects of changing definitions of the high water position on historic maps as well as changes in datum. For example the earliest maps define high water position as the High Water Mark of Ordinary Spring tides, and this persists until publication of the 1983 OS map where Mean High Water is used. For each map the lines marking mean high water (either ordinary or mean tides) was employed. This will generate some inconsistencies in the shoreline position between the cliffed sections. Beach gradients were found for all Environment Agency bi-annual profiles from 1992–2008. Given the current vertical difference between Highest Astronomical Tide and Lowest Astronomical Tide is around 0.3 m in the study region, these gradients produced a mean a horizontal distance between the HAT and LAT of 3.45 m with a standard deviation of 0.54 m. Compared with an overall retreat of around 400 m since 1883, any possible discrepancy arising from these different definitions of shorleline position is around 0.86 (±0.27) %.

The digitised shorelines were analysed in conjunction with the ArcMap extension DSAS Version 3.0 (Digital Shoreline Analysis System) (Thieler et al., 2005) to investigate shoreline change in detail over the past 125 years. This software has formed the basis for a series of United States Geological Survey Open File reports on a national assessment of shoreline change around the coastline of the U.S.A., spanning the period from the 1880s to present and generally utilising four historical shorelines. Other DSAS applications relate to different time periods and locations. For example, a comprehensive historic assessment was carried out for the coastline around Accra, Ghana between 1904 and 2002 where shoreline change rates were found to be on average 1.13±0.17 m a^{-1} (Addo et al., 2008). This study also considered the future response of the shoreline to continued retreat. Limber et al. (2007) used DSAS to compare the wet/dry line on aerial photographs with the Mean High Water line as a test of robustness of different markers of shoreline position. In the U.K., DSAS has been used to investigate historic coastline change since 1884 for the coastline between the Ribble and Mersey Estuaries for a range of coastal habitats (Esteves et al., 2009). No previous application, however, has used DSAS as a platform for considering sediment sources into the nearshore zone.

DSAS is a powerful extension to ArcMap that enables considerable spatio-temporal densification of the analysis of shoreline change. It works by casting shore-normal transects from a baseline located a short distance inland from the most recent shoreline of interest and then calculating the intersection of each shoreline with each transect. In this case, a 10 m interval between each transect was selected, providing a total of 800 transects over the 8 km stretch of coastline from Benacre Ness to Southwold, and 300 transects for the Dunwich – Minsmere cliffs. The simplest reportage of shoreline change using this methodology is through the End Point Rate (EPR), the difference in position between the oldest and youngest shorelines divided by the time elapsed between surveys. In addition, DSAS calculates the linear regression rate (LRR) of change by fitting a least squares regression, using all points where each shoreline intersects each transect. The LRR has the advantage of using all available shorelines and provides a statistically robust analysis but the method is prone to outlier effects (Dolan et al., 1991). For this reason, this analysis used the EPR methodology only.

3.1.2. Establishing coastal recession of the cliffed subunits of the Suffolk coast, 1883-2008

It is clear from cases where independent mapping and observation has been undertaken, that there can be both locational and chronological differences in the field position of MHWS from that shown on published maps (Oliver, 1996). The line of MHWS is also difficult to identify, and thus fix accurately, on aerial photographs. Where cliffs are present, however, a sharp and consistent line that can be clearly identified on historic maps, and one which is easily visible on recent aerial photographs, is the cliff top edge position. This line was chosen for a more detailed study of the cliffed subunits of the Suffolk coastline. Furthermore, whilst the use of this metric is problematic in cliff systems which are characterised by long erosion cycles, as material is conveyed from upper cliff rotational failures to the cliff toe (as discussed by Bray and Hooke, 1997), the Suffolk cliffs appear to have short erosion cycles (Lee and Clarke, 2002) and thus lagged and/or prolonged cliff line response times were not an issue in this analysis.

A second level of analysis, establishing shoreline change in up to six time intervals within the entire time period (1883-2008), was restricted to the six cliffed subunits, utilising only those DSAS transects which covered the cliffed sections of the coastline (see Fig. 3 for northern and southern limits of the spatial analysis window for each of the cliffed subunits). The analysis was also restricted to the time periods during which an identifiable cliffline was present. For some subunits (e.g. Covehithe) a cliffline was present throughout the entire time period (1883-2008); for some subunits a cliffline was formed only as the shoreline retreated into higher ground (a cliffline was present on the 1903 map at Northend Warren but not on the 1883 map); and at some locations, the cliffline only became present in the very recent past (e.g. seen on aerial photographs at Benacre after 1981). Mean rates of cliff face retreat recorded for the seven EA transects between Benacre Ness (SWD2) and Southwold (SWD8) and the three transects (S1C6, S1C7 and S1B1) along the Dunwich-Minsmere cliffs (Fig. 1) for the periods 1992-2008, 1992-2001 and 2001-2008 were used as independent checks on the mean retreat rates of cliff top edge position established from aerial photographs over the same time intervals.

3.2. Determination of cliff volumetric loss rates

3.2.1. Procedures and error estimates

To assess accurately cliff volume change generated by shoreline recession, detailed information concerning ground elevation must be combined with the data on cliff retreat rates. Unfortunately, historical maps provide only limited information concerning height, in the form of relatively sparse individual spot heights and interpolated contour lines between them. In February 2002, the study area was flown using airborne IFSAR (Interferometric Synthetic Aperture Radar) mapping technology, producing elevation data at 5 m horizontal resolution, compatible with the spatial resolution selected when casting the DSAS transects. The elevation data are available as digital terrain model 'NextMap' tiles from the UK NERC Earth Observation Data Centre (NEODC) facility (tiles dtm-tm57 and dtm-tm58 for Benacre-Southwold, dtm-tm46 and dtm-tm47 for Dunwich-Minsmere).

The vertical accuracy of NextMap data has been examined elsewhere by testing against a range of alternative elevation datasets (Dowman et al., 2003). While a vertical accuracy of 1 m is broadly supported for regions of open fields with low vegetation, caution has been advised for built-up areas, areas of woodland or where there are any significant surface features. In such areas there is decreasing accuracy in the elevation data which can lead to errors in height determination of up to 20 m. For much of the cliffline in the study area the landward terrain comprises either open fields divided by hedgerows or areas of low heathland vegetation. However, significant variations in elevation over short distances, such as occurs when moving from near horizontal cliff top surfaces to steeply sloping cliff faces, can compromise the elevation recorded for a 5 x 5 m NextMap pixel. Hence the EA ground survey data from 2008 (except at profile S1C7 (for location see Fig. 1) where, in the absence of later survey, it was necessary to use the winter 2000 profile) were compared with the NextMap elevations at the cliff top edge for each of the 10 EA shore transects in the study area, with the resulting regression equation used to adjust all the NextMap elevations at the cliff top edge (Fig. 4). These revised elevations were then used to provide input into the calculation of cliff sediment volume losses.

Fig. 4 about here

Further elevation correction was carried out in the area of Easton Wood, where there is a significant area of woodland vegetation that leads to a clear vertical distortion of the NextMap data. In this region, elevations on NextMap tiles dtm-tm58 and dtm-tm57 reach up to 30 m at 150 m inland from the 2008 shoreline, clearly diverging from the contour data and spot heights on the most recent (2006) 1:25 000 OS map. Even though there are 30 pixels between these extreme heights and the position of the shoreline, elevations at the shoreline reached 13-14 m in places. Along this short stretch of coastline (300 m), data were screened to keep elevations to a height of 12.5 m, consistent with OS spot heights and regional cliff elevations of the adjacent cliff systems.

3.2.2. Calculation of volumetric sediment inputs to the nearshore zone from retreating cliffs

For the Benacre-Southwold and Dunwich-Minsmere shorelines, the DSAS transects cast in the shoreline recession analysis were overlain on the digitised 2008 shoreline. A point-shapefile was created containing a point for each intersection of the 2008 shoreline with each DSAS transect, and converted to a featureclass file within ArcMap. The NextMap tiles were then used to derive a Triangular Irregular Network (TIN) for the coastline and the ArcMap Surface-Spot tool was used to generate an elevation for each of the points where a DSAS transect was cast along the 2008 shoreline. Correction of the derived elevations was carried out as described above. In total this analysis provided 800 spot heights for the coastal stretch between Benacre Ness and Southwold, as well as 300 spot heights for the Dunwich-Minsmere cliffs.

The spot heights at 10 m spacings were then used to produce an estimate of cliff face area for the cliffed subunits of Benacre, Covehithe, Easton Wood, Easton Bavents (Northend Warren and Easton Cliffs) and Dunwich-Minsmere (Fig. 3). Finally the volume of cliff loss in each of these subunits was found by combining each spot height with its equivalent shoreline recession found from the DSAS analysis, using the EPR for the period 2001-2008. This EPR was chosen to correspond to the years for which NextMap elevation data were available and to ensure that calculated cliff volume losses were based upon a cliff section that was broadly representative of the current (2010) cliffline. Combining the DSAS EPR with the corrected NextMap elevations enabled total volume loss to be found for the period 2001-2008, as well as providing an estimate of average annual sediment inputs from both the Benacre-Southwold and the Dunwich-Minsmere cliff systems.

4. Results

4.1. Cliff recession rates, 1883-2008

For the Suffolk coast between Benacre Ness and Southwold, coastal retreat has been considerable over the 125 year period since 1883, ranging from 550±4 m at the northern end of the study site (near EA profile SWD2; see Fig. 1) to 250±4 m towards the southern end (SWD8). There is a clear north-south trend in the overall retreat in shoreline position over the time period studied, from a mean annual retreat rate of almost 3.5 m a^{-1} at Covehithe to less than 2.4 m a^{-1} at Easton Cliffs (Fig. 5). Although the Dunwich-Minsmere area has traditionally been thought of as having high rates of cliff recession, it is clear that over the period 1883-2008 retreat rates were far lower than for the coastline between Benacre Ness and Southwold. The overall shoreline retreat varied between 90-128±4 m at different locations along this frontage, with mean rates being less than 1.0 m a^{-1} (Fig. 5). For the period between 1826 and 1976, Carr (1979) commented upon the differences between mean erosion at Easton Bavents (1849-1970/72: 2.69-2.95 m a^{-1}) compared with Dunwich – Minsmere (1826-1975/76: 0.91-1.59 m a^{-1}). The N-S trend towards lower retreat rates as well as the contrasting rates between Benacre-Southwold and Dunwich-Minsmere can also be supported in the cliff retreat rates established from the EA shore profiles for the period 1992-2008.

Figs. 5 and 6 about here

The DSAS methodology allows these general long-term temporal trends to be viewed in detail alongshore (Fig. 6). For the Benacre Ness-Southwold shoreline, the pattern of annual average shoreline retreat can be divided into five segments: a region of very low (< 1 m a^{-1}) long-term shoreline recession in the vicinity of Benacre; a region of high annual average retreat, in excess of 4 m a^{-1} between 1.0 and 2.4 km alongshore and reaching 5 m a^{-1} at 1.4 km; a transition zone of declining (4 to < 3 m a^{-1}) recession rates between 2.4 and 3.5 km; a long section characterised by an average annual retreat rate of 3 m a^{-1} between 3.5 and 6.2 km; and, finally a section of declining recession rate (3 m a^{-1} to 2 m a^{-1}) from 6.2 to 7.6 km (Fig. 6A). The area of land lost for this period in this area can be estimated at 1 944 822 m^2 (~ 200 hectares) or 1.6 ha a^{-1}. By contrast, the Dunwich-Minsmere cliffs showed an overall lower shoreline retreat rate, as well as lower alongshore variability (Fig. 6B). The annual average shoreline retreat 1883-2008 increased from 0.5 m a^{-1} at the northern end of the Dunwich cliffs to 1 m a^{-1} at 1.0 km, thereafter staying close to this recession rate before declining towards 0.5 m a^{-1} south of 2.6 km alongshore from Dunwich. There was a greater consistency in retreat rates alongshore (0.5-1 m a^{-1}), with much lower overall shoreline change (Fig. 6B). These rates appear to have been characteristic of a much longer time period; Carr (1979) estimates a recession rate of 1.15 m a^{-1} for the period 1587-1975. From the analysis presented here, the land loss for the Dunwich-Minsmere cliffs can be estimated at 361 341 m^2 (36 ha), or 0.3 ha a^{-1}, between 1883 and 2008.

