

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.

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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 (Airoidi 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

that runs along the bottom of the sea wall exhibits great variability, relying on long-shore sediment movements, exchanges with offshore sand banks, and transmission of fluvial sediment input from the Teign estuary.

Further along the south Devon Coast, at Dawlish Warren, a sand spit covers the mouth of the Exe Estuary, shielding the communities of Starcross and Lypstone and Exeter from direct risk of flooding from wave attack and overtopping. Historically the spit was a natural feature subject to breaching and dynamic exchange of sediment with the complex sub-tidal system of banks and shoals at the estuary mouth.

With the construction of the seawall and railway line, the sediment pathways and supply have been disrupted. Consequently, the spit has been heavily engineered in an attempt to conserve its integrity as a geomorphic feature across the estuary mouth. The railway sea wall abuts a newer seawall protected by a rock revetment, which meets a concrete apron and sea wall, built to armour the root of attachment of the spit to the coast on the south side of the estuary. Further along the spit, wire cage gabions are used to protect dunes from wave increased attack caused by a thinning of the beach width due to loss of sand to off shore shoals; a natural part of the sediment cycle in this system. There are also conservation measures in place to protect the dunes along the spit from damage by the many tourists who visit through the use of boardwalks, and to enhance the entrapment of sediment with brushwood fences. To try to maintain the width of the sandy beach along the remainder of the Dawlish Warren spit, and minimise the risk of breaching and breakup, a wooden groyne field has been emplaced. This is also believed to help prevent a natural tendency for rotation of the spit into the estuary.

Despite these measures, sand loss from the beach remains a problem due to the interruption and perturbation of historical sediment pathways and supply. One possible proposal for the management of this feature and mitigation of loss of beach sediment is to recharge the beach from offshore shoals, in combination with the removal of gabions from in front of the dune system. The aim is to re-stock this observed loss of sediment from the beach, which has resulted in continued thinning near the distal end. The approach hopes to encourage a more natural and sustainable system behaviour, assisted by the artificial recycling of sediment. However, due to its importance as a nesting site for waders and waterfowl the spit has international conservation status (it is designated as a Site of Special Scientific Interest and a Special Area of Conservation). Consequently, any engineering approach needs to pay due consideration to these designations and other ecological issues such as the possible effect of sand nourishment on the recipient invertebrate community (see Sections 4.1.1 and 4.1.2).

Although at different scales, the situations in the Adriatic Sea and the Teign estuary are just two of many examples where hard engineering solutions have failed to deliver effective coastal defence through their negative impact on sediment supply and thus upon natural habitats. It is largely through the recognition that coastal sandy habitats are a linked, dynamic system that hard engineering must be now employed with consideration of their likely impact on the wider geomorphological and biological environment. It is also for these reasons that so-called soft approaches are becoming more common in the planning of coastal defence.

4. Sandy shores – The ‘soft option’ for coastal defence?

Despite possessing a coastline that extends 170,000 km across 20 of 27 member states, (Frankignoulle et al., 2004), there is concern that the European Union is ill-equipped to deal with the threats posed by climate change (Barbosa et al., 2009; Zanuttigh, 2011). The central theme of the THESEUS project is not only to identify the main climate-linked threats to Europe's coasts, but also suggest ways in which coastal systems can be effectively managed to mitigate these threats. One aspect of this work is the appropriate use of traditional coastal engineering, but in addition to a ‘hard defence’ option, ecologically-based

mitigation measures are important to our integrated strategy. It is within that context that we have studied the likely contribution that conservation and management of sub-tidal sand deposits, beaches, and sand dunes can make to coastal defence across Europe.

4.1. Sand nourishment

Softer engineering approaches to the maintenance of sand coastlines often include some form of sediment nourishment. One of the most dramatic examples is taking place in the Netherlands; the ‘sand engine’ (*‘De Zandmotor’*) involves the emplacement of sand into sub-littoral which is then reworked by waves and currents providing a long-term input into the local sediment budget to maintain sediment supply to sand bars, beaches and dune systems many kilometres distant (e.g. van den Hoek et al., 2012). Beach nourishment, which relies on sediment from dredge sites, recycling of sediment from sinks, or frequently the removal of sand from the adjacent inter-tidal, is more common and extensively practised throughout Europe (Hanson et al., 2002; Veloso-Gomes et al., 2004), but it is not without its problems.

4.1.1. The wrong sand? THESEUS case study on the Hel Peninsula, Poland

The Hel Peninsula is a 36 km long sand bar separating the Bay of Puck from the Baltic Sea. Naturally prone to fragmentation, for the last 100 years the Peninsula has been characterised by shifting coastal dynamics. In the period 1908–1937 no significant erosion of the Peninsula base was observed, but after construction of the port at Władysławowo and in particular its breakwaters, coastal sediment transport from west to east has declined markedly and erosion rates have increased steadily. Towards the end of the 20th century average coastline retreat was estimated at over 1 m yr^{-1} (Zawadzka-Kahlau, 1999). Concomitant erosion of dune systems has also been observed with losses east of Kuznica estimated at between 3 and 5 m yr^{-1} (Zawadzka-Kahlau, 1999).

The serious long-term geomorphological implications of sediment deficit for the Hel Peninsula caused by the Władysławowo port construction were recognised and mitigation measures introduced. The first beach nourishment in Poland occurred at Hel Peninsula in the 1980s utilising the sediment that had accumulated around the breakwaters at Władysławowo. By 1993 a total of 5.8 million m^3 of sand was supplied along an 11.1 km section of the Peninsula to five sites near Chałupy and Kuznica and by 2001 the total volume of sand nourished along the Hel Peninsula reached 9.8 million m^3 (Ostrowski and Skaja, 2011). In order to supply this volume of sediment to the transport system, material was dredged from Puck Bay. This sediment is much finer-grained than material taken from the open sea (Zawadzka, 1996) and was prone to subsequent re-dispersal even in low energy wave currents. Consequently, problems with erosion continued despite large volumes of sediment being removed from the leeside of the Peninsula to nourish the littoral transport system.

