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Have we neglected the societal importance of sand dunes? An ecosystem services perspective

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ABSTRACT

1. Coastal sand dunes are widespread worldwide, including around the coasts of the British Isles and Europe, providing a wide range of functions some of which are recognized for their socio-economic benefits.
2. In some localities, their contribution to coastal defence and to tourism and regional character have been acknowledged in local plans, but this is far from ubiquitous.
3. A rapid assessment was undertaken of the range of ecosystem services provided by coastal sand dune systems, using the Millennium Ecosystem Assessment ecosystem services classification augmented with habitat- and locally-appropriate additions.
4. Sand dunes were shown to provide a wide range of provisioning, regulatory, cultural and supporting services, many of which remain substantially overlooked.
5. Although the importance of coastal sand dune for a diversity of characteristic and often rare organisms from a variety of taxa has been addressed, many of the broader ecosystem services that these habitats provide to society have been overlooked. This suggests that coastal sand dune systems are neglected ecosystems of significant and often under-appreciated societal value. Copyright © 2010 John Wiley & Sons, Ltd.

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INTRODUCTION

Coastal sand dunes develop where there is an adequate supply of sand in the intertidal zone and where prevailing winds are strong enough for sand movement to occur. They occur worldwide from the tropics to circum-polar regions (Martinez *et al.*, 2004) and are an important habitat type providing a suite of both environmental and socio-economic functions. However, they have been considered neglected in terms of habitat, ecosystem and physical processes worldwide (Arun *et al.*, 1999; Pua Bar, 2009) and within the UK (Rotheroe, 1993; Defra and Environment Agency, 2001).

Coastal sand dune systems support a broad range of flora and fauna owing to the diversity of the ecological niches found within them. Part of this diversity is due to the complex topography and its concomitant vegetation communities, creating a wide range of habitats from dry dune crests to wet dune slacks — a (usually seasonal) wetland habitat — between the dune ridges. Further internal heterogeneity is generated by aspect on steep dune slopes (Jones *et al.*, in press b), the degree of grazing and disturbance by animals (van Dijk, 1992; Plassmann *et al.*, 2010), and by successional processes in both dry and wet dune habitats (Jones *et al.*, 2008) with development from largely bare sand through to grassland and eventually scrub or woodland as a natural climax community in most temperate systems (Provoost *et al.*, in press). Where the parent sand material contains carbonates or is rich in shell or coral fragments, soil pH alters from calcareous to acidic with age as a result of leaching (Salisbury, 1925), providing different soil chemical environments on the same site. Dune soils can become highly acidic since there is no weathering of bedrock to replace bases lost through leaching. Equally, different areas across coastal sand dune systems can be subject to saline intrusion from sea water and sea spray but also freshwater inputs from rainfall and/or groundwater. In the wet dune slack habitats, diverse vegetation assemblages are a function of both complex

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hydrological regimes (Lammerts *et al*., 2001) and the chemistry of the groundwater which can show high within-site heterogeneity (Sival *et al*., 1997; Jones *et al*., 2006).

The biological importance of sand dunes can be illustrated using examples from the UK. Eleven broad coastal sand dune habitats listed under Annex 1 of the EU Habitats Directive occur in the UK, with legal obligations for their protection. Of these, five are recognized as priority habitats at a European scale: fixed dunes with herbaceous vegetation ('grey dunes'); decalcified fixed dunes with *Empetrum nigrum*; Atlantic decalcified fixed dunes (*Calluno-Ulicetea*); coastal dunes with *Juniperus* spp.; and turloughs (a unique type of disappearing lake found mostly in limestone and almost unique to Ireland). The UK also has special responsibility for two further habitats: humid dune slacks; and machair (http://www.jncc.gov.uk/page-1523). The UK Biodiversity Action Plan (BAP) contains separate Habitat Action Plans (HAPs) for each of these priority sand dune habitats (http://www.ukbap.org.uk/ukplans.aspx?ID = 28). Within the UK, these diverse niches support a wide range of species, including over 680 Red Data Book, or nationally rare/scarce invertebrate species alone (Howe *et al*., in press). Many species dependent on dunes require early successional habitats with sparse vegetation cover and areas of bare sand. Red Data Book vertebrate species for which coastal sand dunes provide important habitats include the natterjack toad (*Epidalea calamita*) (Denton *et al*., 2003), sand lizard (*Lacerta agilis*) and great-crested newt (*Triturus cristatus*) (Brooks and Agate, 2001). Furthermore, coastal sand dunes are an important refugium habitat for a number of lowland calcareous plant species such as fen orchid (*Liparis loeselii*) (Jones, 1998) which have declined across the broader landscape of Britain due to habitat loss resulting from agricultural improvement. Dune slacks are particularly species rich for plant species, supporting many orchid species and of particular importance for a number of bryophytes including the EU Habitats Directive Annex II-listed petalwort (*Petalophyllum ralfsii*). Locally, damp sand dune grassland and dune slacks are important breeding and over-wintering resources for populations of waders (Malcolm and Soulsby, 2001). Dune habitats are particularly important for invertebrates, especially aculeate hymenoptera (bees, wasps and ants) (Archer, 1994) such as the vernal sand-mining bee (*Colletes cunicularius*), dune tiger beetles (*Cicindela maritima* and *Cicindela hybrida*) and some spiders (wolf spider *Arctosa cinerea* and crab spider *Philodromus fallax*) (Houston, 2008). In Wales alone, early successional habitats support 68% of the 462 dune invertebrate species recorded (Howe *et al*., in press). Table 1 shows a sample of the BAP priority species with significant populations in sand dunes.