The Benacre Ness to Southwold EPR for the period 1883-1947 shows remarkable consistency with the data on shoreline recession calculated using a similar methodology and for approximately the same time period, but at 250 m intervals alongshore, by Cambers (1973, 1975) (Fig. 6A). The transects from 0 to 0.5 km alongshore in Fig. 6A show that advance (i.e. negative rates of shoreline change) characterised the period between 1883 and 1947 but that there was a major shift towards erosion over the last 60 years. These changes reflect evolutionary changes in the position and morphology of Benacre Ness. A comparison of the 1883-1947 EPR with the 1883-2008 EPR, shows a decrease in the retreat rate, of up to 1 m a^{-1}, over the last 60 years in the region of 1.7 km alongshore. However, south of 2.9 km, until 6.7 km, the post-1947 cliff retreat rates were higher than the 1883-1947 mean rates, by up to 1 m a^{-1} in places. By contrast for the Dunwich-Minsmere cliffs (Fig. 6B), except in the region of 1.0 km alongshore, the 1883-1941 EPR lies consistently above the 1883-2008 EPR, indicating a decrease in cliff retreat rates, although generally by less than 0.5 m a^{-1}, over the last 60 years. It is noteworthy that here the fit between the results of Cambers (1973, 1975) and both DSAS analyses is highly variable, with a tendency for Cambers' calculations to provide higher estimates of the rate of coastal retreat along the Dunwich cliffs, at several locations by 0.5 m a^{-1} and, exceptionally, by 1 m a^{-1} (Fig. 6B). The significance of these differences is discussed further below.

Figs. 7 and 8 about here

Figs 7 and 8 disaggregate the mean annual cliff recession rate by time period for the Covehithe to Easton Bavents and Dunwich to Minsmere cliffed sections respectively; further statistics are reported in Table 2. At Covehithe, mean annual cliff retreat rates varied between 2.55±1.22 and 3.53±1.07 m a^{-1} between 1883 and 1981. However, for the period 1981-1992, the rate of coastal retreat accelerated to 5.10±0.88 m a^{-1}. Retreat rates remained high, at 4.66±0.55 m a^{-1} in the period 1992-2008. At Easton Wood, no cliffed shoreline was present in 1883 but between 1903 and 1992, the emerging cliffed area showed four phases of progressively increasing shoreline retreat, with mean annual retreat rate rising from 1.17±0.15 m a^{-1} over the period 1903-1925 to 3.62±0.24 m a^{-1} for 1981-1992. The rate of retreat after 1992 fell to 2.88±0.31 m a^{-1}. At Northend Warren, the northern section of the Easton Bavents cliffs, a similar trend in rising retreat rate was seen from 1883-1903, peaking at 5.13±0.28 m a^{-1} in the period 1947-1974. Thereafter there was a significant decline in retreat rate to 1.80±0.14 m a^{-1} in the period 1974-92, before a further rise in retreat rate to 3.25±0.12 m a^{-1}, back to 1925-1947 levels, in the period 1992-2008. At Easton Cliffs, the pattern of change has been more complex, with a statistically significant trend towards declining retreat rates from 3.33±0.71 m a^{-1} between 1883 and 1903 to 0.81±0.78 m a^{-1} between 1925 and 1947. There was then a large rise in retreat rate, to 2.65±0.63 m a^{-1}, in the period 1947-1974. After 1974, retreat rates were broadly comparable if slightly lower, at 2.38±0.40 to 2.23±0.66 m a^{-1}.

For the Dunwich-Minsmere cliffs, Fig. 8 shows that a significant shift in cliffline retreat rate took place after 1925. In the period 1883-1925 the retreat rate varied between 1.49±0.78 and 1.72±0.30 m a^{-1}; between 1925 and 1992 it varied between 0.41±0.21 and 0.65±0.24 m a^{-1}, with a further fall to a retreat rate of 0.25±0.26 m a^{-1} between 1992 and 2008. This reduction is particularly noticeable when the long-term (1883-2008) EPR is plotted alongside the EPR calculated for the periods 1992-2008 and 2001-2008, based on cliffline position as recorded by aerial photography (Fig. 9). Whereas the short-term records for the cliffed sections of the Benacre-Southwold coastline have oscillated around the long-term trend (Fig. 9A), the recent cliff retreat between Dunwich and Minsmere falls well below the long-term trend, apart from an area at the southern end of the Minsmere cliffs, and to a lesser extent the most northerly Dunwich cliffs between 1992 and 2001 (Fig. 9B).

Fig. 9 about here

The periods of short record in Fig. 9 highlight the ‘spiky’ nature of shoreline retreat at the alongshore sampling interval of 10 m and show how over time periods of less than ten years (i.e. comparing 1992-2008 with 2001-2008) coherent but large scale shifts in erosional behaviour can take place over alongshore distances of less than 1 km. Measurements of coastline change from the EA shore profiles for the same periods as the aerial photographs (i.e. EA summer profiles for 1992, 2001 and 2008) are also plotted on this figure. As might be expected, the at-a-point correspondence between the DSAS derived retreat rates and the records of profile change are good but the comparison highlights the difficulty in extrapolating cliffline behaviour at 1 km spacings to the coastline as a whole.

4.2. Volumetric sediment losses from retreating cliffs

Cliff volume loss is the product of the alongshore variation in cliffline elevation and coastal recession rate. The linked methodologies described in this paper – the extraction of cliff top elevation data from digital terrain models and the derivation of retreat rates from the casting of shore normal transects between shorelines of well-constrained age at a sampling interval of just 10 m alongshore – allow a much better estimation of sediment volume inputs into the nearshore zone along the Suffolk coast than has been obtained previously. Table 3 shows the average annual volumetric loss of sediment from each of the cliffed sections on the Suffolk coast over the period 2001-2008. This analysis includes a contribution from shoreline retreat along a coastal section to the north of Covehithe, around Benacre, which was previously undergoing shoreline advance in the period between the 1880s and the 1940s. The northward migration (estimated at 20 m a^{-1}; Babtie Group and Birkbeck College, 2000) of Benacre Ness has resulted in the re-activation of coastal erosion on a fossil cliffline in the vicinity of Benacre. For the northern part of the study region, volumetric losses totalled an estimated 115 341 m^3 a^{-1} between 2001 and 2008. For the southern part of the study region, at Dunwich-Minsmere, the greater cliff heights have been more than offset by lower retreat rates, leading to a total annual sediment loss of just 4 666 m^3 a^{-1} in the same period. The total mean sediment volume input into the nearshore zone from both parts of the study region was thus estimated at ca. 120 000 m^3 a^{-1}. Using the sediment composition established for these different cliff sections (Table 1), it can be assumed that the overwhelming majority (89.0%) of the sediment input was of sand-sized material, with small contributions from the silt/clay (6.8%) and gravel (4.3%) fractions (Table 3).

The period 2001-2008 was a period of generally lower cliff recession rates than in the decade preceding it (Table 3; Figs 7, 8). Due to the lack of detailed cliff top height information for earlier periods, it is not possible to accurately estimate sediment losses for earlier time periods. However, of the two main determinants of volume change, the analysis carried out in this study suggests that variation in retreat rate produces a greater response in sediment volume than variation in clifftop elevation. Thus if one assumes a similar cliff height in the recent past at each of the cliffed sections, then it is possible to estimate sediment volume losses for the period 1992-2001, a phase of higher regional cliff recession rates (Table 3). These estimates suggest inputs of 195 000 m^3 a^{-1} for the Benacre – Southwold shoreline and 13 000 m^3 a^{-1} for the Dunwich – Minsmere cliffs, giving a total mean sediment input to the nearshore zone of 208 000 m^3 a^{-1} (i.e. + 73 % on the 2001-2008 estimate). For the period from 1992 to 2008, encompassing the periods of both relatively higher and relatively lower rates of cliffline retreat, the total estimated input is suggested to be ca. 160 000 m^3 a^{-1} (i.e. + 33% on the 2001-2008 estimate) (Table 3).

5. Discussion

5.1. Cliff recession rates and patterns of alongshore change

This study of coastal cliff recession rates along the Suffolk coast since the late nineteenth century shows that there has been a well-defined and persistent trend towards declining retreat rates from north to south; thus at the largest scale presented here, there is clear evidence for a re-positioning of the East Anglian coastline towards a more N-S orientation. Within this context, it is not surprising, therefore, that much of the concern over high erosion rates on this coast, has focused on land loss near the village of Covehithe (e.g. Robinson, 1966; Steers et al., 1979). In contrast to Robinson's (1966) argument for a progressive decline in shoreline retreat between 1882 and the 1960s, this analysis shows that at Covehithe mean cliff retreat rates have oscillated between 2.5 and 3.5 m a^{-1} for the almost one hundred year period between 1883 and 1981 (Table 2). As a result, for example, the extensive World War II anti-invasion defences, clearly visible on 1940s RAF aerial photography, have now been completely lost to the sea (Newsome, 2003). It is notable, however, that after 1981 retreat rates increased from this already high level, at first (1981-1992) to rates in excess of 5 m a^{-1}, but still greater than 4.5 m a^{-1} after 1992 (Table 2; Fig. 7). Furthermore, even these high mean rates hide some remarkable rates of short-term recession. Thus, for example, 18.3 m of retreat was recorded in a single year, 1887 (Whitaker, 1907); 12-27 m of erosion between 1951 and 1953, in part associated with the impact of the severe 31 January – 1 February 1953 North Sea storm surge (Williams, 1956); 34.8 m of retreat between 1977 and 1979, related in part to the 11 January 1978 storm surge (Steers et al., 1979); and 15.8m of recession occurred between winter 1993 and winter 1994 (Lee, 2008).

Coastal erosion, in the form of a retreating cliffline, appears to have extended southwards historically along this coast. At Easton Wood, 1.6 km south of Covehithe village, no cliffline is depicted on the 1882-1883 map, suggesting low land elevations and associated low sediment release volumes. However, by 1903, a cliffline was mapped on the OS map, suggesting the 'switching on' of cliff retreat and associated sediment release. Thereafter coastal erosion accelerated at Easton Wood reaching rates of retreat typical of the Covehithe cliffed subunit (i.e. 3 m a^{-1}) in the period 1947-1981 (Table 2; Fig. 7). After 1981, Easton Wood mirrored recessional behaviours at Covehithe, peaking in the period 1981-1992 and remaining high between 1992 and 2008. A similar pattern of erosional 'start up' is evident in the record from the small coastal section of Northend Warren, although here a cliff does appear to have been present since the 1880s. Here, rates of coastal recession accelerated from less than 1 m a^{-1} to in excess of 5 m a^{-1} by the period 1947-1981. It is interesting that whereas further north the period between 1981 and 1992 was a phase of accelerated erosion, here retreat rates declined between 1974 and 1992, to less than 2 m a^{-1} (Table 2; Fig. 7). One might speculate that the increased sediment inputs to the nearshore zone from accelerated cliff retreat 1-4 km to the north, and the southerly drift and nearshore sedimentation of this increased sediment supply, might have resulted in a slowing of the rate of cliff recession at this locality.

At Easton Bavents, extremely high rates of coastal retreat were recorded in the nineteenth century (Tables 1 and 3). Carr (1979) reports mean annual rates of retreat of between 2.7 and 3.0 m a^{-1} between 1849 and 1970/72 and this analysis confirms recession of this order of magnitude between 1883 and 1925. However, the pattern thereafter was more complex (Table 2; Fig. 7). The site shows an almost mirror image of the Northend Warren cliff behaviour until the end of the period 1925-47, with rates of cliffline recession progressively falling from in excess of 3 m a^{-1} to less than 1 m a^{-1} (Table 2; Fig. 7). This again suggests, but at a more local scale, shoreline adjustments to patterns of sediment inputs from cliff erosion and subsequent accumulation. There was, however, a strong re-establishment of rates of retreat in excess of 2.5 m a^{-1} in the period 1947-1974 which were maintained above 2 m a^{-1} thereafter (although the most recent (1992–2008) shoreline retreat rates have been influenced by *ad hoc* coastal protection measures emplaced at the cliff foot since 2002).

Major changes in coastal configuration at Dunwich, including the disappearance of a former peninsula, spit development and the shoaling of a previously wide and deep estuary (Chant, 1986; Pontee, 2005; Pye and Blott, 2009), which led to the loss of Roman, Saxon and most of the medieval settlement, have often been used to argue for particularly dramatic rates of concomitant cliff retreat at this locality. However, long-term historical records, often well-constrained by the measured distances of church and monastic buildings from the cliff margin, show a record of unexceptional rates of retreat, albeit punctuated by periods of very rapid recession, often related to severe storm events (and equally periods of cliff line stasis). The long-term (1883-2008) recession rate of 0.94 m a^{-1} sits squarely within these estimates (Table 2). Furthermore, the rates of cliff retreat between 1883-1903 and 1903-1925, at 1.49 and 1.72 m a^{-1} respectively, do not represent significant accelerations on this long-term trend. However, the reduction in retreat rates to <0.5 m a^{-1} in the period 1925-1941, and rates less than 1 m a^{-1} thereafter, is striking and confirms Robinson's (1980, 142) statement that 'since 1925 the rate of cliff recession has diminished dramatically and in recent years part of the cliff face has stabilised to the extent that that it has become grass covered … the present rate of coastal retreat is only a fraction of that taking place in the past' (and see Fig. 2, this paper). How such changes might be explained are considered in more detail below.