Research conducted by THESEUS partners based at the Polish Academy of Sciences in Gdansk suggests that optimum sediment composition for nourishing the central part of the Peninsula is a 50:50 combination of material from open sea borrow-sites and the Władysławowo breakwater (Ostrowski and Skaja, 2011). As a result, subsequent efforts to nourish the Peninsula have now switched to the use of material dredged from near the Władysławowo breakwaters and from open sea borrow sites near Rozewie and Jastarnia on the northern side of the Peninsula. More widely however, the case study in the Hel Peninsula highlights a number of factors in contemporary coastal engineering. First, there is the marked effect that hard engineering has upon coastal sediment budgets and subsequent impacts upon natural ‘soft’ defences. Second are the consequences of using sand from a different provenance for beach nourishment; even large amounts of the ‘wrong sand’ are likely to have little positive effect on sediment budgets (see Hanson et al., 2002). From an ecological perspective there are also issues surrounding sediment

Table 1

Physical characteristics of six beaches along the Italian Adriatic Coast. The two unmanaged beaches are shown by grey shading; the remaining four beaches were subjected to frequent management including raking and nourishment.

Location (Lat:Long)	Management		Total Organic Matter (%)	Grain size (ϕ)	Sorting (ϕ)	Beach width (m)	Slope (index 1/x)	Beach Deposit Index
Lido di Dante 44°23'23"N 12°19'25"E	Backed by dunes and pine forest; the southern section falls within a nature reserve. Dune stabilisation is only active management.	Mean	0.65	1.67	0.48	8.51	14.26	47.16
		SE	0.02	0.03	0.03	0.51	0.83	2.90
Bellocchio 43°48'00"N 12°59'00"E	Protected as a nature reserve. Backed by dunes and alagoon. Dune stabilisation is only active management.	Mean	4.51	4.47	1.06	30.88	51.47	1769.77
		SE	0.52	0.18	0.09	2.23	3.32	217.82
Lido di Spina 44°39'03"N 12°15'09"E	Nourishment; daily raking during the tourist season.	Mean	0.81	1.94	0.73	11.18	26.65	106.87
		SE	0.06	0.03	0.02	0.80	1.89	7.59
Cervia 44°13'20"N 12°19'04"E	Daily raking during the tourist season.	Mean	0.88	2.64	0.63	24.28	36.27	236.51
		SE	0.04	0.07	0.08	0.77	1.28	10.18
Cesenatico North 44°11'59"N 12°24'05"E	Nourishment; daily raking during the tourist season. Engineered management with slightly submerged breakwater.	Mean	0.57	2.58	0.59	16.68	23.33	146.59
		SE	0.02	0.07	0.05	1.30	1.51	10.82
Cesenatico South 44°11'56"N 12°24'05"E	Nourishment; daily raking during the tourist season. Engineered management with emergent breakwaters.	Mean	0.67	2.80	0.59	46.40	80.21	586.73
		SE	0.04	0.04	0.02	5.79	8.68	66.32

provenance, as we shall see below, sand-dwelling invertebrate communities are highly sensitive to changes in sediment type.

4.1.2. Beach nourishment and inter-tidal ecology: THESEUS case study Emilia Romagna, Italy

By their nature, sandy-beaches are prone to frequent and severe physical disturbances and so the recovery of associated invertebrate communities following nourishment can occur very quickly. Nonetheless, if the profile of the nourished beach and the imported sediment does not match the original conditions (for example unnaturally coarse or fine sand), full recovery is unlikely (Peterson et al., 2000, 2006). In addition, artificially flattened and extended sand bodies can be colonised by rapidly moving opportunistic macro-fauna and under these conditions biodiversity can be much reduced (Peterson and Bishop, 2005).

With these issues in-mind, THESEUS partners based at the University of Bologna, Italy conducted studies along the Northern Adriatic coastline to determine the ecological effects of sediment redistribution and nourishment and other ('hard' and 'soft') management interventions on the intertidal invertebrate communities of sandy beaches. The study area is characterised by different degrees of economic development, ranging from heavily used tourist beaches and resorts, to natural beaches with backing sand dune systems. Artificial sand embankments (so-called "winter dunes") are used to protect the tourist beaches. These are normally constructed before the winter season when the probability of storm and beach flooding is particularly high and sand is then redistributed throughout the spring and summer. Although often preferred on economic grounds (Finkl and Walker, 2004), this form of nourishment can nonetheless cause ecological damage to beach habitats, particularly when sand is removed from the inter-tidal to nourish the supra-tidal (Blott and Pye, 2004; Speybroeck et al., 2006).

Environmental and biotic characteristics of six sandy beaches between Lido di Dante and Lido di Spina were sampled during June–July 2011. Two 'natural' beaches were both located within exiting nature

reserves with backing sand dunes (Lido di Dante and Bellocchio), lacked hard structures and had limited human interference. The remaining four beaches (Cesenatico North, Cesenatico South, Cervia and Lido di Spina), lacked natural features, experience heavy tourism in the summer season and due to various degrees of erosion and subsidence, and are subject to frequent beach management including the use of sand embankments (Table 1). To quantitatively sample invertebrate macro-fauna 6 or 8 transects were set laid out along each beach perpendicular to the shoreline, extending from the high tide level to the low tide level (where breakwaters were present, transects were located in front of these structures). Along these transects four sediment samples were taken from each of three sites. Each replicate consisted of pooling four plastic cores (10 cm in diameter) sunk to a depth of 10 cm (total sampling area = 0.0314 m²). All invertebrates were extracted by sieving samples through a 500 μ m mesh before storage in 10% formaldehyde. Four replicate cores of 3 cm inner diameter were taken from the same location to quantify grain size and organic matter analyses. Intertidal beach width and slope were quantified for each transect (intertidal slope was expressed as 1/x, thus higher values correspond to 'flatter' beaches). Beach morphodynamic state was quantified by BDI (beach deposit index), a technique commonly used for microtidal beaches that takes into account beach slope and the sand-particle size (McLachlan and Dorvlo, 2005). This index is highest for reflective beaches with steep slopes and coarse sand, while dissipative beaches with flat slopes and finer sands have low BDI (Soares, 2003).

