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Shifting sands? Coastal protection by sand banks, beaches and dunes

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ABSTRACT

In a closely integrated system, (sub-) littoral sandy sediments, sandy beaches, and sand dunes offer natural coastal protection for a host of environmentally and economically important areas and activities inland. Flooding and coastal erosion pose a serious threat to these environments, a situation likely to be exacerbated by factors associated with climate change. Despite their importance, these sandy 'soft' defences have been lost from many European coasts through the proliferation of coastal development and associated hard-engineering and face further losses due to sea-level rise, subsidence, storm surge events, and coastal squeeze. As part of the EU-funded THESEUS project we investigated the critical drivers that determine the persistence and maintenance of sandy coastal habitats around Europe's coastline, taking particular interest in their close link with the biological communities that inhabit them. The successful management of sandy beaches to restore and sustain sand budgets (e.g. via nourishment), depends on the kind of mitigation undertaken, local beach characteristics, and on the source of 'borrowed' sediment. We found that inter-tidal invertebrates were good indicators of changes linked to different mitigation options. For sand dunes, field observations and manipulative experiments investigated different approaches to create new dune systems, in addition to measures employed to improve dune stabilisation. THESEUS provides a 'toolbox' of management strategies to aid the management, restoration, and creation of sandy habitats along our coastlines, but we note that future management must consider the connectivity of sub-littoral and supra-littoral sandy habitats in order to use this natural shoreline defence more effectively.

1. Introduction

The importance of sand bars, beaches, and dunes has long been understood in terms of the defence and protection they afford coastlines (Doody, 2012; Simm, 1996). From the sub- to the supra-littoral, sandy habitats are important in preventing coastal erosion and flooding, but their value may be enhanced by the many biological processes that complement or even increase their role in coastal defence. For example in addition to their role in nourishment of other sandy systems, shallow, sub-tidal sands also support seagrass beds, a habitat increasingly recognised as important for coastal protection due to their ability to stabilise and accumulate sediment, and attenuate and dissipate waves (Christianen et al., 2013; Ondiviela et al., 2014-this issue). In addition to their value as sources of raw materials, grazing land, recreation, and intrinsic biodiversity, sand dunes have also long provided defence against coastal flooding (Doody, 2012; Everard et al., 2010).

At a time when Europe faces significant economic and environmental challenges, the defensive value offered by natural habitats along Europe's coastlines is increasingly recognised by policy makers. If managed properly, sub-tidal sand flats and bars, beaches and sand dunes could offer a sustainable means of mitigating the effects of sea-level rise and the anticipated increase in storminess over coming decades. Our ability to effect such holistic coastal management will depend on our combining not only an understanding of coastal geomorphology and engineering but also, a detailed knowledge of coastal ecology given that these so-called 'soft-defences' represent dynamic biological systems. In this paper we analyse the key threats to sandy habitats and describe how these systems can help defend Europe's coastline against the challenges posed by climate change. We review a number of examples where restoration and management of beaches and dunes have been attempted and discuss experiments and case studies conducted as part of the EU-funded THESEUS project that seek to illustrate the role that they can play in coastal defence.

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2. Sandy habitats — A dynamic system

A natural sandy shoreline can be viewed as an adaptive structure that is both resilient and responsive to changes in the energy of the forcing conditions so as to maximise the persistence of the structure and minimise the effects of energetic hydrodynamic events. Sandy beaches for instance, respond to increased wave activity by flattening their profiles as the beach face becomes saturated with water and the net cross-shore transport of sediment becomes more biased towards offshore (Dean, 1991). Sand dragged offshore may form or augment sequences of submerged bars. This creates a system in which the bigger waves break more aggressively in the shallow water depths over these bars. A wider, dissipative surf zone develops, reducing the wave energy incident on the shoreline. In extremely energetic conditions, the greater reach of wave run-up may extraordinarily mobilise sediment from dune fields at the top of the beach (Kamphuis, 2010; Simm, 1996). As a result dunes can act as a moveable last line of defence, an emergency sediment supply against which the waves expend their energy, dragging sediment into the near-shore and enhancing further wave dissipation (Everard et al., 2010). Under less energetic conditions, shorter, steeper waves wash onto the more permeable, less saturated beach face forcing sediment back onshore. As a consequence, the beach accretes and steepens, becoming more reflective, pushing wave energy back out to sea. A transfer of this sediment back into the dune system occurs when onshore winds combine with the effects of solar drying of the exposed beach face, an effect enhanced by the occurrence of larger tidal excursion (Anthony et al., 2006).

