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FORUM

On the loss of saltmarshes in south-east England and methods for their restoration

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Summary

1. The saltmarshes of south-east England have been eroding rapidly for about the last 50 years, at a continuing rate of about 40 ha $year^{-1}$, with deleterious consequences for conservation and coastal flood defence. The possible reasons for this erosion and suitability of methods of saltmarsh restoration are discussed.
2. The prevailing hypothesis that the saltmarsh erosion is due to coastal squeeze, where sea walls prevent a landward migration of saltmarsh in response to sea level rise, is rejected because: (i) as the sea level rises saltmarshes accrete vertically as well, at least at the same rate, and may even extend seaward; (ii) in recent decades the rate of rise in sea level has been no higher than in the past when the saltmarshes developed; (iii) the pattern of vegetation loss, mostly of pioneer zone species, is opposite to that predicted by coastal squeeze, where the upper marsh plants should disappear first.
3. Alternative explanations and hypotheses are proposed that relate the recent saltmarsh erosion to changes to the intertidal biota, an increase in abundance of the infaunal polychaete *Nereis diversicolor*, and a decrease in abundance of intertidal seagrasses. Bioturbation and herbivory by *Nereis* cause the loss of pioneer zone plants, increase sediment instability and exacerbate the erosion of saltmarsh creeks. The erosion of the seaward edge of some marshes may also be due to increased wave action, and increased tidal current speeds in estuaries, following the loss of intertidal seagrasses since the 1930s through wasting disease.
4. *Synthesis and applications.* The current strategy for saltmarsh creation is based on managed realignment, where some sea walls are breached to provide new intertidal habitat. The conclusion that the causes of saltmarsh loss are not related to sea level rise calls into question this dependence on management realignment as the most appropriate means of saltmarsh creation, not least because many realignment areas are unlikely to develop vegetation. Other methods should be considered for creating new marshes and for reducing/reversing marsh erosion. These include, alone or in combinations, exclusion of the infauna, use of dredged material for strategic intertidal recharge, and transplantation of intertidal seagrasses.

Key-words: bioturbation, coastal squeeze, herbivory, *Nereis*, saltmarsh erosion

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Introduction

Coastal saltmarshes are areas of herbaceous vegetation that colonize intertidal sediments in wave-sheltered areas and are inundated by seawater by at least the highest spring tides of each lunar month. The plants show a vertical zonation where generally the lower limits of the different species are determined by their varied tolerances to several factors associated with immersion, including high sulphide concentrations, low pH and anoxia of the soil (Davy 2000). The upper limits of their distributions are generally determined by interspecific competition with plants that live at higher elevations, because they are less well adapted to these conditions. Saltmarshes have a high primary productivity

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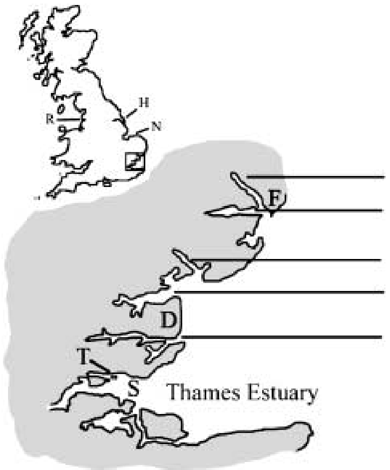

Proportions (%) of saltmarsh lost

	1973–1988		1988–1997/8
	Total	Pioneer zone	Total
Orwell	40	74	23
Stour	44	60	28
Colne	12	53	7
Blackwater	23	74	7
Crouch	26	25	11

Fig. 1. Map of south-east England showing the proportions of saltmarsh area lost from the estuaries of Essex, and the Orwell in Suffolk, from 1973 to 1988 (data from Burd 1992) and from 1988 to 1997–98 (data from Coastal Geomorphology Partnership 2000). Also shown are the locations of Felixstowe (F), Southend (S), the Dengie Peninsular (D) and Two Tree Island (T), referred to in the text. The inset map of Great Britain shows the locations of the Humber (H), Ribble (R) and Norfolk (N), also referred to in the text.

and are crucial to the functioning of the estuarine and coastal ecosystems that contain them. They are natural communities unaffected by anthropological influence (if not grazed by livestock) and they contain nationally rare species of plants and invertebrates (Doody 2001).

In the estuaries of south-east England (mostly in Essex but also in Suffolk and north Kent) (Fig. 1) approximately 40 000 ha of saltmarsh had developed, but after extensive land claims over the past few centuries and recent erosion, only approximately 4400 ha remain (about 10% of the total UK area). The remaining saltmarshes are of international conservation importance, largely because of their significance in the estuaries used by resident, migrating and overwintering birds (Hughes 2004), and more than 80% are covered by one or more national or international conservation designations. These saltmarshes have been eroding rapidly for about 50 years (Fig. 1), and the continuing rate of erosion of 40 ha year^{-1} (Coastal Geomorphology Partnership 2000) accounts for approximately two-thirds of the UK total losses. Saltmarshes are a Biodiversity Action Plan habitat and under the European Union (EU) Habitats Directive the UK is committed to restoring and maintaining saltmarsh to the total area present in 1992 (United Kingdom Biodiversity Group 1999).