The physical characteristics of the study beaches were markedly different (Table 1). The wide beach at Bellocchio was characterised by fine sand with high organic content, while the other natural beach at Lido di Dante had a higher median grain size and a steeper profile (i.e. lower BDI) than all other beaches, perhaps linked to erosion of material from the dunes and pinewood in the backshore. The physical characteristics of four managed beaches were consistent with the fact that they had recently undergone active management where sand was

taken from the inter-tidal and moved above the high-tide level to form sand embankments. The wide, flat beach at Cesenatico South also stood apart from Cesenatico North, Cervia, and Lido di Spina in width, slope and BDI possibly due to the fact that shortly before sampling it experienced fore-shore scraping in order to re-distribute sand to the beach rear for nourishment and also because it is protected by emergent breakwaters.

There were significant differences in species richness and abundance of macro-faunal assemblages among beaches suggesting that variation in management was affecting the invertebrate in-fauna (Table 2 and Fig. 1). The two natural beaches Lido di Dante and Bellocchio generally had the highest species number and only one of the managed sites (Cervia, which is never nourished) had higher organismal abundance. The lowest species number and abundances were found at the heavily managed Lido di Spina and two Cesenatico beaches. It is likely that nourishment by translocation of sand from the inter-tidal and beach raking reduced greatly the diversity and abundance of macro-invertebrate in-fauna in comparison with the natural beaches at Lido di Dante and Bellocchio. In addition, both Cesenatico beaches are protected by breakwaters.

The six beaches were very different also in term of invertebrate community structure. Fig. 2 is a Multi-Dimensional Scaling (MDS) plot where distances between points represent differences among communities (i.e. closer points are more biologically similar). Of the two unmanaged beaches at Bellocchio and Lido di Dante, Bellocchio was most clearly separated from the managed beaches (Fig. 2), showing major community variation due to a higher abundance of *Corophium* spp. amphipods and *Polydora* spp. polychaete worms. Both invertebrate groups are characteristic of the fine grained sediments and undisturbed lagoons found at Bellocchio. The invertebrate community at Lido di Dante was dominated by nematodes and turbellaria flatworms, species characteristic of the coarser sands and steeper beach profile (low BDI) at this site.

Three of the four managed beaches were clearly separated from the unmanaged sites. The wide, dissipative (high BDI) beach at Cervia in particular, stood out in terms of community structure and for having relatively high organismal abundance compared with the other managed beaches. Although heavily impacted by tourism, erosion and accretion this beach is in stable equilibrium, and benthic organisms do not experience the more intense management practices undertaken at Cesenatico and Lido di Spina. The invertebrate community here was dominated by large numbers of the small bivalve *Lentidium mediterraneum* and the polychaete *Scolecopsis squamata*, both typical of low energy, fine sediment, intertidal zones (Bertasi et al., 2007). The two Cesenatico beaches were dominated by species similar to Cervia, but with much reduced abundance, especially for *L. mediterraneum*. These patterns are consistent with the nourishment of the rear of these beaches using sediment taken from the fronting inter-tidal section. The invertebrate fauna at Lido di Spina was broadly similar to Lido di Dante, being characterised by nematode and ribbon worms. Unlike Lido di Dante however, it also supported low densities of *S. squamata*.

This study shows how variation in the invertebrate sediment in-fauna is linked to the use of different management regimes. The practice of removing sediment from the inter-tidal to nourish

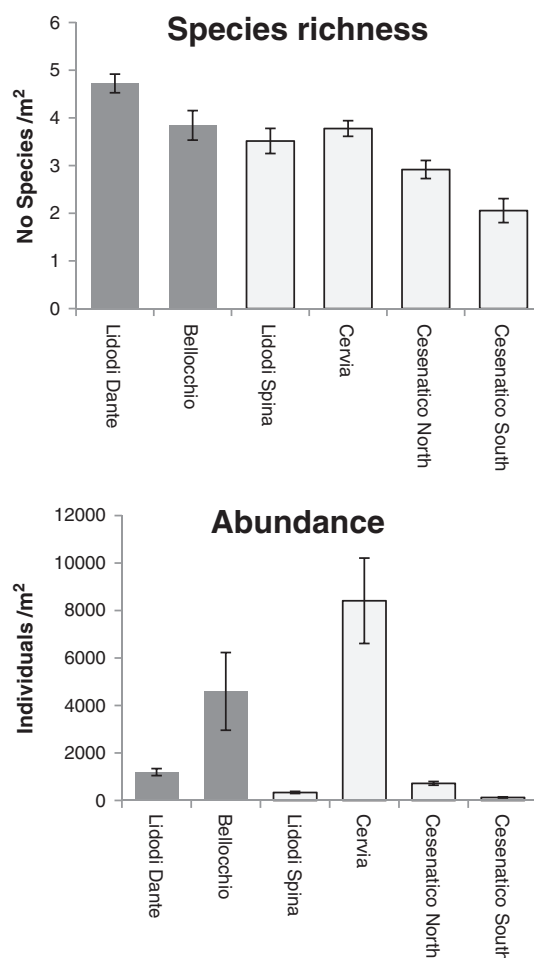


Fig. 1. Species richness (mean $\pm$ SE number per m^2) and relative abundance (organisms per m^2) for macro-invertebrate in-fauna communities in six beaches along the Adriatic Coast, Italy. The two unmanaged beaches are shown in dark grey; lighter grey denotes beaches subjected to frequent raking and nourishment.