Coastal sandy environments thus represent dynamic, linked systems in which tides, waves, currents, and weather control the reworking and exchange of sediment between offshore, beach face and supra-tidal dune systems. Dunes, beaches and sand bars are in constant dynamic equilibrium, with different timescales of morphological response, from intra wave period to annual, inter-annual and even longer cycles dictated by climate change and isostatic forcing. In addition to the interactive dynamic imposed by geomorphological conditions however, it must be remembered that even the most sterile looking environment supports a wealth of organisms which together facilitate and modify how sand bars, beaches and dunes respond to perturbation. The biological interaction between sub- and supra-tidal systems for example is evidenced by the fact that debris derived from sub-tidal seagrass beds is important for beach stabilisation and sand-dune formation (Gallego-Fernandez et al., 2011; Hemminga and Nieuwenhuize, 1990). Consequently, not only is the movement of sand between sub- and supra-littoral environments vitally important in maintaining the integrity of coastal defence, but the ecology of these systems can also play an important part in this dynamic process (Doody, 2012).

3. Threats to sandy environments

3.1. Climate change

The primary contemporary threat to all coastal habitats from climate change is perhaps the very reason why they have such value in coastal defence. In the last 100 years thermal expansion of the seas coupled with meltwater from glaciers and ice sheets has caused a global increase in sea levels with continued rises forecast for the remainder of the 21st century (IPCC, 2007). In isolation, the predicted increase in global sea level probably does not pose a major threat to most adaptive coastal ecosystems. However, the severity of the threat is greater in areas of subsidence, such as in southwest UK, where the combined effects of glacial isostasy and global sea level rise are expected to produce approximately a 1 m increase in water level over the next 100 years. Shifts in sediment transport pathways in conjunction with a likely increased incidence of extreme weather events, are expected to exacerbate coastal erosion and damage (Diermanse and Roscoe, 2011; Mailier et al., 2005; Rangel-Buitrago and Anfuso, 2011).

Europe lost 25% of its sand dunes during the 20th century (Delbaere, 1998) and up to 85% of the remainder may be threatened (Helensfield et al., 2004). The primary reasons for this decline are agricultural improvement, urban development, tourism and recreation. However reduction in sediment supply from other coastal or even inland river catchments has also contributed to sand dune losses (Doody, 2012; Everard et al., 2010). Into the future however, climate change poses the greatest problem for Europe's coastal dunes. Sea-level rise, in tandem with in-land urban and agricultural development, will increase the phenomenon of 'coastal squeeze', but increased storm intensity and frequency are likely to be the major challenges faced by sand dunes (Doody, 2012; Everard et al., 2010). Despite their value to coastal protection however, the exact scale of the threat to Europe's sand dunes from climate change is unclear, partly due to the fact that sediment and erosion pathways are difficult to predict (Pye and Blott, 2008). Nonetheless, Saye and Pye (2007) estimated that some Welsh dune systems will lose up to 100 m of shoreline as a result of increased erosion driven by sea-level rise and Pye and Blott (2008) noted a strong positive link between storm activity and coastal erosion in NW England. It is within the context of threats emanating from climate change that management of Europe's coastal dune and other sandy systems must be based.

3.2. Impact of hard engineering

In addition to climate change, sandy environments are also impacted by coastal development for recreation, industry, and urban expansion. Besides structures associated with coastal development, a variety of hard defences (e.g., breakwaters, groynes, seawalls, dykes, gabions or other rock-armoured structures) have been put in place to counteract coastal erosion. Such measures have proliferated in the second half of the twentieth century, leading to severe 'hardening' of coastal areas and changes in sediment structure (Airoldi et al., 2005). In the north Adriatic Sea for example, over 190 km of artificial structures, mainly groynes and breakwaters, seawalls and jetties, have been built along 300 km of naturally low sedimentary shores (Bondesan et al., 1995; Cencini, 1998). These hard defences have an immediate impact on local biodiversity (see Firth et al., 2014), but coastal armouring also alters local hydrodynamic regimes, which in-turn affects sediment supply, deposition and grain size, with concomitant impacts on adjacent soft-bottom sub-littoral ecosystems (Bertasi et al., 2007; Walker et al., 2008) and beaches (Bastos et al., 2012; Veloso-Gomes et al., 2004).

Erosion is particularly acute for sandy beaches where coastal development and implementation of hard defence measures such as groynes and shore parallel breakwaters disrupt normal patterns of wind, wave, and current movement to disconnect sediment-exchange. Groynes interrupt the littoral drift of sediment driven by long-shore currents, thus allowing up-drift deposition of sediment and the increase of beach width. Groynes also modify the near ground wind fields, with concomitant impact on aeolian transport, scour, and the sediment pathways to adjacent dunes. Segmented or shore parallel breakwaters predominantly modify the wave processes, reducing, diffracting and refracting incident wave fields behind them, thus creating sandy tombolo or salient features (shore normal tongues of sand), which may increase beach width, but can also interrupt long-shore transport of sediment (Finkl and Walker, 2004).

3.2.1. Hard engineering off the rails? THESEUS case study in southern England

Sea walls have several effects on adjacent beaches. As reflective structures they may encourage the generation of standing waves which can enhance mobilisation of sediment to create scour. They also represent a barrier which interrupts exchange and supply of sediment between the natural hinterland and the beach system. This is the case at one of the THESEUS study sites, where the "Brunel" sea wall, along which the Plymouth to London railway runs, has cut off the supply of sediment from the cliffs between Teignmouth and Dawlish. The beach