5.2. Sediment losses from retreating cliffs and regional sediment budgets: a re-appraisal

One of the outcomes of the East Anglian Coastal Research Programme in the 1970s (University of East Anglia, Norwich, UK; Onyett and Simmonds, 1983) was the establishment of sediment budgets for the East Anglian coast, estimating both point-source sediment inputs from cliff erosion and inferring subsequent alongshore sediment transport pathways (Clayton et al., 1983). Within this research programme, the research of Gillian Cambers (Cambers, 1973, 1975; Cambers et al., 1977) focussed on establishing the sediment inputs from eroding cliffs. Cambers' methodology was based on establishing cliff recession rates from UK Ordnance Survey map evidence at 250 m intervals along the coast for the period between the 1880s and the 1950s. The re-analysis in this paper of the areas and general time period of Cambers' analysis, but using the DSAS methodology and transects spaced at 10 m rather than 250 m intervals, shows the robustness of the two different cliff recession estimates for the Covehithe – Easton Cliffs area (Fig. 6A). However, for the Dunwich – Minsmere cliffs, Cambers' estimates do not correspond to the DSAS calculations, with typical differences in recession rates of 50% and in places differences of over 100% between the two methodologies (Fig. 6B). It is not clear why there is good correspondence between the results of this analysis and the earlier methodology in the northern part of the study area and not in the south, although it might be noted that the fit is good in an area of high rates of coastal retreat and poor where low rates of coastal recession make the fixing of former shorelines from map evidence more challenging.

Cambers' analysis (Cambers, 1973, 1975; Cambers et al., 1977) went on to provide a sediment input to coastal budget models of 30 000 m^3 a^{-1} from the cliffs between Covehithe and Easton Bavents (i.e. as far south as Easton Cliffs in the terminology used in this paper). A further analysis by Carr (1981) estimated the inputs from the cliffs at Easton Bavents as 35 309 m^3 a^{-1}. It is unfortunate that the lack of detailed elevation data for the land lost in the hundred year period between the late nineteenth century and the availability of high resolution aerial photographs in the 1990s precludes the development of new, more detailed estimates of average annual sediment inputs over a more extended historical period. However, utilising information for the period since aerial photographs became available in 1992, and taking the same coastline lengths as Cambers, this paper suggests sediment inputs over the period 1992 – 2008 of ca. 150 000 m^3 a^{-1} from the cliffs between Covehithe and Easton Bavents. These figures do not, however, include a component from the recent re-activation of erosion at Benacre Ness; if this sediment input is included in the calculations the total mean annual sediment input rises to ca. 178 500 m^3 a^{-1}. For comparison with Carr (1981), the sediment input from Northend Warren/Easton Cliffs is required; this analysis suggests that figure of ca. 38 000 m^3 a^{-1}, very close (±1%) to Carr's earlier estimate, over the period 1992-2008. Sediment inputs from the Dunwich-Minsmere cliff system can also be compared between this study and the earlier estimates. Cambers' estimated input (Cambers, 1973, 1975; Cambers et al., 1977) was 40 000 m^3 a^{-1}, and Carr's (1981) 56 249 m^3 a^{-1}. The comparable estimate in this analysis for the Dunwich-Minsmere cliff system is ca. 9 500 m^3 a^{-1} (1992–2008), a four- to six–fold decrease on previous rates. Overall, previous estimates for total (Covehithe – Easton Bavents and Dunwich-Minsmere) sediment inputs into the nearshore zone have ranged between 70 000 m^3 a^{-1} (annual average sediment loss 1883–1957; Cambers, 1973) to 91 500

m^3 a^{-1} (annual average sediment loss 1867–1975; Carr, 1981). In summary, this paper suggests that, over the period 1992–2008, the total sediment input has been of the order of 160 000 m^3 a^{-1} and that the spatial distribution of these inputs has been rather different than that suggested previously.

These differences are important in the context of the subsequent mobilization and transport of the released sediments about which there has been considerable debate (McCave, 1978; Vincent, 1979; Onyett and Simmonds, 1983; Halcrow, 2001). Vincent (1979) indicates a southward longshore drift potential of around 65 000 m^3 a^{-1} southward from Covehithe for the period 1964-1976, while McCave, from patterns of beach sediment size grading, suggests that sediment may also move northwards from Covehithe. Onyett and Simmonds (1983) modelled a wave induced longshore transport rate of 105 000 m^3 a^{-1} in the southern part of Benacre in a roughly southwesterly direction. However, subsequent modelling by Halcrow (2001), reported in the Southern North Sea Sediment Transport Study (HRWallingford, 2002) and supported by that study, suggests lower net transport rates of 2 500 m^3 a^{-1} at the southern end of Benacre, 18 250 m^3 a^{-1} around Covehithe and 3 100 m^3 a^{-1} at Southwold, with movement in a generally southwesterly direction. The general conclusion, therefore, is that net longshore transport rates are generally southerly from Benacre Ness to Southwold and have a magnitude of around 20 000 m^3 a^{-1}, although the modelled outcomes depend on the bathymetry that is used for model building purposes. For the Dunwich-Minsmere cliffs, a net transport rate past the cliffs of 12 100 m^3 a^{-1} has been suggested (Halcrow, 2001). For 2 mm and 10 mm gravel, Black and Veatch Consulting Ltd. (2005) modelled a net southerly transport at the cliffs of 13 900 and 3 800 m^3 a^{-1} respectively.

These sediment transports are complicated by the presence of several dynamic offshore bank systems which are thought to act as sinks for much of the sediment source from the eroding cliffs. Furthermore, the banks are likely to play a role in modifying the wave climate and tidal currents (Lees, 1983; Stansby et al., 2006; Horillo-Caraballo and Reeve, 2008), with critical feedbacks existing between eroding cliff sediment sources, longshore sediment movement, dynamic behaviour of the banks as sediment sinks, and continued erosion of the cliffs. Some of this discussion has focussed on the role of the Sizewell and Dunwich Banks which lie immediately offshore from the Dunwich-Minsmere cliffs. Thus, for example, Robinson (1980) argued that the reduction in cliff erosion rates here after 1925, confirmed by this study, could be attributed to the growth of these banks, by changing angles of wave approach and wave heights along the cliffed frontage. Carr (1981) argued that the Dunwich-Minsmere nearshore system is a relatively closed one, with local sediment cycling between the cliffs and the banks immediately offshore, and provided a model balancing inputs from cliff erosion (from Easton Bavents, Dunwich-Minsmere and Thorpeness) and offshore seabed lowering against bank sediment accumulation, with the slight excess of sediment input (of + 17%) explaining bank growth in the period 1867-1965. He had stressed earlier, however, that ‘this argument is only partly justified’ (Carr, 1979, 8). Similarly, Halcrow (2001) showed that beach volumes at Dunwich remain relatively constant over decadal timescales, suggesting that material added from cliff erosion is balanced by the onshore-offshore and alongshore net fluxes of sediment. Carr’s (1981) inputs from the cliff systems at Easton Bavents, Dunwich-Minsmere and Thorpeness totalled ca. 96 000 $m^3 a^{-1}$. It is difficult to test this model in detail because of i) a mismatch in timing between terrestrial mapping of cliff retreat and bathymetric surveys and ii) the long timespan employed in previous studies (1867-1965 by Carr (1981); 1868-1992 by Pye and Blott (2009)) which cut across a major shift in cliff retreat rates between 1903-1925 and 1925-1941 (Table 2; Fig. 8). However, for the period 1992-2008, cliff recession rates in Carr’s three source areas of cliff sediments (Dunwich-Minsmere, Easton Bavents and Thorpeness (supply assumed unchanged in the latter at 2.5 $m^3 a^{-1}$)) have yielded an estimated volume input of ca. 50 000 $m^3 a^{-1}$, only 50% of the cliff input in Carr’s (1981) model. With the virtual shutdown of cliff recession in the Dunwich-Minsmere system after 1925, alongside the general growth of the Dunwich-Sizewell Banks between 1868 and 1992 (Pye and Blott, 2009), it seems likely that, rather than being a local, closed system, sediments to the Dunwich-Sizewell Banks are most probably being additionally supplied with sediment from the rapidly eroding cliffs immediately to the north of the supply from Easton Bavents. These cliffs (at Covehithe, Easton Wood and Benacre) have had the potential to supply an additional 140 000 m^3 a^{-1} of cliff sediments in the period 1992-2008. Particularly at times of high coastal cliff retreat (as in the period 1992-2001; Table 3), there may even be sufficient sediment being released to also feed northward sediment transport, as suggested by both Robinson (1966) and McCave (1978), and growth of the Lowestoft Bank system.

6. Conclusions

There have been considerable changes on the Suffolk coast since Cambers' analyses in the 1970s, which was based on map evidence of coastal change between the 1880s and the 1950s. At Covehithe, for example, cliff heights have risen as the shoreline has retreated westwards. In 1907, when giving evidence to the Royal Commission on Coastal Erosion, on the basis of field observations made in the late 1870s to the late 1880s, William Whitaker described the shoreline at Covehithe as a 'low cliff, not, perhaps, more than half the height of this room' (Whitaker, 1907, 98). By 1947 the cliff height was 11 m and that had increased to 15.5 m by 2008. In addition, the length of the shoreline affected by cliff retreat expanded by 165 m between 1947 and 2008 and the mean cliff recession rate increased from 3 m a^{-1} (average of EPRs, 1883-1947) towards 5 m a^{-1} (EPR for 1992-2008). All these factors combined to give rise to substantial increases in cliff sediment losses and inputs into the nearshore zone over the period of record. Furthermore, to the south, similar changes have characterised the coast at Easton Wood, Northend Warren and Easton Cliffs and, to the north of Covehithe, coastal erosion has been re-activated at Benacre. Conversely, at Dunwich-Minsmere, cliff heights and the length of the eroding cliffline has remained constant (or even shortened with coastal protection at the northern end of the cliffs) and recession rates, for 1992-2008, declined to only 15% of the rate experienced in the period between 1883 and 1925. It is argued that coastal geomorphologists, modellers and managers should now move away from estimates of coastal sediment inputs to this part of the East Anglian coast derived from pioneering studies over 30 years ago and incorporate in their studies and decision making processes, more contemporary estimates of the magnitude and spatial patterning of sediment inputs along the Suffolk coast (Fig. 10). It is clear that there have been re-organisations of this coast over the last one hundred years, which have involved large-scale changes in coastline orientation, ness dynamics and offshore bank growth and decay, and that these changes have resulted in, and from, changing cliff erosion rates. How the cliffs, nesses and offshore banks will respond to changing water depths, storminess and alongshore sediment transport associated with global environmental change is unclear (Halcrow, 2002) but such studies should start from a firmer base provided by the record of historical morphodynamics.

Fig. 10 about here

Quantifying near-future rates of coastal change is highly relevant to those communities that live and work at dynamic coastal margins. Understanding these dynamics, their outcomes and their societal impacts is a major difficulty in soft rock cliff systems which exhibit not only high rates of change but also considerable variability in such rates over space and through time. The methodology outlined in this paper, using the Digital Shoreline Analysis System alongside detailed cliff elevations obtained using the Surface Spot tool with NextMap elevation data, allows spatial variability in cliff behaviour to be identified and assessed, rapidly and at a high level of spatial detail. This approach thus provides, in particular, much-improved estimates of current and future sediment volume release from rapidly eroding cliff systems and, in general, better-informed inputs into coastal management strategies.

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8. References

Addo, K.A., Walkden, M., Mills, J.P., 2008. Detection, measurement and prediction of shoreline recession in Accra, Ghana. ISPRS Journal of Photogrammetry and Remote Sensing 63, 543-558.

Babtie Group and Birkbeck College, 2000. Spits and Nesses. Basic processes and effects on long-term coastal morphodynamics. Report produced for MAFF, January 2000. DEFRA, London.

Bacon, J., Bacon, S., 1988. Dunwich Suffolk. Segment Publications, Colchester.

Balson, P.S., Mathers, S.I., Zalasiewicz, J.A., 1993. The lithostratigraphy of the Coralline Crag (Pliocene) of Suffolk. Proceedings of the Geologists' Association 104, 59-70.

Black and Veatch Consulting Ltd., 2005. Minsmere Frontage: Dunwich Cliffs to Sizewell Power Stations Coastal Processes Report. Report to the UK Environment Agency. Black and Veatch Consulting Ltd., Redhill, Surrey.

Bray, M.J., Hooke, J.M., 1997. Prediction of soft-cliff retreat with accelerating sea-level rise. Journal of Coastal Research 13, 453-467.

Cambers, G., 1973. The retreat of unconsolidated Quaternary cliffs. Ph.D. thesis, University of East Anglia, Norwich, U.K.

Cambers, G., 1975. Sediment transport and coastal change. East Anglian Coastal Research Programme Report No. 3. University of East Anglia, Norwich, U.K.

Cambers, G., 1976. Temporal scales in coastal erosion systems. Transactions, Institute of British Geographers, New Series 1, 246-256.

Cambers, G., Clarke, J., Clayton, K., Simmonds, A.C., 1977. Beach profiles: form and change. East Anglian Coastal Research Programme Report No. 5. University of East Anglia, Norwich, U.K.