supra-littoral beaches seems to have particularly strong effects of on inter-tidal invertebrate community. Significant loss of or change in the beach in-fauna is important for a number of reasons. Inter-

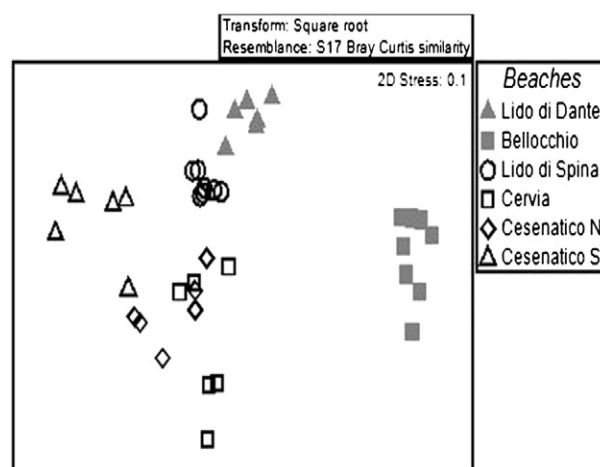


Fig. 2. MDS plot showing variation in inter-tidal macro-fauna assemblages on six beaches along the Adriatic Coast, Italy. The two unmanaged beaches are shown in dark grey, white symbols denote beaches subjected to frequent raking and nourishment. Analysis was performed on Bray–Curtis similarity matrices after square-root transformation of abundance data. Each point represents a replicate transect.

Table 2

Nested ANOVA showing variation in species richness (number per m^2) and relative abundance (organisms per m^2) for macro-invertebrate in-fauna communities in six beaches along the Adriatic Coast, Italy.

Source of variation	df	Species richness			Abundance		
		MS	F	P	MS	F	P
Beach	5	81.20	10.12	0.0001	1250×10^6	4.59	0.004
Transect (beach)	34	8.17	2.20	0.0003	279×10^6	2.59	0.001
Residual	232	3.72			107×10^6		
Total	271						

tidal sediment-dwelling invertebrates provide an index of beach cleanliness and are widely used in environmental impact studies since they are sedentary and cannot escape changes in water quality and pollution (Dauer, 1993; Pearson and Rosenberg, 1978). These organisms also have an important role in nutrient cycling, helping to remove and process organic material from the beach (i.e. helping to keep the sand 'clean') as well as providing food for predatory species such as birds and fish (McLachlan and Dorvlo, 2005). Consequently any alteration in sediment supply to beaches could greatly impact on sandy inter-tidal invertebrate assemblages and thus affect the ecosystem-level processes with which they are linked. In addition to the effects of management for tourism, the effects of flooding mitigation schemes on sediment budget needs include consideration of the effects on ecology as well as geomorphology.

4.2. Sand dunes

Due to a number of large-scale sand drift events throughout the Middle Ages, Europe's sand dunes have been widely managed for centuries and remain at the forefront of coastal protection (Clarke and Rendell, 2010). In the Netherlands for example sand dunes are integral to the defence of a land area that lies below sea-level yet supports 9 million people and yields 70% of National GDP (Arens and Geelen, 2006; Hommes et al., 2011). In order to act as an effective defence, dunes must withstand periodic storm damage and erosion (Diermanse and Roscoe, 2011) a dynamic interaction that depends on dune morphology, sediment supply, accumulation, and stabilisation. When sand delivery rates are high, the fore-dunes become wider rather than taller because sand deposition is spread out over an ever-expanding area, creating a series of long, low fore-dune ridges. In contrast, when sand supply to the beach is negligible (slightly positive or negative), the sand travelling from the beach to fore-dune is deposited over a smaller area thus causing the dune to become taller rather than wider (Psuty, 1986). Likewise, if sand supply is negative, beach erosion and scarping will create shorter and narrower fore-dunes with a greater chance of over-wash by waves. However while the role of dunes in wave attenuation and coastal defence is determined by geomorphological characteristics and sand supply, the presence of vegetation is more important for dunes than any other sandy habitat simply because vegetation aids the accumulation of sediment (Hacker et al., 2012; Psuty, 1986).

4.2.1. Dune nourishment

The standard methods of beach nourishment described in Section 4.1 inevitably impact upon the nourishment of sand dunes further inland. Indeed this method has been used throughout Europe to nourish sand dunes (see Hanson et al., 2002), but as with beaches, careful consideration of the provenance and grain size of the nourishment sand is essential if the technique is to be deployed effectively (van der Wal, 1998). In the most extreme management scenarios, sand must be manually redeployed to nourish, rehabilitate or restore badly degraded sand dunes (Wilcock and Carter, 1977). In one such example, construction of a 300 space car park during the 1960s to allow tourist access to the fronting beach destroyed all but a small fragment of the sand dunes at South Milton, Devon, England. Following the eventual decay of the wooded supports that fronted the car park, the National Trust (who acquired the site in 1980) in consultation with local residents opted to reconstruct the original dune system. In 2009 three new dune ridges, each around 200 m long and 30 m wide, were created using sand moved from the fronting beach. Over 15,500 plugs of the rhizomatous dune grass *Ammophila arenaria* were planted across the sea-ward sides of the three dunes in an attempt to help stabilise the sand (see Section 4.2.3.). The fact that the site owner planted the dune with *Ammophila* highlights one of the key differences between dunes and other sandy habitats: it is possible and often desirable to actively manage dune habitats with physical and biological interventions.

4.2.2. Dune stabilisation by fences

Sand fences (including the use of brushwood branches) work by reducing wind speed which then allows sand accumulation and eventual colonisation by early successional dune species (Doody, 2012). Sand fences have been successfully deployed all around the globe and have the advantage of being inexpensive, and easy to construct, as well as being relatively unobtrusive especially once sand accretion begins (Gallego-Fernandez et al., 2011; Nordstrom et al., 2012). In order to be effective however, fencing must be positioned such that it creates maximum topographic complexity within a restricted area (Grafals-Soto, 2012). Successful positioning often relies on intuition, experience, or luck, but more rigorous modelling approaches could better inform the spatial arrangement of fences.