Saltmarshes are also important in coastal flood defence, as they offer some protection to sea walls from wave action. There is a near-linear relationship between the loss of the width of a fronting saltmarsh and the increase in expenditure necessary to maintain a given standard of flood protection, until the loss of the final thin strip necessitates an exponential rise in expenditure (Dixon, Leggett & Weight 1998). King & Lester (1995) calculated that the loss of saltmarsh from Essex alone would cost £600 million for the increased maintenance of the sea walls. On this basis the annual loss of 1% is valued at £6 million. Consequently, preserving or restoring even small areas of saltmarsh may lead to substantial cost savings and a sustainable coastal defence solution, particularly for the 25% of the Essex coast in which increased maintenance of the sea walls is deemed uneconomic as it would cost more than the value of the land protected (Agricultural Select Committee of the House of Commons 1998). Saltmarsh loss is arguably the most important habitat conservation problem in the UK, not only because of its conservation importance, economic value and the increasingly large areas that have to be replaced, but also because of the lack of a clear understanding of the causes, and therefore the appropriate remedial actions.

This forum has four main aims: (i) to argue that the accepted explanation for saltmarsh loss in south-east England (coastal squeeze) is incorrect; (ii) to present alternative explanations and testable hypotheses; (iii) to question whether the current strategy for saltmarsh creation, managed realignment (see below), is the most appropriate means of increasing saltmarsh area; and (iv) to briefly suggest other management options. Some of these issues were discussed by Pye (2000), French (2001) and French & Reed (2001), who emphasized the physical processes associated with saltmarsh erosion (e.g. tidal asymmetry, tidal range, wave action) but here the thesis is that the problems are largely biological in origin.

The accepted explanation for saltmarsh losses: coastal squeeze

Saltmarsh losses are thought to be particularly high in south-east England because of sea level rise leading to coastal squeeze (Burd 1992; English Nature 1992; United Kingdom Biodiversity Group 1999; Covey & Laffoley 2002). A rise in relative sea level (RSL) causes saltmarshes to move landward, because the upper and lower limits to the vertical niche spaces of the plant species move upward. However, if sea walls prevent this migration the marshes ultimately disappear because they become 'squeezed' between the rising sea level and the static defences. Coastal squeeze is thought particularly applicable in south-east England because of isostatic land subsidence, which leads to a rise in RSL of about 1·5 mm year^{-1} (Shennan 1989). RSL is stable or falling in northern England and Scotland, where generally the marshes are not eroding. The acceptance of coastal squeeze by the conservation and flood defence agencies (The Environment Agency, English Nature, Royal Society for the Protection of Birds, The Wildlife Trusts) has limited consideration of the options for saltmarsh restoration to managed realignment (also known as retreat or set-back), where sea walls are breached or neglected to allow land to become intertidal. If the land is sufficiently high it will provide a habitat at the appropriate elevation for the saltmarsh plants, and if not it will accumulate sediment until the appropriate elevation is reached. Several managed realignment schemes have been constructed and more are planned (Paramor 2002; Paramor & Hughes 2004). The processes affecting the dynamics of subsiding coastlines, such as in south-east England, are seen to presage what may occur more generally under accelerated sea level rise due to global warming, and the problems and management responses on the Essex coastline have attracted international interest.

Is coastal squeeze responsible for saltmarsh losses in south-east England?

RSL has been rising in many locations around the world for several millennia and during this time extensive saltmarshes developed, including the predominantly organogenic marshes in the eastern and southern USA and the predominantly minerogenic marshes of north-west Europe. Saltmarshes may develop in two ways, other than by migrating landward under a rise in RSL, if the supply of sediment is sufficient.

First, saltmarshes also develop vertically under RSL rise because there is a relationship between the depth of water over the marsh and the rate of sediment accretion (Pethick 1981). Sediment accretion on relatively low saltmarshes is relatively rapid, because more sediment is carried over the marsh and has longer to fall out of suspension. As the marsh increases in elevation relative to sea level, the rate of deposition declines and the marsh achieves an asymptotic elevation dependent on a dynamic equilibrium determined by the biological and physical processes that affect erosion and deposition. Once this equilibrium is achieved the net accretion rate on a marsh keeps pace with any rise in RSL (Jennings, Carter & Orford 1995; Nydick *et al.* 1995; Orson, Warren & Neiring 1998; Pye 2000; Hartig *et al.* 2002). This relationship is sufficiently robust that changes in the elevation of saltmarshes, deduced from ageing sediment in deep cores, are used to estimate past changes in RSL (Nydick *et al.* 1995). Palaeoecological evidence from cores up to 9 m deep in the reclaimed marshes on the north Norfolk coast (Fig. 1) indicates that the elevation of these marshes has kept pace with sea level rise for several millennia (Funnell & Pearson 1989). On smaller time scales, Cahoon *et al.* (2000), who measured the increase in elevation of a marsh surface directly, and Pye (2000), who examined the rate of burial of caesium 137, both concluded that sediment deposition on some Essex marshes has been at least sufficient to keep pace with sea level rise.

Secondly, if sediment is sufficiently abundant the usual trend is for saltmarshes to extend seaward, even when sea level is rising (Doody 2001). Seaward development is evidence that the rate of sediment accretion on the mudflat below the marsh was greater than RSL rise, as the mudflats were raised to an elevation suitable for pioneer saltmarsh plant colonization. This may indicate high concentrations of suspended sediment and/or biologically enhanced accretion rates, for example through the presence of intertidal seagrasses (see below). Seaward development of saltmarshes has occurred in south-east England, most notably where it has allowed successive seaward enclosures, and where it has separated once-coastal ports from the sea, for example Cley in Norfolk and Rye in southern England, both of which are now more than 1 km inland. In Essex, even the open coast barrier marsh on the Dengie Peninsula (Fig. 1), the most wave-exposed marsh on this coast, developed up to 700 m seaward after the construction of the sea wall about 200 years ago (Pye 2000).