Carr, A.P., 1962. Cartographic record and historical accuracy. Geography 47, 135-144.

Carr, A.P., 1969. The growth of Orford spit: Cartographic and historical evidence from the 16th century. The Geographical Journal 135, 28-29.

Carr, A.P., 1979. Sizewell-Dunwich Banks Field Study. Topic Report: 2. Long-term changes in the coastline and offshore banks. Report No. 89. Institute of Oceanographic Sciences, Taunton, pp.1-25.

Carr, A.P., 1981. Evidence for the sediment circulation along the coast of East Anglia. Marine Geology 40, M9-M22.

Chant, K., 1986. The history of Dunwich (3rd reprint). Trustees of Dunwich Museum, Dunwich, pp.1-20.

Clayton, K.M., 1989. Sediment input from the Norfolk cliffs, eastern England: A century of coast protection and its effects. Journal of Coastal Research 5, 433-442.

Clayton, K.M., McCave, I.N., Vincent, C.E., 1983. The establishment of a sand budget for the East Anglian coast and its implications for coastal stability. In: Institute of Civil Engineers, (Eds.), Shoreline Protection. Proceedings of a conference organised by the Institute of Civil engineers, University of Southampton, 14-15 September 1982. Thomas Telford, London, pp.63-68.

Cooper, E.R., 1907. Evidence to the Royal Commission. Royal Commission on Coast Erosion (Part 1). Wyman & Sons, London, 302-303.

Dolan, R., Fenster, M.S., Holme, S.J., 1991. Temporal analysis of shoreline recession and accretion. Journal of Coastal Research 7, 723–744.

Dowman, I., Balan, P., Renner, K., Fischer, P., 2003. An evaluation of NextMap terrain data in the context of U.K. national datasets. Report prepared for GetMapping, University College London, Department of Geomatic Engineering.

Ehlers, J., Gibbard, P.L., 1991. Anglian glacial deposits in Britain and the adjoining offshore regions. In: Ehlers, J., Gibbard, P.L., Rose, J., (Eds.), Glacial Deposits in Great Britain and Ireland. Balkema, Rotterdam, pp.17-24.

Esteves, L.S., Williams, J.J., Nock, A., Lymbery, G., 2009. Quantifying shoreline changes along the Sefton Coast (UK) and the implications for research-informed coastal management. Journal of Coastal Research SI 56 (Proceedings of the 10th International Coastal Symposium), 602 – 606.

Fortnum, B.C.H., Hardcastle, P.J., 1979. Waves recorded at Aldeburgh, Dunwich and Southwold on the east coast of England. Institute of Oceanographic Sciences Report 65/79, Taunton, pp.1-9.

French, P., 2001. Coastal Defences: Processes, Problems and Solutions. Routledge, London.

Funnell, B.M., West, R.G., 1962. The Early Pleistocene of Easton Bavents, Suffolk. Quarterly Journal of the Geological Society of London 118, 125-141.

Gibbard, P.L., Zalasiewicz, J.A., (Eds.), 1988. Pliocene -Middle Pleistocene of East Anglia Field Guide. Quaternary Research Association, Cambridge.

Gibbard, P.L., Zalasiewicz, J.A., Mathers, S.J., 1998. Stratigraphy of the marine Plio-Pleistocene crag deposits of East Anglia. Mededelingen Nederlands Instituut voor Toegepaste Geowetenschappen TNO 60, 239-262.

Gibbard, P.L., Cohen, K.M., Boreham, S., Moscariello, A., 2007a. Global chronostratigraphical correlation table for the last 2.7 million years. Subcommission on Quaternary Stratigraphy, International Commission on Stratigraphy, Cambridge.

Gibbard, P.L., Moscariello, A., Bailey, H.W., Boreham, S., Koch, C., Lord, A.R., Whittaker, J.E., Whiteman, C.A., 2007b. Comment: Middle Pleistocene sedimentation at Pakefield, Suffolk, England. J.R. Lee, J. Rose, I. Candy and R.W. Barendregt (2006). Journal of Quaternary Science 21, 155-179. Journal of Quaternary Science 23, 85-92.

Gray, J.M., 1988. Coastal cliff retreat at the Naze, Essex since 1874: patterns, rates and processes. Proceedings of the Geologists' Association 99, 335-338.

Guthrie, G., Cottle, R., 2002. Suffolk coast and estuaries coastal habitat management plan. Report prepared for English Nature / Environment Agency. Posford Haskoning UK Ltd., Peterborough, U.K. Available at: http://www.eclife.naturalengland.org.uk/champs/pilots.asp (Accessed 20 July 2010).

Halcrow, 1991. The Anglian Sea Defence Management study – Stage III. Study Report. Report prepared for NRA Anglian Region. Sir William Halcrow and Partners, Swindon, U.K..

Halcrow, 2001. Lowestoft to Thorpeness Coastal Processes and Strategy Study. Volume 2: Coastal Processes. Report produced for Waveney District Council, Suffolk Coastal District Council, Environment Agency. Sir William Halcrow and Partners, Swindon, U.K.

Halcrow, 2002. Futurecoast. Three CD set comprising reports, interactive map browser and oblique aerial photography of the coastline of England and Wales. Department of Envirobnment, Food and Rural Affairs, London, U.K. Available at: http://www.halcrow.com/Our-projects/Project-details/Futurecoast-England (Accessed 20 July 2010).

Hamblin, R.J.0., Moorlock, B.S.P., Booth, S.J., Jeffrey, D.H., Morigi, A.N., 1997. The Red Crag and Norwich Crag formations in eastern Suffolk. Proceedings of the Geologists' Association 108, 11-23.

Hanson, S., Nicholls, R.J., Balson, P., French, J.R., Spencer, T., Sutherland, W.J., 2007. Capturing coastal morphological change within regional integrated assessment: an outcome-driven fuzzy logic approach. Tyndall Centre for Climate Change Research, University of East Anglia, Working Paper 113, 1-39.

Harley, J.B., 1972. Maps for the local historian: A guide to the British sources. National Council of Social Service for the Standing Conference for Local History.

Hellard, R.C., 1907. Evidence to the Royal Commission. Royal Commission on Coast Erosion (Part 1). Wyman & Sons, London, 46.

Hey, R.W., 1967. The Westleton Beds reconsidered. Proceedings of the Geologists' Association 87, 69-82.

Horrillo-Caraballo, J.M., Reeve, D.E., 2008. Morphodynamic behaviour of a nearshore sandbank system: The Great Yarmouth Sandbanks, U.K. Marine Geology 254, 91-106.

Horsburgh, K.J., Williams, J.A., Flowerdew, J., Mylne, K., 2008. Aspects of operational forecast model skill during an extreme storm surge event. Journal of Flood Risk Management 1, 213-221.

HRWallingford, 2002. Southern North Sea Sediment Transport Study, Phase 2. Sediment Transport Report. HRWallingford Report EX4526, Howbery Park, Wallingford, Oxford, UK.

James, J.W.C., Lewis, P.M., 1996. Sediment input from coastal cliff erosion. Technical Report 577/4/A, Environment Agency, Peterborough.

Jones, J.R., Cameron, B., Fisher, J.J., 1993. Analysis of cliff retreat and shoreline erosion: Thompson Island, Massachusetts, U.S.A. Journal of Coastal Research 9, 87-96.

Lee, E.M., 2008. Coastal cliff behaviour: Observations on the relationship between beach levels and recession rates. Geomorphology 101, 558-571.

Lee, E.M., Clark, A.R., 2002. Investigation and Management of Soft Rock Cliffs. Thomas Telford, London.

Lee, J.R., Rose, J., Candy, I., Barendregt, R.W., 2006. Sea-level changes, river activity, soil development and glaciation around the western margins of the southern North Sea basin during the Early and early Middle Pleistocene: evidence from Pakefield, Suffolk, UK. Journal of Quaternary Science 21, 155-179 (Erratum, 419-420).

Lees, B.J., 1983. Observations of tidal and residual currents in the Sizewell-Dunwich area, East Anglia, U.K. Ocean Dynamics 36, 1-24.

Limber, P.W., List, J.H., Warren, J.D., 2007. Management applications of Lidar-derived mean high water shorelines in North Carolina. Proceedings, Coastal Zone 07 Portland, Ore., 22-26 July 2007.American Society of Civil Engineers, Reston, VA.

Long, P.E., 1974. Norwich Crag at Covehithe, Suffolk. Suffolk Natural History 16, 199-208.

McCave, I.N., 1978. Grain-size trends and transport along beaches: Example from eastern England. Marine Geology 28, M43-M51.

Marine Aggregate Levy Sustainability Fund, 2009. The outer Thames Estuary regional environmental characterisation. Report No: 09/J/1/06/1305/0870. ALSF-MEPF Secretariat, Cefas, Lowestoft, Suffolk, U.K.

Mathers, S.J., Zalasiewicz, J.A., 1996. A gravel beach-rip channel system; the Westleton Beds (Pleistocene) of Suffolk, England. Proceedings of the Geologists' Association 107, 57-67.

Moore, L.J., 2000. Shoreline mapping techniques. Journal of Coastal Research 16, 111-124.

Mottram, H.B., 1989. The Upper Caenozoic sequences around Long Row, Covehithe. Suffolk Natural History 25, 86-91.

Mottram, H.B., 1997. The channel gravels of the Dunwich and Minsmere cliffs. Suffolk Natural History 33, 77-80.

Muir-Wood, R., Drayton, M., Berger, A., Burgess, P., Wright, T., 2005. Catastrophe loss modelling of storm-surge flood risk in eastern England. Philosophical Transactions of the Royal Society of London, Series A 363, 1407-1422.

Newsome, S., 2003. The coastal landscapes of Suffolk during the Second World War. Landscapes 4, 42-58.

Nicholls, R. J., Wong, P.P., Burkett, V.R., Codignotto, J., Hay, J.E., McLean, R.F., Ragoonaden, S., Woodroffe, C.D., 2007. Coastal Systems and Low-lying Areas. In: Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., Hanson, C.E., (Eds.), Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp. 315-356.

Nicholson-Cole, S.A., O'Riordan, T., 2009. Adaptive governance for a changing coastline: science, policy and the public in search of a sustainable future. In: Adger, W.N., Lorenzoni, I., O'Brien, K., (Eds.), Living with Climate Change: Are there limits to adaptation? Cambridge University Press, Cambridge, pp.368-383.

Oliver, R., 1996. Taking to the water: some examples of OS mapping of the coast. Sheetlines 45, 9-27.

Onyett, D., Simmonds, A., 1983. Beach transport and longshore transport. East Anglian Coastal Research Programme Report No. 8. University of East Anglia, Norwich, U.K.

Pethick, J., 1996. Coastal slope development: temporal and spatial periodicity in the Holderness cliff recession. In: Anderson, M.G., Brooks, S.M., (Eds.), Advances in Hillslope Processes. John Wiley and Son, Chichester, pp. 897-917.

Pontee, N., 2005. Management implications of coastal change in Suffolk. Proceedings of the Institution of Civil Engineers, Maritime Engineering 158, Issue MA2, 69–83.

Pugh, D.T., 1987. Tides, Surges, and Mean Sea Level. John Wiley and Sons, Chichester.

Pye, K., Blott, S.J., 2006. Coastal processes and morphological change in the Dunwich – Sizewell area, Suffolk, UK. Journal of Coastal Research 22, 453-473.

Pye, K., Blott, S.J., 2009. Progressive breakdown of a gravel-dominated coastal barrier, Dunwich–Walberswick, Suffolk, U.K.: Processes and implications. Journal of Coastal Research 25, 589-602.

Reeve, D.E., Fleming, C.A., 1997. A statistical-dynamical method for predicting long term coastal evolution. Coastal Engineering 30, 259-280.

Reid, C., 1907. Evidence to the Royal Commission. Royal Commission on Coast Erosion (Part 1). Wyman & Sons, London, 99-100.

Richards, K.S., Lorriman, N.R., 1987. Basal erosion and mass movement. In: Anderson, M.G., Richards, K.S., (Eds.), Slope stability. John Wiley and Son, Chichester, pp. 331-357.

Robinson, A.H.W., 1966. Residual currents in relation to shoreline evolution of the East Anglian coast. Marine Geology 4, 57-63, 67-84.

Robinson, A.H.W., 1980. Erosion and accretion along part of the Suffolk coast of East Anglia, England. Marine Geology 37,133–146.

Seymour, W.A., 1980. A history of the Ordnance Survey. Dawson: Folkestone.

Shennan, I., Horton, B.P., 2002. Holocene land- and sea-level changes in Great Britain. Journal of Quaternary Science 17, 511–526.

Stansby, P., Cui-Ping Kuang, Laurence, D., Launder, B., 2006. Sandbanks for coastal protection: implications of sea-level rise. Part 1: Application to East Anglia. Tyndall centre for Climate Change Research, Working Paper 86. University of East Anglia, Norwich, U.K.