Brushwood fences are commonly employed on sand dune systems along Poland's Baltic Coast. Not only are they highly effective in facilitating sand accumulation, but also they are inexpensive due to the availability of natural material and a very simple construction method. Nonetheless how best to deploy brushwood fences remained poorly defined; within THESEUS we attempted to determine the most effective spatial geometry for brushwood fences along a section of the Baltic Coast at Lubiatowo, Poland (54°48'42"N, 17°50'26"E). From summer 2009 to spring 2011 a detailed geodesic survey of the dunes and brushwood fences was carried out, in tandem with measurements of wind speed and direction. This allowed us to develop a mathematical model explaining the relationship between brushwood fence size and position and optimum sand accumulation (Fig. 3). We show that fencing is most effective when the supra-tidal beach width w (with respect to the long-term mean sea level at high tide) is at least 35 m and the elevation of the dune base above the sea level h (defined within the same manner as w) exceeds the 100-year return storm surge period. An additional criterion related to a so-called surf scale parameter ε (namely the condition $\varepsilon > 150$) should also be satisfied. The parameter ε is determined by the formula:

$$\varepsilon = \frac{2\pi^2 H_b}{gT^2 \tan^2 \beta}$$

in which β is an angle of the mean seabed inclination in the near-shore zone (averaged over a 500 m long distance stretching seawards from the shoreline), H_b is the breaking wave height, T denotes wave period, and g acceleration due to gravity. In addition fences should be located as straight line segments at a distance of 1–3 m from the dune base with 0.3 m of the total 1.0 m height buried into the sand.

It must be remembered that this model was developed for micro-tidal environments like the Baltic or Mediterranean Seas and at best is applicable to meso-tidal coasts. On macro-tidal shores or shores with a steeply inclined coastal sea bed, fences may be ineffective due to the fact that the aeolian transport is much reduced (sand has less opportunity to dry out). Moreover, where artificial nourishment of dunes is employed, changes to dune geomorphology make influence several parameters in the model equation. Nonetheless, this broad approach could help better position and align dune fencing to optimise sand capture and facilitate more effective dune stabilisation and management.

4.2.3. Dune stabilisation by vegetation

Stabilisation by forestation or use of other sand-binding vegetation has for the most part helped maintain the defensive role played by coastal dune systems (Clarke and Rendell, 2010; Hommes et al., 2011). Although some contemporary opinion is pushing for a shift away from over-stabilisation of dunes, this view is partly driven by the assumption that the use of monocultures or non-native plants has major negative impacts on native biodiversity (Doody, 2012; Everard et al., 2010). There are many examples where the introduction of non-native plants for dune stabilisation has caused both significant negative ecological impacts (D'Antonio and Mahall, 1991; Hacker et al., 2012; Vranjic et al., 2012) and reduced dune stability by changing the local

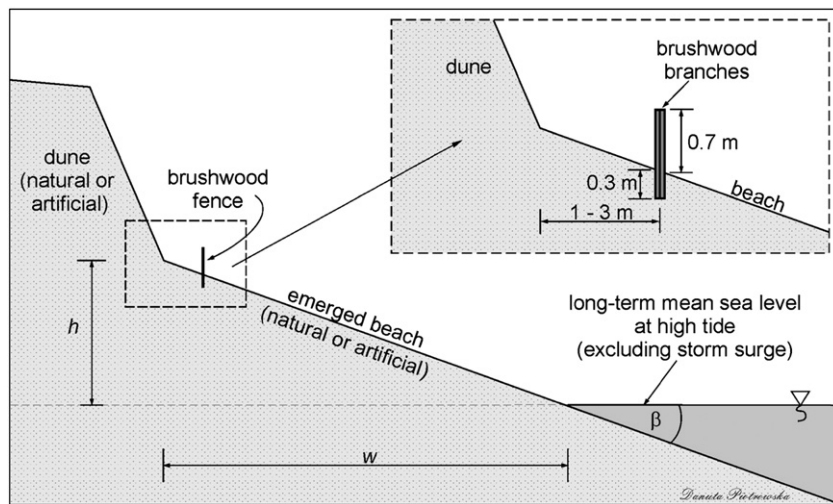


Fig. 3. Optimum design criteria for brushwood fences deployed in sand dune systems adjacent to micro-tidal coasts.

dune profile from that provided by native plant species (Hilton, 2006). However, contemporary restoration efforts now rely on planting dominant native grasses such as *Ammophila* species that function as dune builders due to their extensive root systems and ability to grow under constant sand burial (Emery and Rudgers, 2009; Maun, 2009; Seabloom and Wiedemann, 1994).

Such an approach was adopted at South Milton in Devon in order to stabilise the newly restored sand dunes constructed in 2009. As part of the THESEUS project we surveyed changes in *Ammophila* cover and associated plant biodiversity in fixed quadrats on each of the three dunes. Four 1 m² quadrats were established along three longitudinal transects running along the top, middle and foot of each dune (i.e. 12 quadrats per dune). In each quadrat percentage vegetation cover was recorded in October 2011, July 2012 and June 2013. In addition, over a 3 month period at that start of the monitoring program daily sand accumulation was estimated from the foot and the top of the sand dunes by positioning astro-turf mats near to the fixed quadrats (following Steiger et al., 2003).