Table 1. BAP priority species with significant populations in sand dunes, derived from the UK coastal sand dunes HAP (http://www.ukbap.org.uk/ukplans.aspx?ID = 28)

- Bright wave moth *Idaea ochrata cantiana*
- Spider wasp *Evagetes pectinipes*
- Tiger beetle *Cicindela hybrida*
- Ground beetle *Panagaeus crux-major*
- Dune gentian *Gentianella uliginosa*
- Fen orchid *Liparis loeselii*
- Sea bryum (Moss) *Bryum warneum*
- Petalwort (Liverwort) *Petalophyllum ralfsii*

In addition to their biodiversity, coastal sand dunes are also increasingly becoming recognized for their socio-economic functions. The porous structure of sandy beaches and dunes absorbs and dissipates wave energy, and stores of sand in the fore-dunes provide additional material which re-enters the marine transport system and forms a new beach profile after erosion events. These natural processes allow sandy coasts to adapt their morphology and maintain their natural coastal defence role with minimal human intervention necessary, providing there is space to allow natural dynamics to operate. Through their capacity for energy dissipation, sand dunes can also support artificial defences, reducing the cost of hard engineering solutions. They thereby absorb energy from wind, tide and wave action, and are a natural sea defence barrier. In the Netherlands (Arens and Geelen, 2006) and in the USA (French, 2001), sand dunes perform a primary coastal defence role. Locally in the UK, they are also recognized for this function, for example in Shoreline Management Plans for St. Bees Head to River Sark (http://www.allerdale.gov.uk/environment-and-planning/shoreline-management-plan.aspx), Ceredigion (http://www.ceredigion.gov.uk/external/shoreline/english/smp/ceredigionsmp.htm), Angus (http://www.angus.gov.uk/ac/documents/roads/SMP/3-0.pdf), the Severn Estuary (http://www.severnestuary.net/secg/docs/Issues%20and%20Objectives%20leaflet_Kingston%20Seymour%20and%20S and%20bay.pdf) and Liverpool Bay (http://www.sefton.gov.uk/PDF/TS_cdef_LBSMP_1.pdf). Sand dunes may also serve water purification roles, for example as part of the water purification infrastructure for Amsterdam, where the dunes supply 50 million m^3 $year^{-1}$ drinking water to 1.5 million people (Beekelaar and Geelen, 1999; Van der Meulen *et al*., 2004). However, no such actively managed sand dune treatment schemes are known in the UK. Sand dunes also provide characteristic landscapes of cultural value (Nordstrom, 2000), considerable amenity value, and support a range of other ecosystem services. Large dune systems provide a focal point of recreation in countries such as Denmark and the Netherlands, while in the rest of Europe they form part of the 'coast experience' for many coastal tourists. They are increasingly valued for their wildness and as a place of escape and solitude (Doody, 1997; Houston, 1997).