Steers, J.A., 1953. The East Coast Floods January 31–February 1 1953. The Geographical Journal 119, 280-298.

Steers, J.A., 1964. The coastline of England and Wales. Cambridge University Press, Cambridge.

Steers, J.A., Stoddart, D.R., Bayliss-Smith, T.P., Spencer, T., Durbridge, P.M., 1979. The storm surge of 11 January 1978 on the east coast of England. The Geographical Journal 145, 192-205.

Suffolk Coastal District Council, 2010. Final Report, First Review of Shoreline Management Plan Sub-Cell 3c. Available at: http://www.suffolksmp2.org.uk (Accessed 20 July 2010).

Thieler, E.R., Himmelstoss, E.A., Zichichi, J.L., Miller, T.L., 2005. Digital Shoreline Analysis System (DSAS) version 3.0: An ArcGISc extension for calculating shoreline change. US Geological Survey Open-File Report 2005-1304.

Thorne, C., Evans, E.P., Penning-Rowsell, E.C., (Eds.), 2007. Future Flood and Coastal Erosion Risks. Thomas Telford, London.

Tukey, J.W., 1977. Exploratory Data Analysis. Addison-Wesley. New York.

Valiela, I., 2006. Global Coastal Change. Blackwell Publishing, Oxford.

Vincent, C.E., 1979. Longshore sand transport rates – a simple model for the East Anglian coastline. Coastal Engineering 3, 113-136.

West, R.G., 1980. The pre-glacial Pleistocene of the Norfolk and Suffolk coasts. Cambridge University Press, Cambridge.

West, R.G., Funnell, B.M., Norton, P.E.P., 1980. An early Pleistocene cold marine episode in the North Sea: pollen and faunal assemblages at Covehithe, Suffolk, England. Boreas 9, 1-10.

Whitaker, W., 1887. The geology of Southwold, and of the Suffolk coast from Dunwich to Covehithe. Memoirs of the Geological Survey of England and Wales, pp.1-87.

Whitaker, W., 1907. Evidence to the Royal Commission. Royal Commission on Coast Erosion (Part 1). Wyman & Sons, London, 98-99.

Williams, W.W., 1956. An east coast survey: some recent changes in the coast of East Anglia. The Geographical Journal 122, 317–334.

Woodworth, P.L., Teferle, F.N., Bingley, R.M., Shennan, I., Williams, S.D.P., 2009. Trends in UK mean sea level revisited. Geophysical Journal International 176, 19–30.

Zalasiewicz, J.A., Mathers, S.J., Hughes, M.J., Gibbard, P.L., Peglar, S.M., Harland, R., Nicholson, R.A., Boulton, G.S., Cambridge, P., Wealthall, G.P., 1988. Stratigraphy and palaeoenvironments of the Red Crag and Norwich Crag Formations between Aldeburgh and Sizewell, Suffolk, England. Philosophical Transactions of the Royal Society of London Series B322, 221-272.

Figure Captions

Fig. 1. Location of the study sites, Suffolk coast, UK. Bathymetry taken from Admiralty Chart 1543 (Winterton Ness to Orford Ness) 17th edition, June 2005. Positions of the UK Environment Agency (EA) (Anglian Region) Sea Defence Management Study (SDMS) shore profiles are indicated.

Fig. 2. Cliff topography and stratigraphy. A) 12 m high cliffs to the north of EA profile SWD4 (for location see Fig. 1), looking north towards SWD3. Note exposure of the basal Baventian clay; B) 10 m cliff between EA profiles SWD3 and SWD4, looking south. Note gravel lenses within the Westleton Beds Member; C) 12 m high cliffs at Easton Wood, looking south towards EA profile SWD5; D) 12 m high cliffs near EA profile SWD7 at Easton Bavents; E) 17 m high cliffs at Dunwich, looking south near EA profile S1C6. Note vegetated nature of cliff profile; and F) 16 m high cliff at EA profile S1B1 (note profile marker post at bottom left). Note extensive Westleton Gravel Member deposits near the top of the profile and the vegetated nature of the lower cliff profile (Photographs: T Spencer, 27th October, 2008 (A); S Brooks, 9th June, 2009 (B); T Spencer, 27th December, 2009 (C, D); T Spencer, 15th December, 2009 (E, F)).

Fig. 3. Alongshore transect (1:50 vertical exaggeration) of shoreline elevations, and locations of EA (Anglian Region) SDMS shore profiles, from A) Benacre Ness to Southwold and B) Dunwich to Minsmere. Figure shows limits to cliffed areas used for the calculation of historical shoreline retreat rates and recent sediment volume releases.

Fig. 4. Relationship between cliff margin elevations extracted from winter 2008 (all profiles except S1C7) and winter 2000 (profile S1C7) EA (Anglian Region) SDMS profile ground surveys and corresponding elevations derived from February 2002 ‘NextMap’ tiles across the study area.

Fig. 5. Variation in shoreline recession rate (m a^{-1}) between 1883 and 2008 for the five cliffed sub-units between Covehithe and Dunwich-Minsmere, Suffolk coast, UK. Exploratory Data Analysis box-whisker plot (after Tukey, 1977) shows box of inter-quartile range (with median value) and whisker to hedge representing the lowest/highest data point within 1.5x box length from the lower/upper quartile respectively. Methodology: EPR (End Point Rate) calculations from Digital Shoreline Analysis System (DSAS).

Fig. 6. Shoreline change (m a^{-1}) using the Digital Shoreline Analysis System (DSAS) between A) Benacre and Southwold and B) Dunwich to Minsmere. Analysis based upon digitised MHWS/cliff base shorelines at a 10m alongshore sampling interval for the time periods 1883-1947 and 1883-2008. Also shown are rates of shoreline retreat calculated at a 250 m interval alongshore by Cambers (1973, 1975).

Fig. 7. Shoreline recession rates (m a^{-1}) for intermediate time periods between 1883-2008 for A) Covehithe; B) Easton Wood; C) Northend Warren; and D) Easton Cliffs. Boxes in box-whisker plots are placed at the mid-point of the time period covered; see Table 2 for details. Methodology: EPR (End Point Rate) calculations from Digital Shoreline Analysis System (DSAS).

Fig. 8. Box-whisker plots of shoreline recession rates (End Point Rate, m a^{-1}) for intermediate time periods between 1883-2008 for Dunwich-Minsmere cliff system. Boxes are placed at the mid-point of the time period covered; see Table 2 for details.

Fig. 9. Shoreline change (EPR m a^{-1}) over three time periods using the Digital Shoreline Analysis System (DSAS) between A) Benacre and Southwold and B) Dunwich to Minsmere. Analysis based upon digitised MHWS/cliff base shorelines at a 10m alongshore sampling interval for the time period 1883-2008. Analysis at a 10 m sampling interval of cliffed

sections only, and based on top-of-cliff position from aerial photography, for the time periods. Also shown for 1992-2008 and 2001-2008 are rates of shoreline retreat at ca. 1 km spacing alongshore derived from the EA (Anglian Region) SDMS bi-annual profile surveys.

Fig. 10. Main panel: revised sediment volume inputs (m^3 sediment a^{-1}) for the retreating Suffolk cliffs (Benacre, Covehithe, Easton wood, Easton Cliff and Dunwich-Minsmere), 2001-2008. Pie diagrams indicate likely sediment composition of inputs on basis of logs of cliff section materials in May/June 1995 (James and Lewis, 1996). Upper left panel: earlier estimate of sediment input from Cambers (1973, 1975). Lower panels: 2001-2208 estimated inputs (left) compared with estimates for periods of intermediate (centre; 1992-2008) and high (right; 1992-2001) cliff recession rates. See text for detailed discussion.

Tables

Table 1: Alongshore differences in geological composition of the cliff-forming sediments from sediment logs undertaken by the British Geological Survey in May/June 1995 (for methodology see James and Lewis, 1996)

Location	**Sediment composition (%)**		
	Silt / clay	**Sand**	**Gravel**
Benacre	22	76	2
Covehithe	2	95	3
Easton Wood	6	84	10
Northend Warren	35	61	4
Easton Cliffs	7	92	2
Dunwich	4	93	3
Minsmere	2	86	12

Sediment composition is predominantly sand of the Norwich Crag, with silt/clay arising from intertidal mudflat environments. Westleton Bed gravels reflect nearshore rip channels (Covehithe and Easton Wood) or tidal inlets between barrier islands (Dunwich-Minsmere)

Table 2: Shoreline retreat rates (m a^{-1}) in the five cliffed sub-units (see Fig. 3 for locations) for intermediate time intervals within the period 1883-2008, based upon the End Point Rate (EPR) statistic, Digital Shoreline Analysis System (DSAS).

		1883-2008	**1883-1903**	**1903-1925**	**1925-1941**	**1925-1947**	**1941-1981**	**1947-1974**	**1947-1981**	**1974-1992**	**1981-1992**	**1992-2008**
Covehithe	Mean	**3.49**	3.16	2.55		3.53			3.16		5.10	4.66
	St deviation	**0.4**	0.27	1.22		1.07			0.39		0.88	0.55
Easton Wood	Mean	**3.02**		1.17		2.06			3.00		3.62	2.88
	St deviation	**0.07**		0.15		0.23			0.27		0.24	0.31
Northend Warren	Mean	**2.75**	0.72	1.74		3.11		5.13		1.80		3.25
	St deviation	**0.02**	0.30	0.20		0.22		0.28		0.14		0.12
Easton Cliffs	Mean	**2.33**	3.33	2.57		0.81		2.65		2.38		2.23
	St deviation	**0.22**	0.71	0.26		0.78		0.63		0.40		0.66
Dunwich - Minsmere	Mean	**0.94**	1.49	1.72	0.41		0.65				0.61	0.25
	St deviation	**0.16**	0.78	0.30	0.21		0.24				0.40	0.26

Table 3: Estimated cliff volumetric loss (m^3 sediment a^{-1}) for the periods 1992 - 2008, 1992 - 2001 and 2001 – 2008., by cliffed sub-unit (see Fig. 3). For the period 2001-2008 losses calculated by combining DSAS EPR statistic with cliff elevations from corrected NextMap data (see Fig. 5) are disaggregated by sediment type (see Table 1).

Location	**Sediment volumetric loss (m^3 sediment a^{-1})**			**Sediment composition (%)**					
	1992 - 2008	**1992 - 2001**	**2001 - 2008**	**Silt / clay**	**Silt / clay**	**Sand**	**Sand**	**Gravel**	**Gravel**
Benacre	26974	32653	19629	22	4318	76	14918	2	393
Covehithe	85055	198897	54179	2	1084	95	51470	3	1625
Easton Wood	28166	30468	24665	6	1480	84	20719	10	2467
Easton Bavents[1]	38274	55234	16868	7	1181	92	15519	2	337
Total Benacre - Southwold	**178469**	**317252**	**115341**		8063		102626		4822
Dunwich - Minsmere	9260	13492	4666	3	140	90	4199	8	373
Total	**187729**	**330744**	**120007**		**8203**		**106825**		**5195**