We found a significant increase in *Ammophila* cover (ANOVA, $F_{(2,99)} = 4.37$ $P = 0.015$) through time (October 2011 to June 2013 – Fig. 4) indicating that establishment of the *Ammophila* plugs was successful. Establishment and growth varied with position on the dune however; there was significant increase in *Ammophila* cover only at mid-level ($F_{(2,30)} = 3.57$ $P = 0.041$) and particularly at the dune base ($F_{(2,30)} = 10.67$ $P < 0.001$). This corresponds with variation in sand

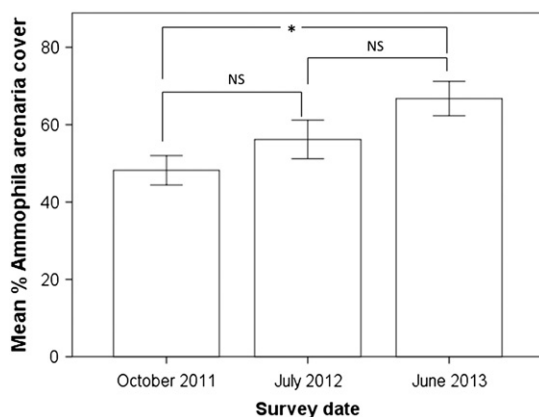


Fig. 4. Mean percentage cover of *Ammophila arenaria* planted in to a newly restored (2009) sand dune system at South Milton, Devon, England. Cover was recorded on 3 survey dates October 2011, July 2012 and June 2013. Error bars = ± 1 SE. * = significant at $P < 0.05$, NS = not significant following one-way ANOVA and post-hoc SNK tests.

deposition; an average 14.5 g m² d⁻¹ of sand was deposited at the dune base compared to only 2.3 g m² d⁻¹ at the top. At first glance this may seem counter-intuitive, but in fact there is much evidence that several sand dune species, *Ammophila* included, demonstrate enhanced growth where sand deposition is relatively high (see Maun, 2009 for a detailed synthesis).

Thirty further species were recorded within our dune quadrats, but all species were observed at only very low abundances and there was no significant variation in species number through time (ANOVA, $F_{(2,99)} = 1.71$ $P = 0.186$). More interestingly perhaps, of the thirty species observed, only 7 are typically associated with sand dune habitats. The remainder were generalist ruderals (weeds). Consequently while *Ammophila* establishment has been successful at South Milton, plant community biodiversity is limited, possibly due to limited movement of propagules from nearby natural sand dunes.

One way of overcoming the problem of seed limitation is to introduce seeds directly into the dunes, but this method is often unsuccessful due to burial, erosion and desiccation (Maun, 2009). One potential way to deal with these problems is to combine physical and biological sand stabilisation. In THESEUS we examined how biodegradable geotextile matting affected the regeneration success of common European dune building/stabilising plant species. A combination of geotextile and direct seed sowing or planting may offer an inexpensive and (for seeds) less labour intensive method for stabilising sediments and ensuring that a range of sand dune species can be introduced to newly established or recently eroded dune systems. Nonetheless, the efficacy of this approach is largely untested, especially over a large geographic area.

Our experiments were conducted at three contrasting locations. South Milton (50°15'31"N, 03°51'28"W) is a small, newly restored dune system located at the Western end of the English Channel in Devon, England. The Carnon dunes (43°33'22"N, 04°01'55"E) near Montpellier, SE France are also newly restored but unlike the other two sites which are Atlantic dune systems, face the Mediterranean Sea. Our third site was located in the Liencre dune system (43°26'43"N, 03°58'14"W), near Santander, NW Spain, a site that also underwent restoration in the early 2000s.

At South Milton we monitored the regeneration success of seeds sown directly into the upper and lower fore-dunes at the sand dunes within and without textile matting. We established sixteen 0.6 m × 0.6 m plots within each of the three restored dunes; eight were located at random points along the foot of the dune with the remainder located towards the top of the dune crest at the steepest point. At each height four different seeding techniques were established (1) seeds sown into holes with covering geotextile, (2) seeds surface sown with covering geotextile, (3) seeds sown in holes without geotextile, (4) seeds surface sown

without geotextile, such that there were two replicate plots of each treatment at each height on each of the three dunes. Seeds of four plant species (*Cackile maritima*, *Lotus corniculatus*, *Leontodon taraxiodes* and *Leymus arenarius*) were collected from numerous parent plants an adjacent natural sand dune; a local seed source is important in order to ensure genetic continuity with local native vegetation but multiple parent plants provide natural genetic variation to combat disease and other environmental factors (Mortlock, 2000; Waters et al., 2007). These species were chosen to provide variation in taxonomy and growth form as well as successional differences, but all four are common dune species in NW Europe. Within each plot 10 seeds were stationed approximately 170 mm apart in a 4 × 4 array such that there were 4 replicate patches of each species in each plot. Seeds in holes were sown to a depth of 30-mm and covered loosely with sand. Surface-sown seed was placed into a slight (5 mm) indentation to reduce immediate movement. Pre-cut 600 × 600 mm squares, of Jute fabric Geotextile (500 g m⁻² density, 15 mm × 22 mm mesh size; supplied by Greenfix, Eaglescliffe, UK) were placed over half of the plots and secured firmly with metal pegs and their edges covered with sand to prevent removal.

The experiment at South Milton began when seeds were sown in late October 2011. Seedling numbers were first counted one month after sowing and then weekly for a further 4 weeks until winter storms and excessive sand deposition buried and killed all seedlings. By early January only 22 (all *Leymus*) seedlings of a maximum 242 seedlings (8th December) survived. Of the 4 plant species investigated, only *L. arenarius* exhibited substantial germination and we found no enhancement of *Leymus* emergence in plots covered with geotextile even when maximum seedling numbers were recorded (45 days after sowing) ($t_{(46)} = 0.02$, $P > 0.05$). Similarly there was no variation in seedling emergence depending on dune location ($t_{(46)} = 0.29$, $P > 0.05$) or whether seeds were planted in holes or surface sown ($t_{(46)} = -0.98$, $P > 0.05$) (Table 3).