The importance of sea level rise in south-east England in maintaining saltmarshes as accreting systems in the tidal frame has largely not been appreciated (Davy 2000). It is against this background of the association of sea level rise with prolonged marsh development, until the last half-century, that the proponents of the coastal squeeze hypothesis argue for a rise in RSL as the cause of saltmarsh loss in south-east England. Sea walls may prevent the landward marsh expansion, but not the compensating increase in vertical elevation of saltmarshes, nor any seaward development, and cannot be used as an explanation for saltmarsh loss under rise in RSL, only for reducing or preventing an increase in their area.

The argument that the recent erosion has occurred in response to an increased rate of RSL rise, possibly through the effects of global warming adding to the underlying isostatic sea level rise (Boorman, Goss-Custard & McGrorty 1989; Crooks & Pye 2000), is not supported by tide gauge data. For example, the mean monthly sea level data for Southend and Felixstowe (Fig. 1) show high variability (Fig. 2). The data for Southend show a highly variable and non-significant trend of a mean rise of 1·25 mm year^{-1} from 1933 to 1983, which is typical of south-east England (Woodworth *et al.* 1999). However, most of this rise occurred before 1950 and the trend from 1950 to 1983, when the saltmarshes were eroding particularly rapidly, was only about 0·1 mm year^{-1}. The trend in the data for Felixstowe indicates a fall in RSL

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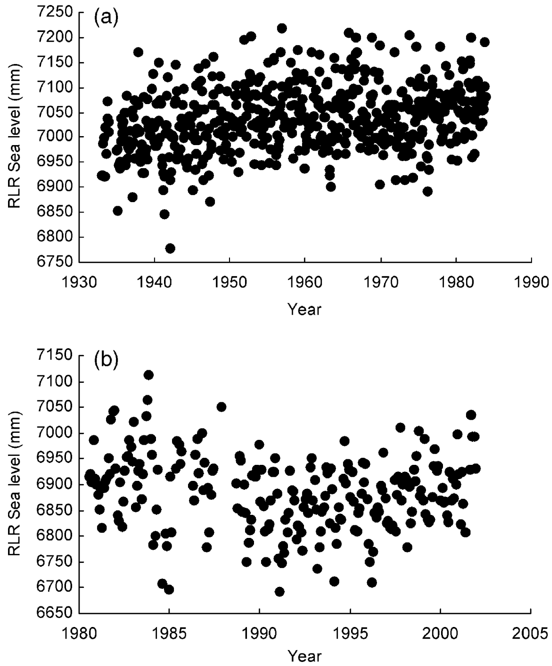

Fig. 2. The mean monthly sea levels for (a) Southend and (b) Felixstowe (for the years for which data are available from the Permanent Service for Mean Sea Level; Proudman Oceanographic Laboratory 2003). Sea level data are related to an initial 'revised local reference' (RLR), defined to be approximately 7000 mm below mean sea level.

of 1·8 mm year^{-1}. The spatial and temporal variability within these tidal data, combined with the established association of saltmarsh development under RSL rise, indicate that an explanation for the recent losses of saltmarsh based on a sea level rise is untenable.

Although sea level rise can exceed saltmarsh accretion rates where there is an insufficient sediment supply (and/or peat deposition on organogenic marshes), this is unlikely where saltmarshes still exist after several centuries of sea level rise, and especially in south-east England given the high turbidity of the water and the high rates of accretion achieved experimentally (Paramor 2002; Paramor & Hughes 2004). Cundy & Croudace (1996) reported saltmarsh accretion rates of 4–5 mm year^{-1} in response to local crustal subsidence on the south coast of England. If the marshes of southern England can accrete at this rate then the marshes of the south-east should be able to keep pace even with the maximum predicted rate of sea level rise of 6 mm year^{-1} as a consequence of global warming (UNEP 2003).

The pattern of loss of saltmarsh species is also evidence against coastal squeeze. Under coastal squeeze the loss of saltmarsh species should be seen as loss first of the upper marsh species, then of the mid-marsh species, and finally of the low marsh pioneer zone species, those most adapted to inundation by seawater, which should disappear last. However, the greatest losses have been of pioneer zone species (Fig. 1), contrary to the expectation of coastal squeeze. The lower limit of pioneer zone saltmarsh vegetation is around mean high water neap tide level (MHWNTL), but observations of saltmarshes around south-east England show that potential niche space above MHWNTL is available but often unoccupied (Fig. 3). The absence or scarcity of pioneer zone plants is often unrelated to this tidal level and therefore to any rise in this level. There is a scarcity of upper marsh plant species in south-east England, as expected under coastal squeeze, but this is due to the history of extensive enclosure that removed the upper marsh from tidal influence. If the marshes accrete only at a rate similar to RSL rise then the upper marsh community is not expected to redevelop.