[1] **Easton Bavents = Northend Warren + Easton Cliffs**

Figure 1

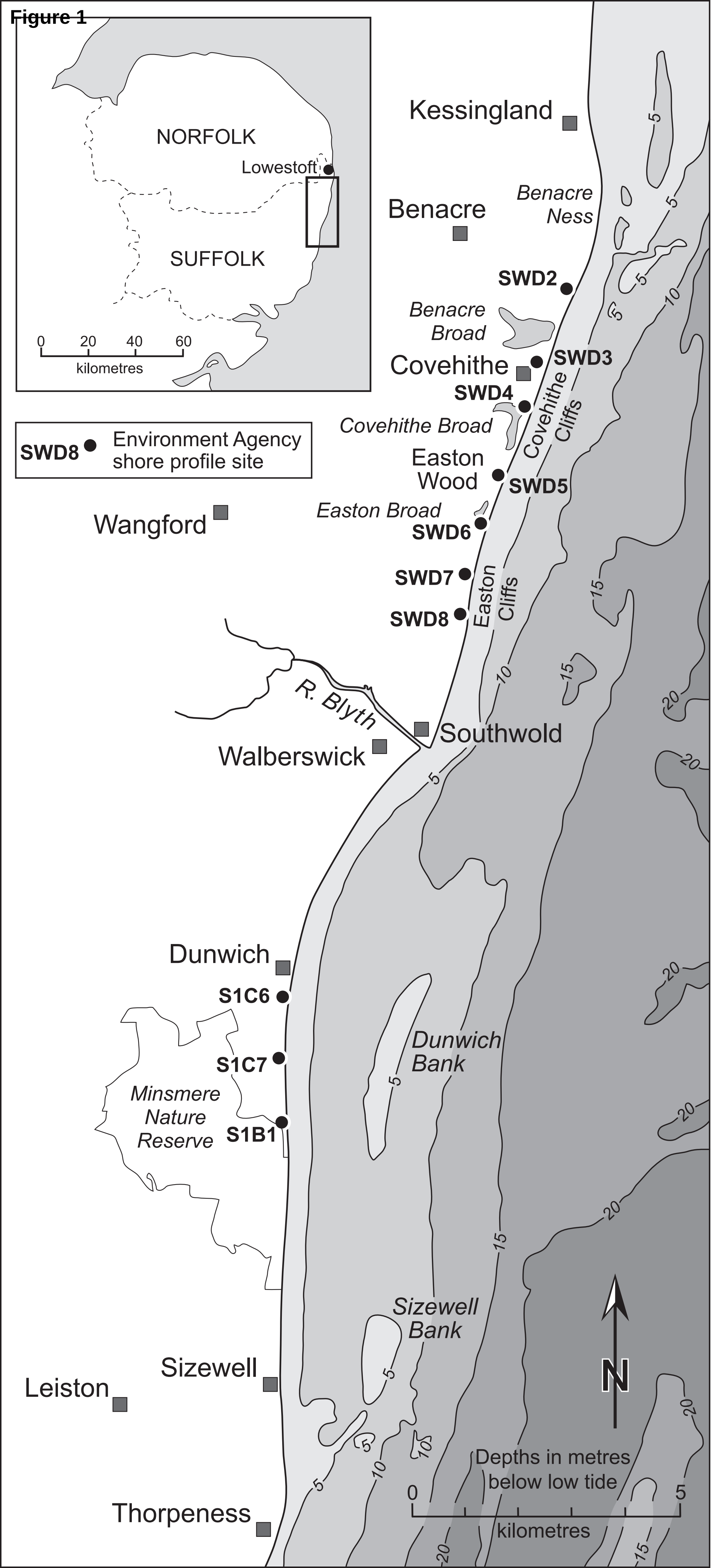

NORFOLK
Lowestoft
SUFFOLK
0 20 40 60
kilometres
SWD8 Environment Agency shore profile site
Kessingland
Benacre
Benacre Ness
SWD2
Benacre Broad
Covehithe
SWD3
SWD4
Covehithe Broad
Covehithe Cliffs
Easton Wood
SWD5
Easton Broad
SWD6
SWD7
SWD8
Easton Cliffs
Wangford
R. Blyth
Southwold
Walberswick
Dunwich
S1C6
S1C7
S1B1
Minsmere Nature Reserve
Dunwich Bank
Sizewell Bank
Sizewell
Leiston
Thorpeness
Depths in metres below low tide
0 5
kilometres
N

Figure 2 (black and white)

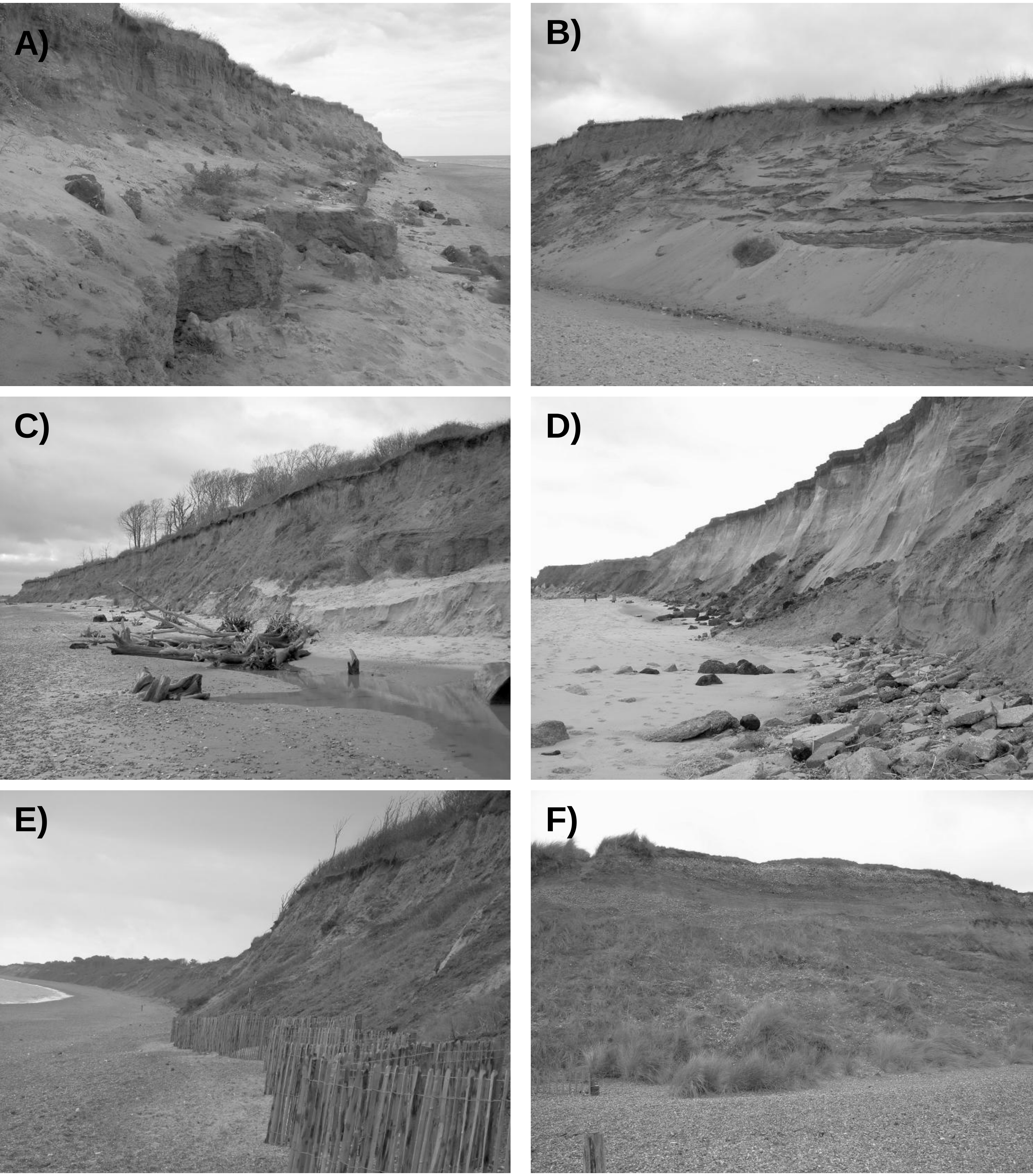


Figure 3

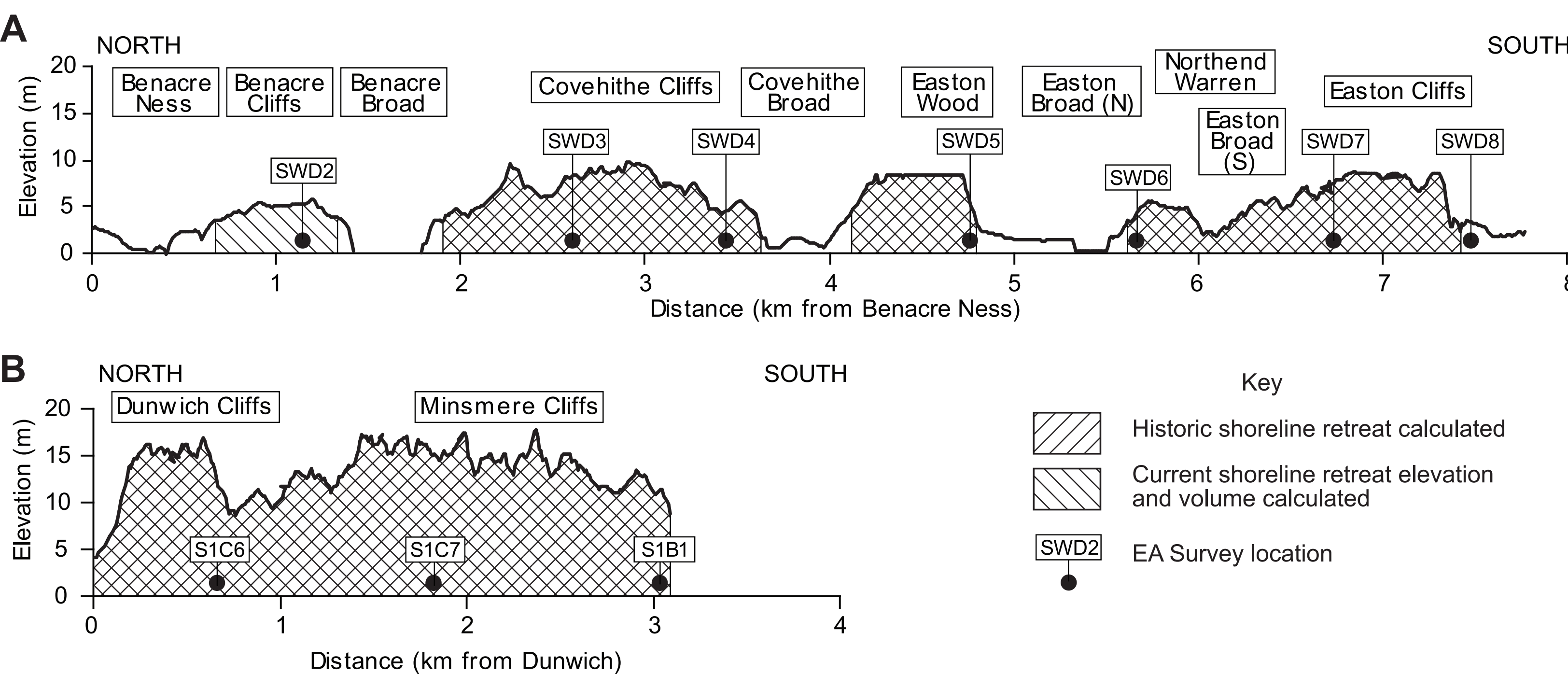
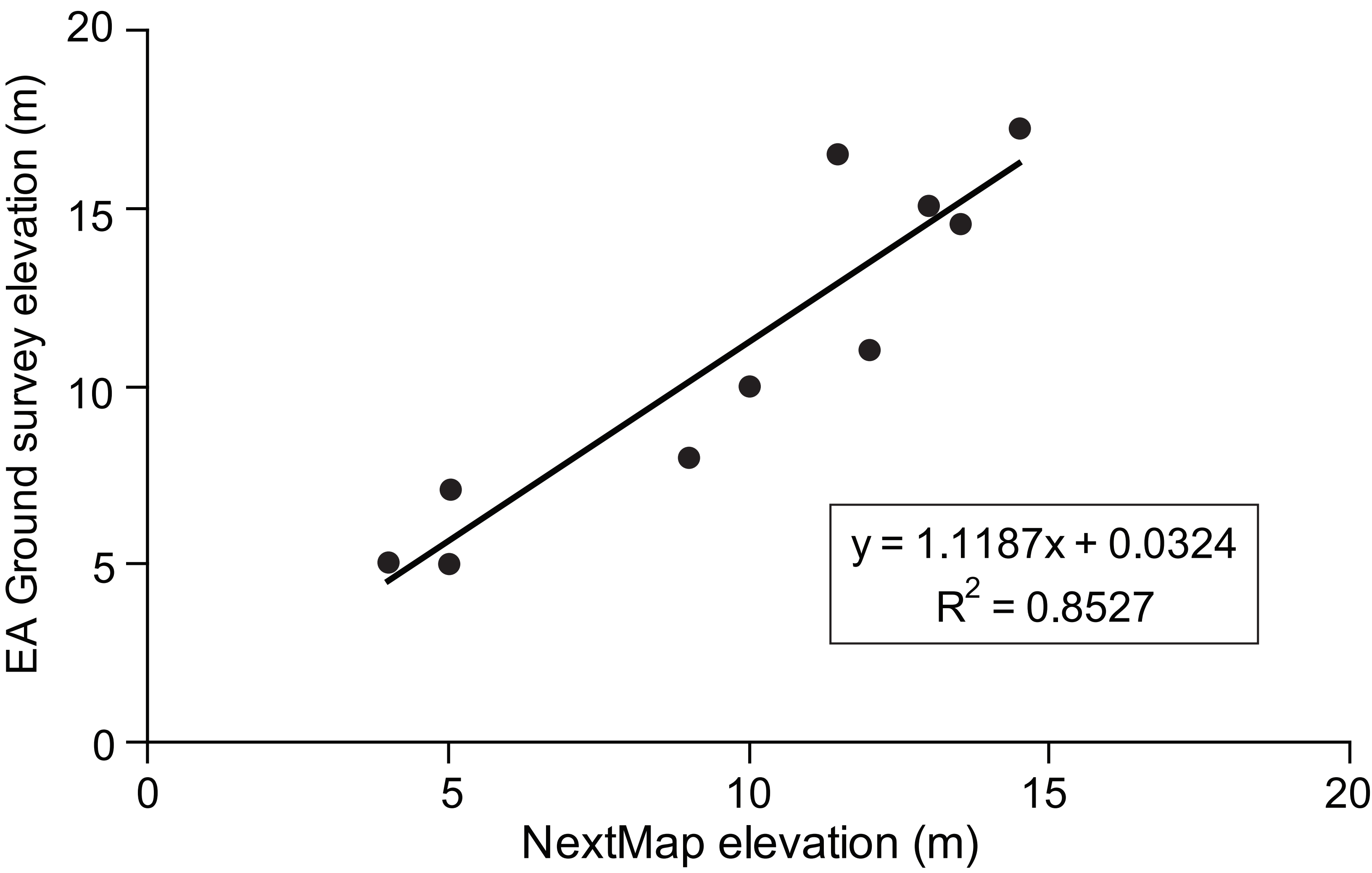