Sand dunes formerly occupied a greater area of the UK than at present. It is estimated that 30% of the dune area has been lost on the Sefton Coast, one of the largest dune areas in England (Doody, 1991). This trend is consistent with a 30% loss across the UK between 1900 and 1998, and a net loss of 25% all over Europe over the same period (Delbaere, 1998). Primary causes of habitat loss in the past include agricultural improvement, commercial afforestation and urban development (Jones *et al*., 1993; Mifsud, 2007). Habitat loss in the UK has slowed since many areas gained protection in the 1960s. However, across Europe, it is estimated that 85% of the current resource is under threat (Heslenfeld *et al*., 2004). The legislation pertaining to sand dune protection in the UK is summarized in Table 2, including both statutory and 'near-statutory' instruments. Current pressures causing loss or damage to sand dune habitat include falling water tables, grazing, recreational use by holiday-makers, sea defence and stabilization works, beach management that interferes with the accretion of wind-blown sand, forestry, atmospheric nitrogen pollution, expansion and development of golf courses, military

Table 2. Legal and near-statutory instruments related to UK sand dunes

Legislation	Provision
European Union (EU) Habitats Directive	Natura 2000 habitats include 'Fixed coastal dunes with herbaceous vegetation', under which 21 sites in the UK have been selected as candidate SACs (Special Area for Conservation) for their sand dune features Support for European protected species of animals listed in Annex IV (a) to the Habitats Directive, whose natural range includes any area in Great Britain (and also listed in Schedule 2 to the UK's Conservation (Natural Habitat &c.) Regulations 1994). These may include support for 'natterjack toad' (*Epidalea calamita*) and also species of 'marine turtle'
EU Birds Directive	The EU Birds Directive (CEC, 1979) requires designation of Special Protection Areas (SPAs) which are then implemented under the SSSI/ASSI system (see below)
EU Water Framework Directive	Protection for Habitats Directive SACs, including 'Fixed coastal dunes with herbaceous vegetation', are also prioritized for protection under the EU WFD
Ramsar Convention	The international Ramsar Convention definition of 'wetlands' covers sand dunes. Some sand dunes in the UK fall within designated Ramsar sites (i.e. within the Severn and Exe estuaries), but controls are managed under the SSSI/ASSI system (discussed below)
UK SSSI/ASSI designations	A range of legislation applicable to the UK makes reference to sand dunes. The UK HAP records that a large proportion of the sand dune resource in the UK is designated as SSSI (Site of Special Scientific Interest), or ASSI (Area of Special Scientific Interest) in Northern Ireland. Of 121 sites in England surveyed between 1987 and 1990, 56 were wholly or almost wholly designated and another 23 were partly designated. In a partial survey of Scottish dunes, 24 of the 34 sites surveyed were designated as SSSI. In Wales, 24 of the 49 sites surveyed were designated as SSSI. In Northern Ireland, 10 of the 26 sites surveyed were designated as ASSI with a further four sites as potential ASSI
UK Government policies	Planning policy in the coastal zone is guided in England and Wales by *Policy Guidelines for the Coast* and *Planning Policy Guidance — Coastal Planning* (PPG 20) (Department of the Environment and Welsh Office, 1992), in Scotland by *Coastal Planning* (NPPG 13) (http://www.scotland.gov.uk/Publications/1997/08/nppg13-coastal), and in Northern Ireland by *Planning Strategy for Rural Northern Ireland* (http://www.planningni.gov.uk/index/policy/policy_publications/rural_strategy.htm) which all have provisions relating to development, access and conservation of the coast The serious summer flooding in the UK in 2007, and the government review which followed (Pitt Review) (Pitt, 2007) shifted public perception and government policy. The Pitt Review recommendation No.27 emphasized '*…greater working with natural processes…*'. This theme is picked up in the UK Department of the Environment -Defra's draft Flood and Water Management Bill (Defra, 2009) which also sets out an aspiration to consider '*…natural processes*' Shoreline Management Plans (http://www.planningni.gov.uk/index/policy/policy_publications/rural_strategy.htm) have been compiled for much of the British coast, and are likely to play an increasingly important role in the future management of soft coasts particular as integrated with flood risk management initiatives
Nature Reserves and National Parks	Designation of Local Nature Reserves (LNRs) and National Nature Reserves (NNRs) may enable the creation of by-laws to assist with management and the regulation of recreational pursuits in coastal areas. The Ainsdale Sand Dunes National Nature Reserve (NNR) on the Sefton Coast of north-west England, for example, includes 508 ha of extensive sand dunes. Equally, some National Parks encompass sand dune systems and may provide opportunities for their protection