Alternative explanations and hypotheses for saltmarsh erosion

If recent saltmarsh losses are not due to coastal squeeze then other explanations should be sought. There are

Fig. 3. Photograph of a saltmarsh in Norfolk showing the absence of a pioneer zone vegetation and a lower limit of mid–low marsh vegetation (mostly *Puccinellia* and *Limonium*) approximately 1·5 m above the level of high water of a neap tide (arrow).

several possible reasons why saltmarsh should be lost on a local scale (Pye 2000). Land claim and the construction of sea defences have been responsible for about 5% of recent marsh loss (Covey & Laffoley 2002). Mason *et al*. (2003) considered that the increased use of agricultural herbicides over the past few decades may have contributed to the decline of the microphytobenthos, sediment stability and saltmarsh vegetation in areas of run-off. However, the problem of saltmarsh loss is particularly acute across the south-east region and explanations need to be appropriate at this geographical scale, should identify differences with other regions where the marshes are not generally eroding, and should explain why the problem has occurred particularly over the past half-century.

BIOTURBATION AND HERBIVORY

One alternative explanation is that saltmarsh losses are due to relatively recent and regional-scale increases in bioturbation and herbivory by the invertebrate infauna. Much of the loss of vegetation has been of pioneer zone species (Figs 1 and 3) and earlier studies in Essex have shown that these plants can exist at lower elevations than they normally occur if protected from bioturbation and herbivory by the ragworm *Nereis diversicolor* and, to a lesser extent, the amphipod *Corophium volutator* (Gerdol & Hughes 1993; Smith, Hughes & Cox 1996; Hughes 1999; Hughes *et al*. 2000; Paramor & Hughes 2004). Hughes *et al*. (2000) and Hughes (2001) suggested that two alternative states may exist at the saltmarsh–mudflat interface. One state is domination by plants that exclude burrowing invertebrates, with their roots and by compacting the sediment, and the other state is domination by invertebrates that prevent plant colonization by bioturbation and herbivory, including consumption of seeds. This alternative states hypothesis was recently supported by Paramor (2002) and Paramor & Hughes 2004), who showed that plants can deter burrowing by *Nereis* and that pioneer zone vegetation could develop when *Nereis* were excluded. A recent shift in dominance from the former state to the latter could explain the relatively recent regional-scale losses of pioneer zone vegetation. Hughes (1999, 2001) considered some evidence for significant increases in the abundance of *Nereis*, which is abundant and widespread in these estuaries (Hughes & Gerdol 1997). Beardall, Dryden & Holzer (1988) considered that sewage pollution could have been responsible for an increase in their abundance in the Orwell Estuary (Fig. 1).

In addition to loss of pioneer zone vegetation, mid- and upper saltmarsh vegetation are being lost by erosion of saltmarsh creeks (Burd 1992; Coastal Geomorphology Partnership 2000; Pye 2000). Paramor & Hughes (2004) confirmed that creek erosion, in one marsh at least, was caused by *Nereis*, because when the worms were excluded sediment accretion occurred instead of erosion. Consequently, creek erosion could not be attributed to physical processes alone, including those associated with sea level rise and an increase in tidal range, as suggested by Pye (2000). If the sediments in the creeks have become more erodable relatively recently because of increased *Nereis* abundance, then it may be predicted that the equilibrium morphology of a creek will be larger, particularly near the mouth, and erosion towards this equilibrium morphology will occur until sufficient lateral expansion of the creeks has occurred to reduce the velocities of the tidal currents to the point where the erosion and deposition of sediments are in dynamic equilibrium (Paramor & Hughes 2004).

INCREASED WAVE ACTION

While most saltmarsh erosion is by lateral expansion of internal creeks, some erosion also occurs at their seaward edge (Burd 1992), notably on the coastal barrier marsh of the Dengie Peninsula (Pye 2000). Doody (1992) and Pethick (1992) suggested that this might be due to sea level rise leading to increased wave erosion, because the wave energy reaching the marsh would be attenuated less by the deeper mudflats. However, the pattern of marsh-edge erosion in south-east England generally does not support an explanation based on wave action alone. The maps of Burd (1992) show erosion in some wave-sheltered locations, but none in some relatively wave-exposed locations.

A rise in RSL may not necessarily lead to increased wave erosion as the elevation of the mudflats may also increase, at least at a compensating rate, as it does for marshes and for similar reasons. The mudflats may even accrete at higher rate, leading to seaward extension of the saltmarshes, as happened on the Dengie saltmarshes (see above). However, if the elevations of the mudflats were reduced, either actually or relative to rising sea level, then increased wave erosion of the marsh faces would be expected. An increase in wave size and/or frequency, as suggested by Pye (2000), would reduce mudflat elevations by erosion, as would the increase in *Nereis* abundance, which would lead to increased mudflat sediment erodability. There is more evidence for the latter than the former.

Some saltmarshes may also be more vulnerable to wave action because of the loss of intertidal seagrasses that were once common but which have declined in abundance and distribution since the 1930s (Hughes *et al*. 2000). The decline of *Zostera marina* in particular has been attributed to a wasting disease that affected seagrasses on a global scale (Den Hartog & Phillips 2001). In south-east England the remaining seagrasses, *Z. marina* and dwarf eelgrass *Zostera noltii*, which is now the more common species (Hughes *et al*. 2000), have an unusually high distribution, from the saltmarsh edge down to just below mean tide level, probably because of the high turbidity of the water (Nicholls 2004). The losses of seagrass would have been from the same unusually high elevations and would have led to sediment erosion directly in front of the saltmarshes, increasing their vulnerability to wave action. The effect of seagrasses in protecting saltmarshes from wave action can be seen at the largest remaining seagrass bed, in the Thames Estuary. At the eastern, seaward end of Two Tree Island (Fig. 1) the saltmarsh is protected by seagrasses and has a well developed pioneer zone and a gradual slope to plants at higher elevations. However, just 100 m to the west in otherwise more wave-sheltered conditions, but outside the seagrass bed, the marsh has an eroding cliff up to 1·5 m high and no pioneer zone. The mudflat in front of this cliff has high densities of *Nereis* (R.G. Hughes, unpublished data) and, in addition to limiting the distribution of the seagrasses, the polychaetes may be decreasing the equilibrium height of these, and other, mudflats, allowing more wave erosion of the marsh face.