A
NORTH
SOUTH
Benacre Ness
Benacre Cliffs
Benacre Broad
Covehithe Cliffs
Covehithe Broad
Easton Wood
Easton Broad (N)
Northend Warren
Easton Broad (S)
Easton Cliffs
SWD2
SWD3
SWD4
SWD5
SWD6
SWD7
SWD8
Elevation (m)
0
5
10
15
20
0
1
2
3
4
5
6
7
8
Distance (km from Benacre Ness)
B
NORTH
SOUTH
Dunwich Cliffs
Minsmere Cliffs
S1C6
S1C7
S1B1
Elevation (m)
0
5
10
15
20
0
1
2
3
4
Distance (km from Dunwich)
Key
Historic shoreline retreat calculated
Current shoreline retreat elevation and volume calculated
SWD2
EA Survey location

Figure 4



20
15
10
5
0
EA Ground survey elevation (m)
0
5
10
15
20
NextMap elevation (m)
y = 1.1187x + 0.0324
R2 = 0.8527

Figure 5

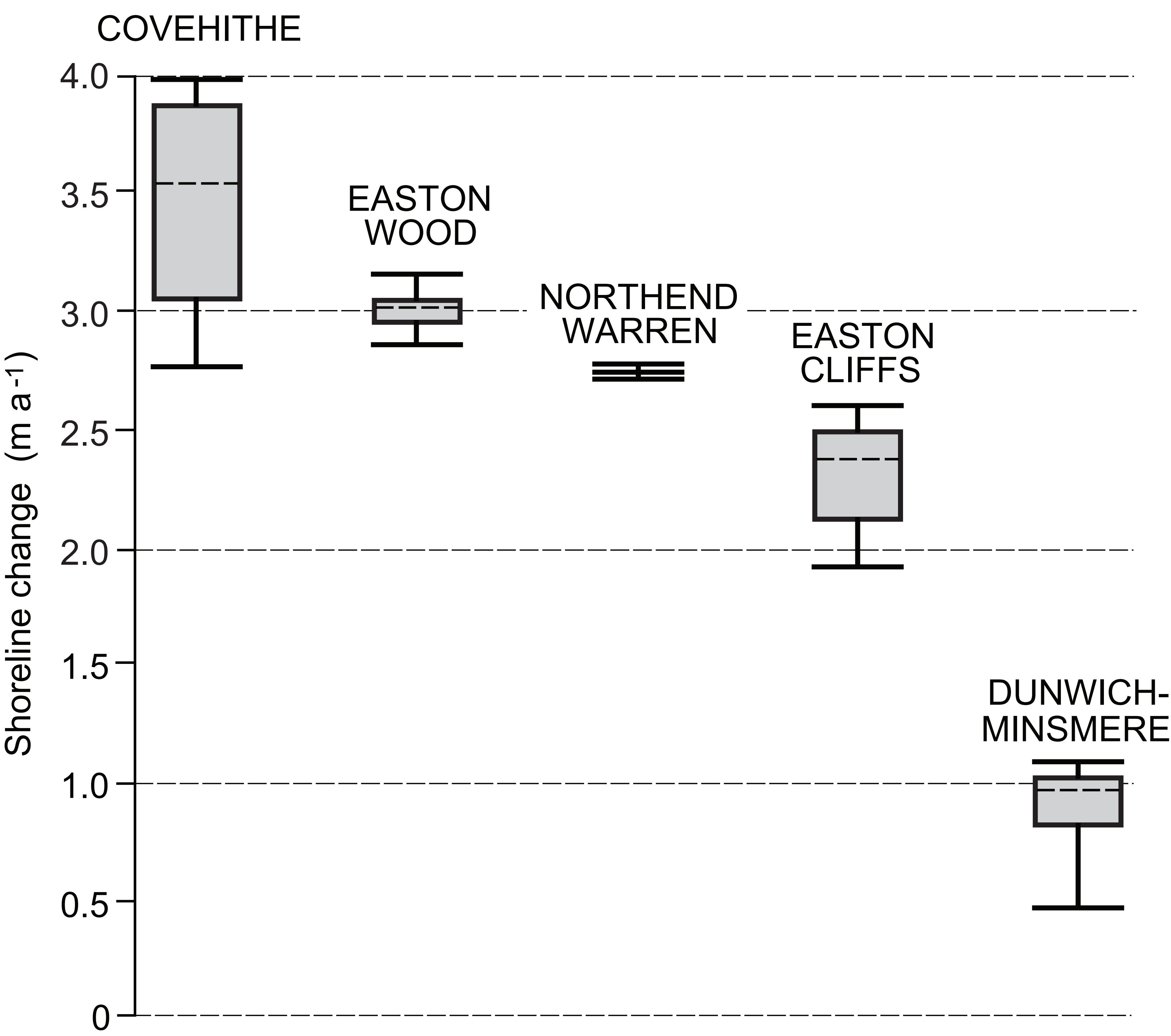
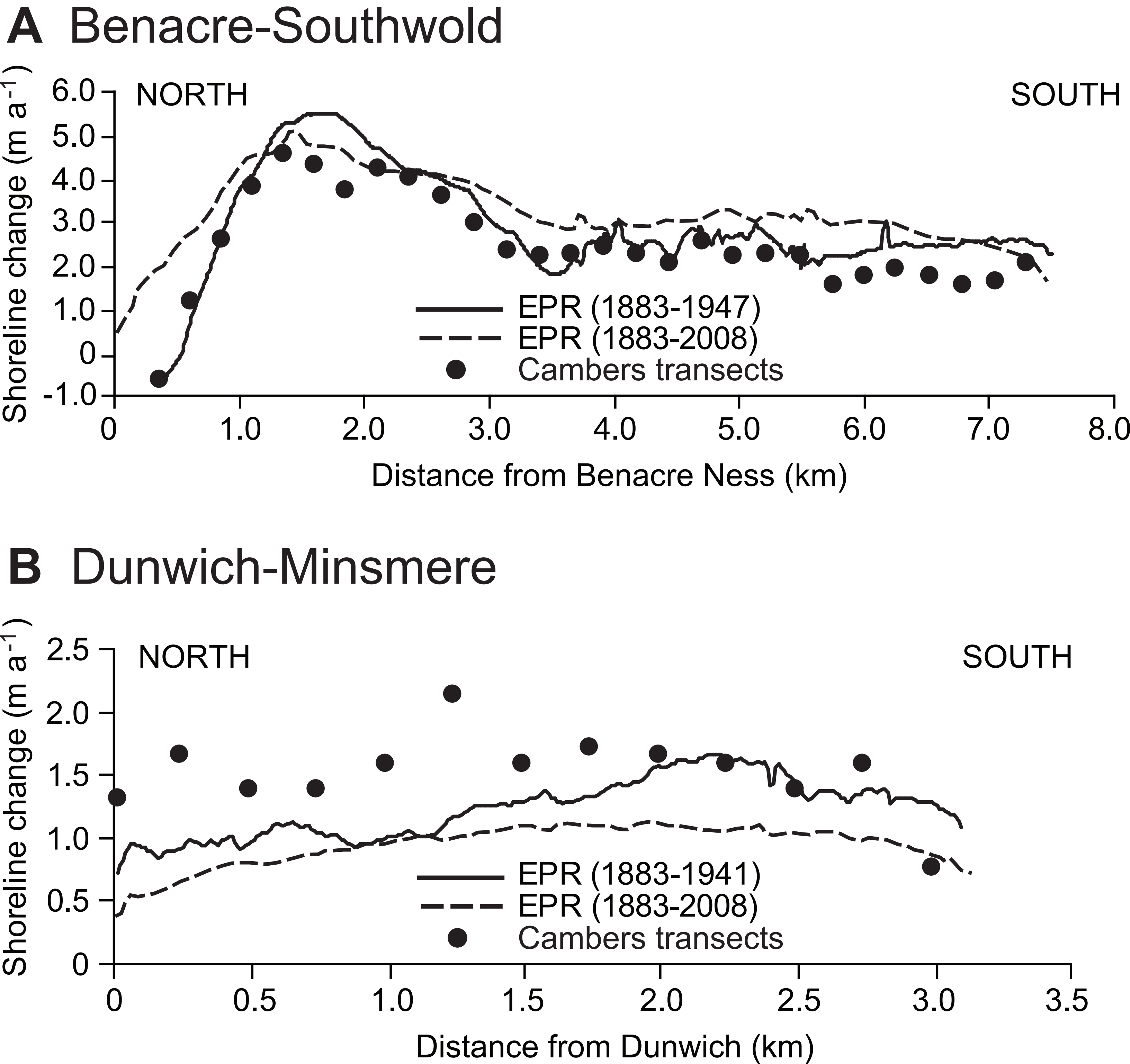

COVEHITHE
EASTON WOOD
NORTHEND WARREN
EASTON CLIFFS
DUNWICH-MINSMERE
Shoreline change (m a-1)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0

Figure 6


A Benacre-Southwold
Shoreline change (m a^{-1})
NORTH
SOUTH
6.0
5.0
4.0
3.0
2.0
1.0
0
-1.0
EPR (1883-1947)
EPR (1883-2008)
Cambers transects
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Distance from Benacre Ness (km)
B Dunwich-Minsmere
Shoreline change (m a^{-1})
NORTH
SOUTH
2.5
2.0
1.5
1.0
0.5
0
EPR (1883-1941)
EPR (1883-2008)
Cambers transects
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Distance from Dunwich (km)

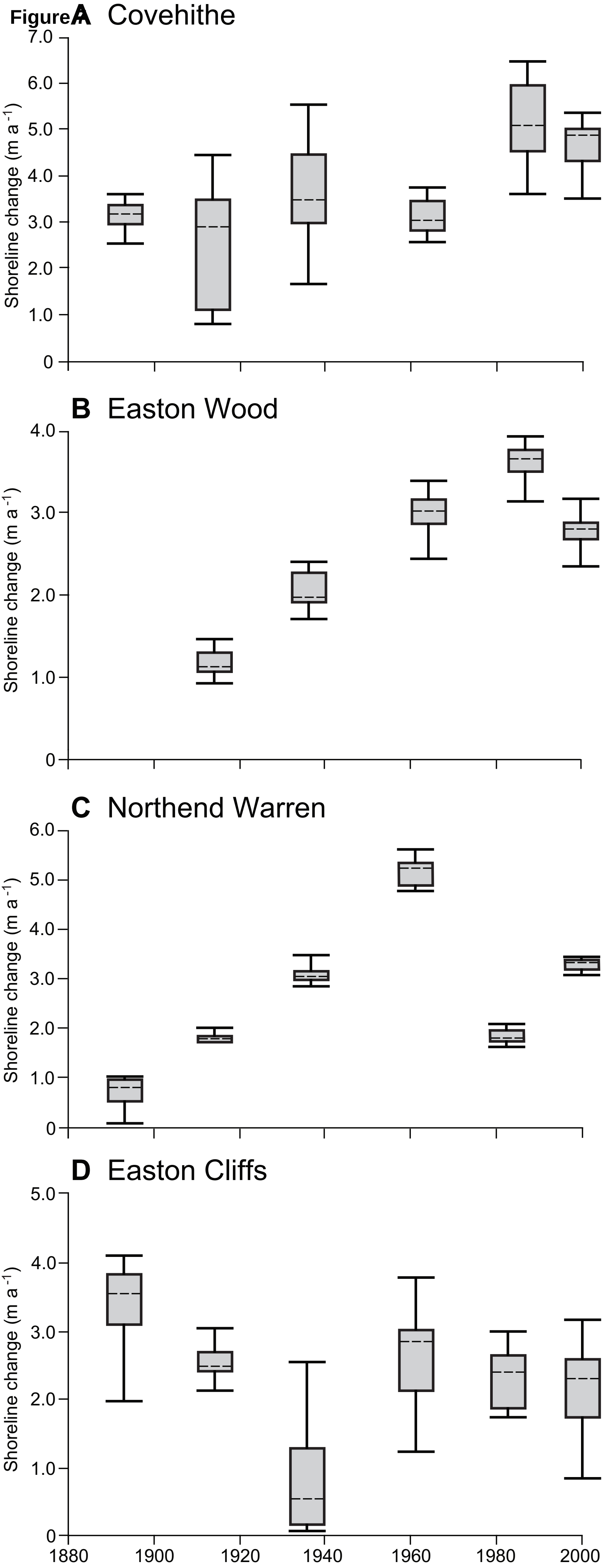


Figure
A Covehithe
B Easton Wood
C Northend Warren
D Easton Cliffs
Shoreline change (m a-1)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1880
1900
1920
1940
1960
1980
2000