use including defensive installations and training, and other human influences including housing and industrial development, waste tips, fly tipping and sand extraction (Doody, 1985; Davidson *et al.*, 1991). Both over-grazing and under-grazing can be problematic for sand dunes, leading, respectively, to erosion or invasion by coarse grasses and scrub. Pressures arising from recreational use by holiday-makers include footfalls, parking for cars and in some cases driving of four-wheel-drive vehicles or motorcycles. Climate change via rising sea levels is thought likely to affect the extent of some systems. In Wales, some sites are predicted to lose up to 100 m of shoreline as a result of increased erosion driven by sea-level rise (Saye and Pye, 2007), although others may gain due to variations in sand supply. As a consequence of both sea-level rise and inland development pressures, sand dunes are likely to suffer a degree of coastal squeeze, similar to that occurring on saltmarshes (Wolters *et al.*, 2005).

The Sand Dune Vegetation Survey of Great Britain (1993–1995) (Joint Nature Conservation Committee, undated) gives the total area of sand dunes in the UK as 11 897 ha in England (Radley, 1994) and 8101 ha in Wales (Dargie, 1995), with a further 50 002 ha of dune and machair in Scotland (Dargie, 2000) of which 31 436 ha are dune (Ritchie and Mather, 1984). Further data published by May and Hansom (2003) records 70 000 ha of dune in Great Britain, 71% (50 000 ha) in Scotland of which 30 000 ha is machair and the remaining 20 000 ha is sand dune. There is generally good agreement between these assessments of the extent of English, Welsh and Scottish sand dunes and machair. In addition, there are approximately 3000 ha of dunes in Northern Ireland. Major dune systems are widely distributed within the UK, being found on all English coasts except the English Channel (other than Sandwich Bay) and the Thames Estuary. They occur on the north and south coasts of Wales and in the northern half of Cardigan Bay. In Scotland, dunes are particularly extensive in the Western Isles and Inner Hebrides where they are associated with machair. Though found on all coasts, they are less frequent on the rocky coasts of north-west Scotland and in Shetland. In Northern Ireland, the largest dune systems are located along the north and south-east coasts.

Notwithstanding their widespread distribution around the British coast, sand dunes are not ubiquitously recognized for their potential coastal defence, nature conservation, amenity and other values, although locally their importance is sometimes acknowledged (http://www.angus.gov.uk/ac/documents/roads/SMP/3-0.pdf; Burke and Totterdell, 2004). In fact, they appear to be largely neglected in national priorities despite the probability of high functional importance. Their protection to date has largely focused on their amenity and biodiversity roles, and to a lesser extent on geomorphological values. Their

potential wider significance to society is largely unnoticed. This neglect may be explained in part by their common occurrence as linear coastal habitats, consideration of the total area of which may mask their importance as ecotones. Furthermore, area-based analysis may under-represent their distribution. Also, in common with other coastal margin habitats such as saltmarsh or sea cliffs, they are neither seen as truly terrestrial nor as fully marine.

This paper therefore makes a rapid assessment of the potential contribution of ecosystem services from sand dunes, informing consideration of whether the societal importance of sand dune systems is currently overlooked. The assessment has a temperate European focus. However, the ecosystem services identified are relevant to temperate dune systems worldwide.

METHODS

Determination of the functional importance and potential public value of coastal sand dune systems entailed an assessment of the likely contribution of sand dunes to the suite of 27 ecosystem services in the Millennium Ecosystem Assessment reclassification (Millennium Ecosystem Assessment, 2005). This was based upon literature where available but also expert judgement, assigning a score for contribution of services based on the importance of sand dunes in providing that service on a per-unit-area basis. Two scoring systems were applied: an 'importance score' at national/international level; and a 'specificity score' reflecting the extent to which a service provided by sand dunes is unique to sand dunes or whether it is better or alternatively provided by other habitats or land-use types. The scoring systems are replicated in the foot of Table 3. The framing question in considering the provision of this service is how much service sand dunes provide relative to their total loss.