Increased tidal action

Wave action cannot explain the erosion of the outer edge of saltmarshes in wave-sheltered inner estuary areas, and here the erosive forces must be in tidal currents. One view of estuaries is that they 'behave like a water bed – push down on one end and the water will rise in another' (Covey & Laffoley 2002), so that a reduction in volume, by saltmarsh enclosure and land claim, will need to be compensated for by tidal amplification elsewhere in the estuary, leading to erosion of marshes or mudflats (Covey & Laffoley 2002; Pethick 2002). However, the opposite view is that estuaries are not hydrostatic (like water beds) but of variable volume where the amount of water that flows into them is determined largely by the volume available to each tide. Most evidence supports this view, as saltmarsh enclosure has generally stimulated accretion through a reduction in the tidal volume of the estuary and consequently a reduction in current velocities (Doody 1992; Pye 1992; Van der Wal, Pye & Neal 2002). (For a fuller discussion of these issues see Pye 2000 and Pethick 2002). Uncles, Stephens & Smith (2002) established and modelled the positive association between estuary size and tidal current speeds.

Loss of intertidal seagrasses preceded the period of increased saltmarsh erosion and may have been partly responsible for it by destabilizing the estuaries. The loss of *Zostera* from the River Stour (Fig. 1) caused the erosion of 15 million m^3 of sediment and increased its tidal volume by 30% (Beardall, Dryden & Holzer 1988). Such an increase in volume would lead to faster tidal currents, particularly nearer the mouth, as more water floods and ebbs within one tidal period, and would cause further erosion (Brampton 1992; French 2001). The same kind of instability suggested for saltmarsh creeks (see above) may have occurred on the larger scale of whole estuaries, because the sediments have become more erodable and the volumes increased. The erosion of the outer edges of saltmarshes may reflect erosion that is progression towards new equilibrium morphologies of estuaries. Although it is becoming increasingly apparent that biological processes that stabilize or destabilize sediments will have an effect on estuarine morphology, most of the few interdisciplinary studies have not been at the appropriate medium space- and time-scales (Uncles 2002) and further research is required.

Comparison of south-east England with other regions

Comparisons with other regions, where saltmarshes are important but not generally eroding, may help answer the questions of why the saltmarshes of south-east England should be particularly vulnerable and why the problem has been particularly acute in the past half-century. The relatively recent changes to the biota in the past few decades, loss of *Zostera* and increase in abundance of *Nereis*, may have occurred unusually high in the intertidal zone, and the resultant decreases in sediment stability here may have been exacerbated by relatively fast current velocities because of a high tidal range. The loss of *Zostera* from an unusually high intertidal distribution has been discussed above. In less turbid waters seagrasses have a lower distribution, intertidally and subtidally, and their losses may have had different consequences for the pattern of sediment erosion and redeposition, including movement of sediment from the lower shore and subtidal channels to the upper shore. In Essex *Nereis* has a high intertidal distribution, being particularly abundant in the saltmarsh creeks above MHWNTL and in saltpans at elevations up to mean high water spring tide level (Paramor & Hughes 2004). The worms can tolerate long periods of emersion as they can feed when the tide is out, unlike other infaunal invertebrates, but why they occur at high elevations is not clear. Consequently the increase in abundance of *Nereis* in the south-east may have had a particularly severe impact on the saltmarshes compared with elsewhere, where they are either less abundant or have a lower intertidal distribution.

Two UK locations have been chosen for comparison, the Skeffling area of the Humber Estuary in north-east England, because it was the location of some extensive recent studies of saltmarshes and sediment–infauna interactions (Black, Paterson & Cramp 1998), and the Ribble Estuary in north-west England, the subject of a recent geophysical study (Van der Wal, Pye & Neal 2002). The mean rates of sea level rise for the Humber (Immingham) and Ribble (Heysham) estuaries, 1·04 and 1·7 mm $year^{-1}$, respectively (Proudman Oceanographic Laboratory 2003), are not different to those of the south-east and confirm the conclusion (above) that sea level rise and coastal squeeze cannot explain regional differences in saltmarsh erosion.

As the flood tidal wave moves south along the east coast of England it becomes funnelled into the shallow and narrow southern North Sea and its amplitude increases progressively. For example, the spring tide amplitude increases from about 2 m in Norfolk (Great Yarmouth), to 3·5 m at Felixstowe to 5·3 m at Southend. Further similar increases in tidal amplitude occur within some of the estuaries, for example to 6·5 m in London. In the Humber Estuary there are also high spring tidal amplitudes (6 m at Immingham) but the dominant infaunal invertebrate on the upper mudflats is the bivalve *Macoma balthica* (Widdows & Brinsley 2002), which cannot feed when the sediment surface is emersed. Similarly, the Ribble Estuary, which is generally accreting (Van der Wal, Pye & Neal 2002), has a high spring tidal amplitude (8·3 m at Heysham) but *Nereis* is not common either. The Mermaid database of the Joint Nature Conservation Committee (2003) indicates that *Nereis* (as *Hediste*) was found only occasionally in north-west England and only rarely was it a 'characterizing species'. Consequently the saltmarshes in the Humber and the Ribble may not be so exposed to the deleterious effects of bioturbating infauna at elevations above high water of neap tides. *Nereis* is abundant in parts of the Waddensea, on the coasts of Denmark, Germany and the Netherlands (see References in Hughes 1999), but here the tidal range is relatively small, about 1·7 m, and many of the marshes are open coastal or back barrier marshes and not confined in semi-enclosed estuaries, and therefore subject to relatively slow tidal currents. Here the erosion is mostly due to wave action (Houwing 2000).