Figure 8

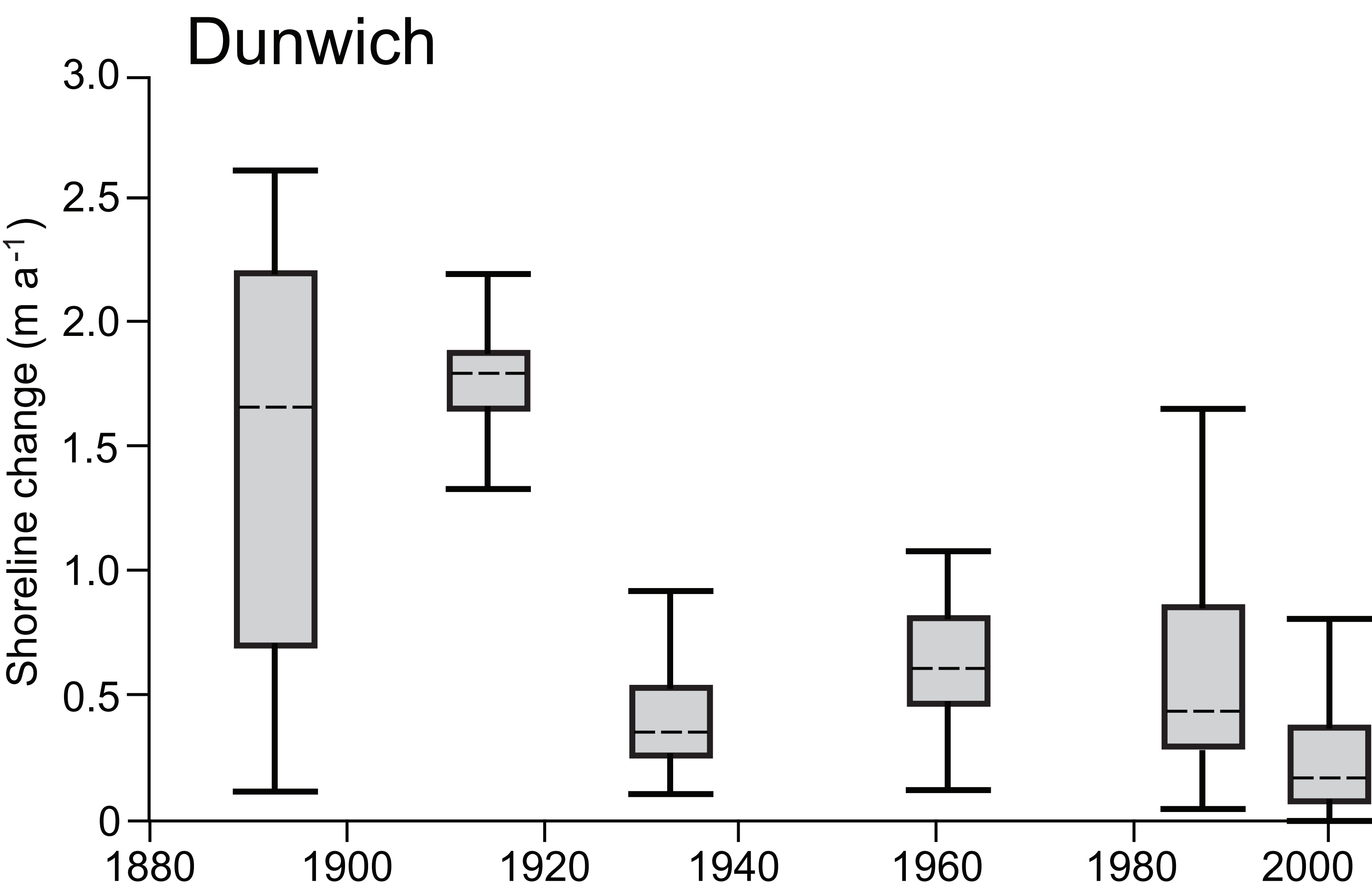

Dunwich
3.0
2.5
2.0
1.5
1.0
0.5
0
Shoreline change (m a-1)
1880
1900
1920
1940
1960
1980
2000

Figure 9

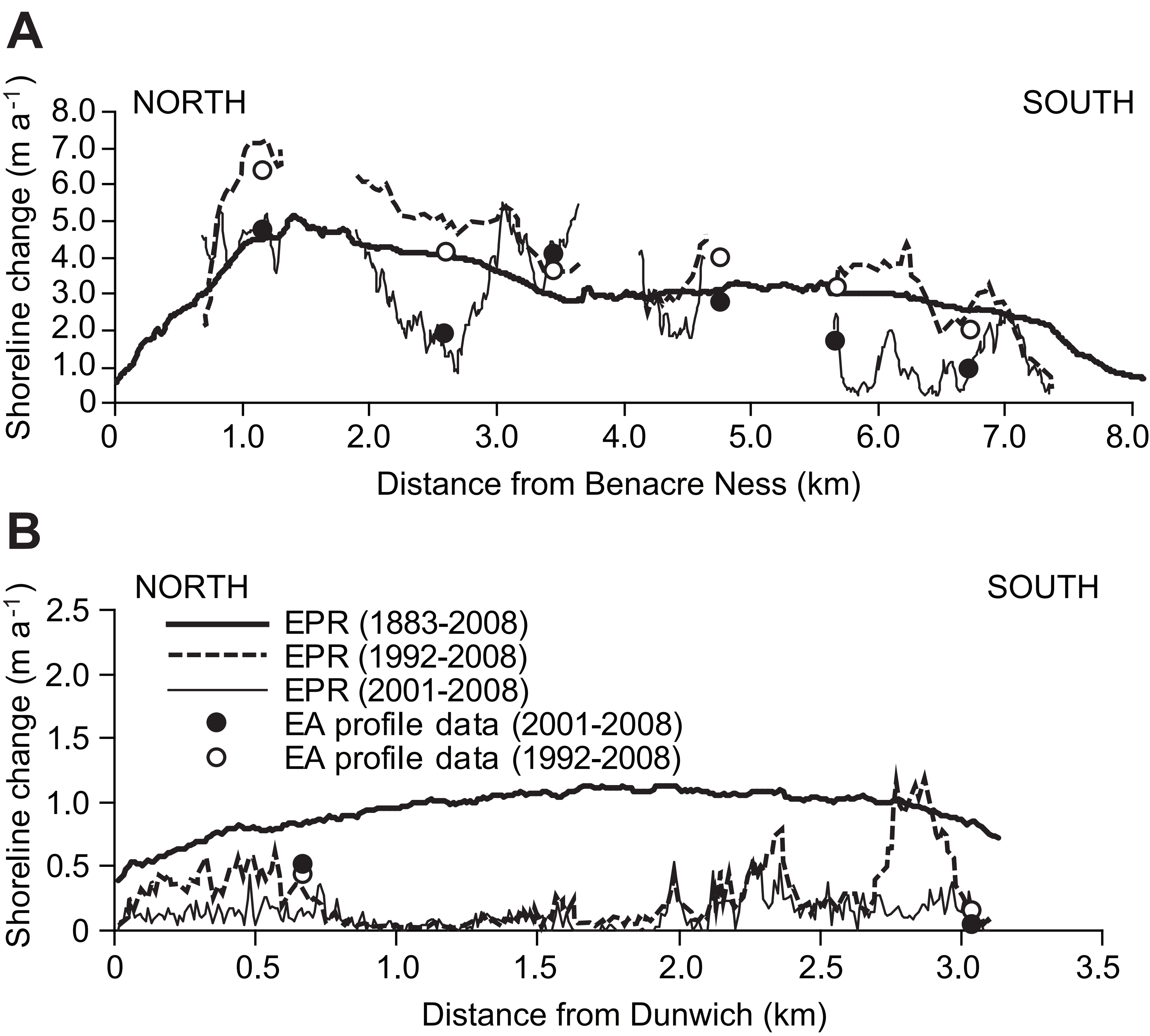
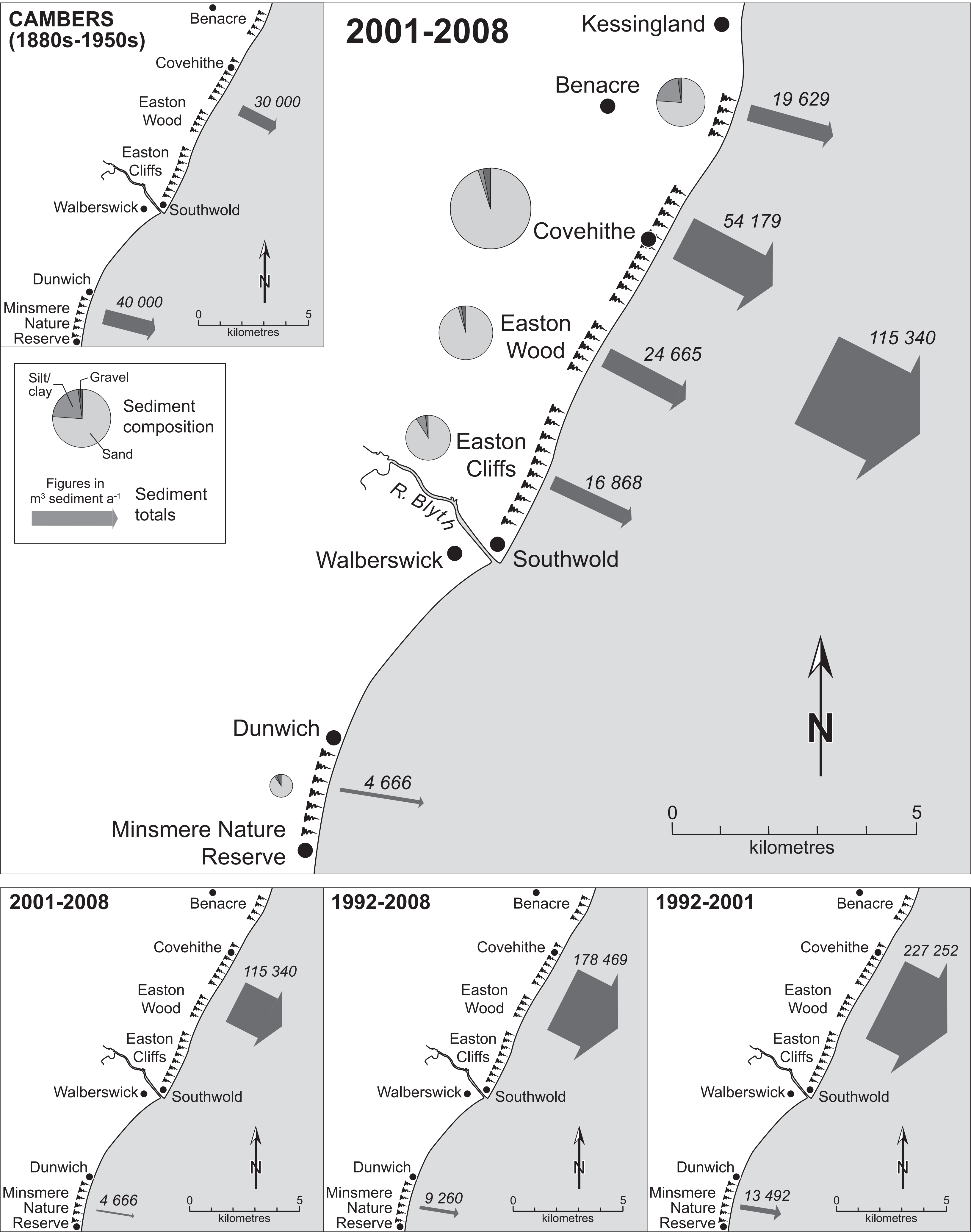

A
NORTH
SOUTH
Shoreline change (m a^{-1})
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Distance from Benacre Ness (km)
B
NORTH
SOUTH
Shoreline change (m a^{-1})
2.5
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Distance from Dunwich (km)
EPR (1883-2008)
EPR (1992-2008)
EPR (2001-2008)
EA profile data (2001-2008)
EA profile data (1992-2008)

Figure 10



CAMBERS (1880s-1950s)
Benacre
Covehithe
Easton Wood
Easton Cliffs
Walberswick
Southwold
Dunwich
Minsmere Nature Reserve
30 000
40 000
N
0
5
kilometres
Silt/ clay
Gravel
Sand
Sediment composition
Figures in m3 sediment a-1
Sediment totals
2001-2008
Kessingland
Benacre
19 629
Covehithe
54 179
Easton Wood
24 665
115 340
Easton Cliffs
R. Blyth
16 868
Walberswick
Southwold
Dunwich
4 666
Minsmere Nature Reserve
N
0
5
kilometres
2001-2008
115 340
4 666
1992-2008
178 469
9 260
1992-2001
227 252
13 492