The work conducted in France and Spain was broadly similar to that done in England, but here we also used vegetative fragments and repeated the experiment in autumn and spring. In Spain the geotextile used was Fijavert Coco 250 Coconut fibre Geotextile (250 g m⁻² density, 30 mm × 30 mm mesh size; supplied by Projar, Valencia, Spain) while the geotextile used in France had a the same weave and density to that used in the UK. Seeds or fragments were planted directly into sand dunes within and without geotextile matting, but unlike South Milton 50 surface sown-seeds were scattered over the entire 1 m² plot and covered with about 5 mm of sand. At Lienes, Spain, seeds

or fragments of two plant species (*Helichrysum stoechas* and *A. arenaria*) were collected from within the dune system. *Ammophila* is a dominant, clonally spreading, dune building species found on 'mobile' fore-dunes throughout Europe while *Helichrysum* is a seed establishing species restricted to the 'fixed' rear dunes of southern Europe. We established 2.5 m × 2 m (5 m²) areas in each of two dunes, one fixed rear-dune and one mobile fore-dune. Four 5 m² plots were established in the rear-dune site where we examined the establishment of *Helichrysum* from seed using similar treatments to South Milton; i.e. 10 seeds were sown into five holes per plot with or without covering geotextile or 50 seeds were surface sown with or without covering geotextile. Six 5 m² plots were established in the fore-dune site where we examined *Ammophila* establishment from seed and vegetative fragments i.e. 10 seeds were sown into twenty-five holes per plot with or without covering geotextile, 50 seeds were surface sown with or without covering geotextile, or 25 vegetative fragments were planted with or without covering geotextile.

In Spain the spring experiment began in late May 2011 and the autumn experiment in late November 2011 and the experiments lasted until mid-March 2012. Neither *H. stoechas*, nor *A. arenaria*, exhibited substantial germination (the former failing to germinate in the autumn experiment) and there was no enhancement of seedling emergence or fragment survival in plots covered with geotextile. Similarly there was no variation in seedling emergence depending on whether seeds were planted in holes or surface sown (Table 4). *Ammophila* fragments did however, show greater survival when planted in autumn ($t_{(38)} = 7.94$, $P < 0.001$).

The work conducted in France investigated the effects of geotextile on germination of three species (*A. arenaria*, *Artemisia campestris*, and *H. stoechas*) and establishment from vegetative fragments for *A. arenaria* and *Elymus farctus* (the latter being a common dune pioneer species found throughout Western Europe). Aside from very limited germination in *Ammophila*, no seedlings were recorded in either autumn or spring experiments and we report here only the results of experiments with vegetative fragments.

Five vegetative fragments of each species were each planted into five separate 1 m × 1 m plots in May 2011 and October 2011, with or without covering geotextile as described for the experiment conducted in Spain and varying in slope (steep versus shallow). No fragments of either species planted in spring survived the Mediterranean summer. However, although percentage survival was low, there was some indication that autumn-planted *Ammophila* fragments with geotextile protection survived better than those planted without geotextile, at least on steeper slopes ($t_{(8)} = 2.67$, $P = 0.029$) (Table 5). *Elymus*

Table 3

The effects of geotextile coverage on seedling emergence of three common sand dune species (*Lotus corniculatus*, *Leontodon taraxiodes* and *Leymus arenarius*: a fourth species *Cackile maritima*, was used but did not germinate) 45 days after seeds were sown into a newly restored sand dune system at South Milton, Devon, England. Ten seeds of each species were sown onto the sand surface or into 30-mm holes into two locations on the dune (the shallow sloped dune base or the steeper sloped dune crest).

Treatment			Species			Total seedlings
			<i>Lotus</i>	<i>Leontodon</i>	<i>Leymus</i>	
Geotextile	Sown in to holes	Dune base	Mean	0.2	0.0	5.5
			SE	0.2	0.0	2.7
		Dune crest	Mean	0.2	0.5	3.0
			SE	0.2	0.5	1.7
	Surface-sown	Dune base	Mean	0.0	0.3	5.7
			SE	0.0	0.2	3.3
		Dune crest	Mean	0.2	0.0	4.5
			SE	0.2	0.0	2.2
No geotextile	Sown in to holes	Dune base	Mean	0.2	0.2	4.5
			SE	0.2	0.2	2.4
		Dune crest	Mean	0.0	0.3	1.8
			SE	0.0	0.3	1.5
	Surface-sown	Dune base	Mean	0.2	0.7	7.0
			SE	0.2	0.5	3.4
		Dune crest	Mean	0.0	0.3	5.2
			SE	0.0	0.2	3.0

Table 4

The effects of geotextile coverage on mean percentage seedling survival of two common sand dune species (*Ammophila arenaria* and *Helichrysum stoechas*) recorded in March 2012 for seeds were sown into a sand dune system at Lienes, Cantabria, Spain in May and November 2011. Mean percentage survival (March 2012) of vegetative fragments of *Ammophila* planted in November 2011 with and without geotextile is also shown.

Treatment		Species & season			
		Spring		Autumn	
		<i>Ammophila</i>	<i>Helichrysum</i>	<i>Ammophila</i>	
Geotextile	Sown in to holes	Mean	0	0	7.6
		SE			1.0
		Mean	0	0.4	0
	Surface-sown	SE		0.4	
		Mean	8.0		13.6
		SE	4.9		1.0
No geotextile	Sown in to holes	Mean	0	0	8.4
		SE			0.8
		Mean	0	0.4	0
	Surface-sown	SE		0.4	
		Mean	0.6		18.4
		SE	0.4		1.0

Table 5

Mean percentage survival of vegetative fragments of *Ammophila arenaria* and *Elymus farctus* with and without geotextile 2 months after vegetative fragments were planted into a sand dune system at Carnon, near Montpellier, France. Fragments were planted in spring and autumn 2011 but due to complete mortality of spring-planted fragments, data for the autumn planting only are shown.