Regional differences in the physical environment may also be important in explaining differences in rates of saltmarsh erosion. Pye (2000) concluded that generally the marshes in the south-east are ebb dominated and those in the north and west tend to be flood dominated, and these characteristics would tend to promote erosion and deposition, respectively. Crooks & Pye (2000) reported regional-scale variations in geotechnical properties of saltmarsh sediments, those in Essex having a higher moisture content and liquid limits, lower bulk densities and lower undrained shear strengths than saltmarshes in other parts of Britain. These properties would make the sediment more erodable than elsewhere, particularly as the high saturation states of these sediments may allow *Nereis* to be more active at higher elevations than in other areas where more permeable sediments are drier when emersed.

Implications for coastal management

The rejection of the coastal squeeze hypothesis as an explanation for saltmarsh loss in south-east England calls into question the current practices of saltmarsh restoration. Acceptance of the coastal squeeze explanation has limited the apparent options for saltmarsh creation to managed realignment (also known as retreat or set-back), where breaching or neglect of the sea wall allows some higher land to become intertidal and provide a habitat for the plants at the suitable elevation, either immediately or after a period of sediment accretion. On land with a shallow slope a new sea wall may need to be built on higher ground, and for a long-term economic benefit this will need to be protected by new saltmarsh so that it can be smaller and cheaper. The primary motive for managed realignment in the UK was for saving expenditure on coastal defence (Pethick 2001) and the success of a realignment scheme can be defined by saltmarsh development, for this reason and for the conservation benefits (Ministry of Agriculture, Fisheries & Food 1999). More recently realignment has also been used under European legislation in mitigation for habitats lost elsewhere, and where the development of saltmarsh was not necessarily required.

Managed realignment is acknowledged as being an inadequate response for saltmarsh creation. Covey & Laffoley (2002) reported that in England only 150 ha had been created, while the requirement from the Biodiversity Action Plan is for 60 ha year^{-1}, with an additional 40 ha year^{-1} for 15 years to recreate the total saltmarsh area to that of 1992. The gap between the rates of loss and creation of saltmarsh is growing. Moreover, in the south-east many realignment sites will not develop vegetation because the land is reclaimed saltmarsh and 0·5–2 m lower than the existing saltmarshes, because of compaction, shrinkage and the rise in RSL since it was claimed (Burd 1995). Consequently, sediment will have to accrete before saltmarsh can develop, but this will first become colonized by infauna that will prevent marsh development (Paramor 2002; Paramor & Hughes (2004). Many old (unmanaged) realignment areas remain as bare mudflats (French *et al*. 2000) or have eroding marshes within them for this reason (Hughes 2001); most of the recent studies in Essex that showed that exclusion of the infauna was necessary to allow colonization of mudflats by saltmarsh plants (see above) were conducted in old or new realignment sites. Consequently, the economic benefits and conservation objectives that depend on saltmarsh development in realignment sites may not be realized and the future of the policy becomes more questionable.

Managed realignment cannot be the main method for the UK to meet its international obligations for creating and maintaining saltmarshes. However, as sea level rise is not responsible for marsh losses, realignment is not the only method available, and other techniques should be considered. Paramor & Hughes (2004) suggested that saltmarsh creek erosion could be reduced, or reversed to deposition, by use of small partial barriers that retain some water between tides. These would reduce the tidal volume and hence current velocities. In addition, growth of saltmarshes in front of existing sea walls should also be possible, and has been achieved on a small experimental scale by excluding the infauna (Paramor 2002). This approach would be particularly valuable given the exponential increase in value of developing marshes that protect some sea walls. If, as suggested above, the estuaries are eroding towards new equilibrium morphologies because of a historical increase in their tidal volume, recharge of intertidal sediments using dredged material could reduce tidal volumes and current speeds and help redress any instability. Pye (2000) and French (2001) also recommended the beneficial use of dredged sediment in coastal management, although not for this reason. Transplanting intertidal seagrasses offers a means for stabilizing recharged or natural sediment and increasing natural sedimentation. The conditions necessary for successful transplanting of the two intertidal *Zostera* species have been identified (Nicholls 2004). Transplanting intertidal seagrasses would carry a double benefit as both *Zostera* species are Biodiversity Action Plan species.

References

Agricultural Select Committee of the House of Commons (1998) *Flood and Coastal Defence*. 6th Report. Agricultural Select Committee of the House of Commons, London, UK. http://www.publications.parliament.uk

Beardall, C.H., Dryden, R.C. & Holzer, T.J. (1988) *The Suffolk Estuaries*. The Suffolk Wildlife Trust, Saxmundham, UK.

Black, K.S., Paterson, D.M. & Cramp, A. (1998) *Sedimentary Processes in the Intertidal Zone*. Special Publications No. 139. Geological Society, London, UK.

Boorman, L., Goss-Custard, J.D. & McGrorty, S. (1989) *Climatic Change, Rising Sea Level and the British Coast*. ITE Research Publication No. 1. HMSO, London, UK.

Brampton, A.H. (1992) Engineering significance of British saltmarshes. *Saltmarshes, Morphodynamics, Conservation and Engineering Significance* (eds J.R.L. Allen & K. Pye), pp. 115–122. University of Cambridge Press, Cambridge, UK.

Burd, F. (1992) *Erosion and Vegetation Change on the Saltmarshes of Essex and North Kent Between 1973 and 1988*. Research and Survey in Nature Conservation No. 42. Nature Conservancy Council, Peterborough, UK.

Burd, F. (1995) *Managed Retreat: A Practical Guide*. English Nature, Peterborough, UK.

Cahoon, D.R., French, J.R., Spencer, T., Reed, D.J. & Möller, I. (2000) Vertical accretion versus elevational adjustment in UK saltmarshes: an evaluation of alternative methodologies. *Coastal and Estuarine Environments; Sedimentology, Geomorphology and Geoarchaeology* (eds K. Pye & J.R.L. Allen), pp. 223–238. Special Publications No. 175. Geological Society, London, UK.

Coastal Geomorphology Partnership (2000) *Erosion of the Saltmarshes of Essex Between 1988 and 1998*. Department of Marine Sciences and Coastal Management, University of Newcastle, Newcastle, UK.

Covey, R. & Laffoley, D. d'a (2002) *Maritime State of Nature Report for England; Getting onto An Even Keel*. English Nature, Peterborough, UK.

Crooks, S. & Pye, K. (2000) Sedimentological controls on the erosion and morphology of saltmarshes; implications for flood defence and habitat recreation. *Coastal and Estuarine Environments; Sedimentology, Geomorphology and Geoarchaeology* (eds J.R.L. Allen & K. Pye), pp. 207–222. Special Publications No. 175. Geological Society, London, UK.

Cundy, A.B. & Croudace, I.W. (1996) Sediment accretion and recent sea level rise in the Solent, southern England: inferences from radiometric and geochemical studies. *Estuarine and Coastal Shelf Science*, **43**, 449–467.

Davy, A.J. (2000) Development and structure of salt marshes: community patterns in time and space. *Concepts and Controversies in Tidal Marsh Ecology* (eds M.P. Weinstein & D.A. Kreeger), pp. 137–156. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Den Hartog, C. & Phillips, R.C. (2001) Common structures and properties of seagrass beds fringing the coasts of the world. *Ecological Studies*. Vol. 151. *Ecological Comparisons of Sedimentary Shores* (ed. K. Reise), pp. 195–212. Springer Verlag, Berlin, Germany.

Dixon, M., Leggett, D.J. & Weight, R.S. (1998) Habitat creation opportunities for landward coastal realignment: Essex case studies. *Journal of the Institution of Water and Environmental Management*, **12**, 107–112.

Doody, J.P. (1992) The conservation of British saltmarshes. *Saltmarshes, Morphodynamics, Conservation and Engineering Significance* (eds J.R.L. Allen & K. Pye), pp. 80–114. University of Cambridge Press, Cambridge, UK.

Doody, J.P. (2001) *Coastal Conservation and Management: An Ecological Perspective*. Kluwer Academic Publishers, Dordrecht, the Netherlands.

English Nature (1992) *Coastal Zone Conservation. English Nature's Rationale, Objectives and Practical Recommendations*. English Nature, Peterborough, UK.

French, C.E., French, J.R., Clifford, N.J. & Watson, C.J. (2000) Sedimentation–erosion dynamics of abandoned reclamations. *Continental Shelf Research*, **20**, 1711–1733.

French, J.R. & Reed, D.J. (2001) Physical contexts for saltmarsh conservation. *Habitat Conservation: Managing the Physical Environment* (eds A. Warren & J.R. French), pp. 179–228. John Wiley and Sons, Chichester, UK.

French, P.W. (2001) *Coastal Defences. Processes, Problems and Solutions*. Routledge, London, UK.

Funnell, B.M. & Pearson, I. (1989) Holocene sedimentation on the North Norfolk barrier coast in relation to relative sea-level change. *Journal of Quaternary Science*, **4**, 25–36.

Gerdol, V. & Hughes, R.G. (1993) Effect of the amphipod *Corophium volutator* on the colonisation of mud by the halophyte *Salicornia europaea*. *Marine Ecology Progress Series*, **97**, 61–69.

Hartig, E.K., Gornitz, V., Kolker, A., Mushacke, F. & Fallon, D. (2002) Anthropogenic and climate-change impacts on saltmarshes of Jamaica Bay, New York City. *Wetlands*, **22**, 71–89.

Houwing, E.-J. (2000) Morphodynamic development of intertidal mudflats: consequences for the extension of the pioneer zone. *Continental Shelf Research*, **20**, 1735–1748.

Hughes, R.G. (1999) Saltmarsh erosion and management of saltmarsh restoration; the effects of infaunal invertebrates. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **9**, 83–95.

Hughes, R.G. (2001) Biological and physical processes that affect saltmarsh erosion and saltmarsh restoration: development of hypotheses. *Ecological Studies: Ecological Comparisons of Sedimentary Shores* (ed. K. Reise), pp. 173–192. Springer Verlag, Berlin, Germany.

Hughes, R.G. (2004) Climate change and loss of saltmarshes; consequences for birds. *Ibis Online*, in press.

Hughes, R.G. & Gerdol, V. (1997) Factors affecting the distribution of the amphipod *Corophium volutator* (Pallas) in two estuaries in south eastern England. *Estuarine and Coastal Shelf Science*, **44**, 621–627.