Treatment			Species	
			<i>Ammophila</i>	<i>Elymus</i>
Geotextile	Steep slope	Mean	52.0	0
		SE	8.0	
	Shallow slope	Mean	20.0	4.0
		SE	6.3	4.0
No geotextile	Steep slope	Mean	20.0	12.0
		SE	9.0	8.0
	Shallow slope	Mean	8.0	8.0
		SE	4.9	4.9

displayed very low survival and there were no obvious trends related to geotextile coverage or slope ($t_{(18)} = 1.63$, $P > 0.05$).

While our failure to observe substantial long-term plant establishment from seed was disappointing, these experiments highlight the general unpredictability of seedling establishment in natural systems. The seedling stage is the most vulnerable part of a plant's life history and a number of different factors including disease, disturbance, nutrient stress, drought, and competition significantly limit seedling growth and survival (Fenner and Thompson, 2005). The storms that affected the south Devon Coast during winter 2011/2 causing the loss of our entire seedling cohort show how extreme weather events can impact upon regeneration from seed. The fact that seedling establishment was so poor across all three sites irrespective of slope, geotextile protection, or season strongly suggests that restoration of sand dune systems using seed alone is unlikely to be a reliable management option.

Results in France with directly planted *Ammophila* fragments were a little more encouraging, although rather inconsistent in terms of seasonal responses. Nonetheless it seems that the use of geotextile could potentially facilitate the establishment of small *Ammophila* fragments especially when planted in the autumn. Good *A. arenaria* establishment is particularly desirable as the species is one of the most commonly used dune stabilising plants (Emery and Rudgers, 2009; Seabloom and Wiedemann, 1994). Nonetheless in our study vegetative establishment of *Ammophila* was relatively poor, even with geotextile. It seems therefore that planting small fragments, even with some form of protective barrier against sand deposition/erosion, is potentially less effective than the use of large individuals planted into the sand as used in the restoration of the dunes at South Milton.

5. Synthesis and future directions

Despite the relatively well understood interaction between sub- and supra-littoral sandy environments, sand bars, beaches and dunes have traditionally been managed in isolation at relatively local scales. The loss of sediment supply through sand dredging, or hard-engineered coastal development can have significant effects on the dynamic geomorphological processes that help maintain sandy habitats many kilometres distant (Zanuttigh, 2011). Coastal engineers, geomorphologists, and ecologists are only now beginning to appreciate fully the inter-connectedness of sandy environments and how their individual disciplines can and should be combined to deliver effective, integrated coastal management and defence. This is particularly timely as rising sea-levels and alterations to coastal currents due to climate change, may pose the greatest threat yet to our coastlines.

Fundamental to contemporary coastal management is an understanding of the role of biological systems in maintaining habitat integrity and function. The concept of ecosystem service provision (Costanza

et al., 1997) is currently applied to coastal ecosystems, but often from the perspective of the provisioning of food resources, water purification, carbon capture, or cultural services (Alves et al., 2009; Polidoro et al., 2010; Waycott et al., 2009). By comparison, less emphasis is placed on the direct contribution a properly functioning littoral sand or dune ecosystem plays in maintaining coastal defence (but see Roebeling et al., 2013). Indeed, although sandy beaches represent nearly 80% of the ice-free coasts of the world, ecological studies of this valuable coastal ecosystem are widely neglected. One fruitful possibility for future research would be to examine how changes in beach ecology impact on the physical resistance and resilience of littoral sandy environments in the face of extreme weather events, and even how changes to the beach fauna and micro-flora influence processes in nearby sub- and supra-littoral sandy systems.

Further up the shore, the ecology of sand dunes has been studied extensively (Gallego-Fernandez et al., 2011; Hemminga and Nieuwenhuize, 1990; Maun, 2009). Nonetheless, even for dunes, how species diversity and functional characteristics affect the stability of the system when faced with major perturbation remains unclear. Dunes are frequently prone to breach and flooding by sea water during winter storms, yet there have been few systematic studies of the response of dune vegetation to sea water flooding (but see Hoggart et al., 2014-in this issue). The effects of other major perturbations on dunes are similarly poorly explored; particularly within the context of how intervention strategies can limit physical damage caused by sand erosion/accretion and encourage the development and spread of dune vegetation at a time when sand dunes are at the forefront of coastal defence.

In THESEUS we found that small patches of geotextile had little or no beneficial effect on seedling emergence but with the caveat that our experiments in the UK were truncated by excessive sand accretion from winter storm activity while spring sowing in France experienced unusual drought. This, in itself, highlights the stochastic nature of ecosystem processes on any highly dynamic habitat and the fact that managers must take a long-term view of restoration and intervention strategies and tailor management to meet specific goals. If for example, the establishment of a more bio-diverse ecosystem is the goal, then introduction of new plant species by seed may be viable where repeat sowing is possible and rapid establishment is not a priority. However, if the primary role of vegetation is the capture and stabilisation of sand, then measures to establish sand-building plant species like *Ammophila* are appropriate. Biodiversity and dune stabilisation may not be mutually exclusive however. We suggest that future research could focus on the way in which sand fences and other physical management options impact upon seedling establishment. There could be great potential to combine the strategic modelling approach we describe for locating sand fences along the Baltic Coast with a better understanding of sediment dynamics and thus a way of predicting where sand accretion and erosion are stable enough to allow seedlings to establish and so facilitate re-vegetation. Companion sowing with dune stabilising plant species such as *Ammophila* may also be a way of increasing plant species diversity on newly restored areas. Although the general principle of companion planting is proven for sand dunes (Roze and Lemauiel, 2004), there is much potential for a more systematic approach wherein manipulation of different spatial arrangements and densities of nursemaid plants like *Ammophila* could be trialled to determine the most effective combination of environmental conditions for successful seedling establishment. Such an approach is one of many ways in which a combination of skills and expertise from coastal engineering, geomorphology, and ecology could be synthesised to better protect Europe's coastlines into the 21st century.

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