Hughes, R.G., Lloyd, D., Ball, L. & Emson, D. (2000) The effects of the polychaete *Nereis diversicolor* on the distribution and transplanting success of *Zostera noltii*. *Helgoland Marine Research*, **54**, 129–136.

Jennings, S.C., Carter, R.W.G. & Orford, J.D. (1995) Implications for sea-level research of salt marsh and mudflat accretionary processes along paraglacial barrier coasts. *Marine Geology*, **124**, 129–136.

Joint Nature Conservation Committee (2003) Joint Nature Conservation Committee, UK. http://www.jncc.gov.uk/mermaid/.

King, S.E. & Lester, J.N. (1995) The value of saltmarsh as a sea defence. *Marine Pollution Bulletin*, **30**, 180–189.

Mason, C.F., Underwood, G.J.C., Baker, N.R., Davey, P.A., Davidson, I., Hanlon, A., Long, S.P., Oxborough, K., Paterson, D.M. & Watson, A. (2003) The role of herbicides in the erosion of salt marshes in eastern England. *Environmental Pollution*, **122**, 41–49.

Ministry of Agriculture, Fisheries and Food (1999) *Tollesbury Managed Realignment Experimental Site. Summary Report of Research and other Activities, 1994–96*. Ministry of Agriculture Fisheries and Food, London, UK.

Nicholls, J.C. (2004) *Aspects of the ecology of the intertidal seagrasses* Zostera noltii *Hornem. and* Zostera marina *L. at Leigh National Nature Reserve, Thames Estuary*. PhD Thesis. University of London, London, UK.

Nydick, K.R., Bidwell, A.B., Thomas, E. & Varekamp, J.C. (1995) A sea level rise curve from Guildford, Connecticut, USA. *Marine Geology*, **124**, 137–159.

Orson, R.A., Warren, R.S. & Neiring, W.A. (1998) Interpreting sea level rise and rates of vertical marsh accretion in a southern New England tidal saltmarsh. *Estuarine and Coastal Shelf Science*, **47**, 419–429.

Paramor, O.A.L. (2002) *Interactions between benthic macroinvertebrates and saltmarsh plants: consequences for saltmarsh restoration and the policy of managed realignment on the coast of S.E. England*. PhD Thesis. University of London, London, UK.

Paramor, O.A.L. & Hughes, R.G. (2004) The effects of bioturbation and herbivory by the polychaete *Nereis diversicolor* on loss of saltmarsh in south-east England. *Journal of Applied Ecology*, **41**, 449–463.

Pethick, J.S. (1981) Long term accretion rates on tidal saltmarshes. *Journal of Sedimentary Petrology*, **51**, 571–577.

Pethick, J.S. (1992) Saltmarsh geomorphology. *Saltmarshes, Morphodynamics, Conservation and Engineering Significance* (eds J.R.L. Allen & K. Pye), pp. 41–62. University of Cambridge Press, Cambridge, UK.

Pethick, J.S. (2001) Coastal management and sea-level rise. *Catena*, **42**, 307–322.

Pethick, J.S. (2002) Estuarine and tidal wetland restoration in the United Kingdom: policy versus practice. *Restoration Ecology*, **10**, 432–437.

Proudman Oceanographic Laboratory (2003) Proudman Oceanographic Laboratory. http://www.pol.ac.uk/psmsl/.

Pye, K. (1992) Saltmarshes on the barrier coastline of north Norfolk, eastern England. *Saltmarshes, Morphodynamics, Conservation and Engineering Significance* (eds J.R.L. Allen & K. Pye), pp. 148–178. University of Cambridge Press, Cambridge, UK.

Pye, K. (2000) Saltmarsh erosion in south east England: mechanisms, causes and implications. *British Saltmarshes* (eds B.R. Sherwood, B.G. Gardiner & T. Harris), pp. 359–396. Linnean Society of London, London, UK.

Shennan, I. (1989) Holocene crustal movements and sea level changes in Great Britain. *Journal of Quaternary Science*, **4**, 77–89.

Smith, D., Hughes, R.G. & Cox, E. (1996) Predation of epipelic diatoms by the amphipod *Corophium volutator* and the polychaete *Nereis diversicolor*. *Marine Ecology Progress Series*, **145**, 53–61.

Uncles, R.J. (2002) Estuarine physical processes research: some recent studies and progress. *Estuarine, Coastal and Shelf Science*, **55**, 829–856.

Uncles, R.J., Stephens, J.A. & Smith, R.E. (2002) The dependence of estuarine turbidity on tidal intrusion length, tidal range and residence time. *Continental Shelf Research*, **22**, 1835–1856.

UNEP (2003) UNEP. http://www.grida.no/climate/vital/24.htm.

United Kingdom Biodiversity Group (1999) *Tranche 2 Action Plans*. Vol. V. *Maritime Species and Habitats*. English Nature, Peterborough, UK.

Van der Wal, D., Pye, K. & Neal, A. (2002) Long-term morphological change in the Ribble Estuary, northwest England. *Marine Geology*, **189**, 249–266.

Widdows, J. & Brinsley, M. (2002) Impact of biotic and abiotic processes on sediment dynamics and the consequences to the structure and functioning of the intertidal zone. *Journal of Sea Research*, **48**, 143–156.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A. & Shennan, I. (1999) A review of the trends observed in British Isles mean sea level data measured by tide gauges. *Geophysical Journal International*, **136**, 651–670.

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