RESULTS

The results of this rapid appraisal, with supporting evidence, are provided in Table 3. From the scores in this table, a number of more significant services provided by sand dunes become evident, assuming that this is signified by an 'importance score' as well as a 'specificity score' of 2 or greater (from a range 0–3). From the provisioning, provision of 'drinking water' is the most important current use based on this prioritization system, although 'food' (rabbits, asparagus, meat) and 'timber' production had a high historic importance. Other current priority provisioning services include 'mineral extraction' as well as suitability of 'pipeline landfalls' and 'military use'. Priority regulatory services include 'water regulation' (water storage), 'natural hazard regulation' (storm protection), and 'purification of water'. The priority cultural services revealed by analysis in Table 3 include 'cultural heritage', 'recreation and tourism', 'aesthetic value' as well as 'social relations' for specific interest groups such as bird watchers. Finally, the supporting services that appear most important include 'soil formation', 'nutrient cycling' and 'provision of habitat'.

DISCUSSION

Based on scores recorded in Table 3, the supply of provisioning services from sand dunes is generally of low to medium importance, with the exception of water abstraction, which is of high importance (scoring 3 for 'importance' but 2 for 'specificity') in a number of European countries, and also generally of medium specificity to sand dune habitats. In a capitalist market still largely shaped by the forces of the Industrial Revolution, the value assigned to biodiversity and its services has largely reflected its capacity for rapid commercialization through, for example, fishing, timber production, intensive farming and other forms of commercial exploitation (Everard, 2009a). In an increasingly globalized economy with cheap food accessible through international markets, the historic importance of sand dunes as a local source of both food and timber has declined substantially. Consequently, perception of the value of sand dunes based solely on provisioning services may account for the relatively low priority currently assigned to them.

Turning to the regulatory services, the service 'Water regulation' is assigned high importance, with 'Natural hazard regulation' assigned medium importance on the basis that artificial flood defences can replicate some of this role though at considerable cost and, arguably, lower efficiency with greater maintenance requirements. Although the role of sand dunes is acknowledged in some localities in terms of coastal defence (http://www.allerdale.gov.uk/environment-and-planning/shoreline-management-plan.aspx; http://www.ceredigion.gov.uk/external/shoreline/english/smp/ceredigionsmp.htm; http://www.angus.gov.uk/ac/documents/roads/SMP/3-0.pdf; http://www.severnestuary.net/secg/docs/Issues%20and%20Objectives%20leaflet_Kingston%20Seymour%20and%20Sand%20bay.pdf; http://www.sefton.gov.uk/PDF/TS_cdef_LBSMP_1.pdf), the overall high and medium importance weightings for a range of regulatory services suggests significant societal value. This importance is mirrored in the supply of a range of cultural services weighted as of medium importance but high or medium specificity ('Cultural heritage', 'Recreation and tourism', 'Aesthetic value' and some 'Social relations'). Also, among the supporting services, 'Provision of habitat' is considered of high importance and specificity, while 'Soil formation', 'Nutrient cycling' and 'Water recycling' are considered of medium importance and specificity.

Regulation of water, natural hazard and erosion are recognized in various UK Shoreline Management Plans (Liverpool Bay Coastal Group, 1999), with their contribution to landscapes and tourism potential reflected in regional and local development strategies (Department of the Environment and Welsh Office, 1992; http://www.scotland.gov.uk/Publications/1997/08/nppg13-coastal; http://www.planningni.gov.uk/index/policy/policy_publications/rural_strategy.htm). These are likely to form a major contribution to society. However, monetarization of this societal value has not yet been attempted, although valuations have been conducted for other coastal systems such as saltmarsh (Everard, 2009b).

Some early work suggests that these regulatory benefits can be substantial, dependent on the location of habitat in relation to where the advantages of an ecosystem service is delivered. For example, a study of options to address flooding in the Lower Derwent (Defra, unpublished) valley in the East Midlands of the UK, drawing on the benefits transfer approach (Brander *et al.*, 2006), suggests that the 'environmental benefits' (mainly an expression of cultural services but which explicitly omit regulatory services) from the creation of wetland habitat upstream of the city of Derby were

Table 3. Importance and specificity scores applied to MA ecosystem service types on coastal sand dunes

MA ecosystem services	Importance score (0–3)	Importance notes	Specificity score (0–3)	Specificity Notes
Provisioning Services				
Fresh water				
• Drinking water	3	Drinking water abstraction is important in the Netherlands, Germany and Denmark (e.g. van Dijk, 1989)	2	A large dune aquifer exists along the North Sea coast
• Irrigation	1	There is some small abstraction for golf course watering in the UK (Birchall and Elliott, 2001)	$1\sharp^{L}$	Localized extraction only, dune aquifers are not the only water source
Food (e.g. crops, fruit, fish)				
• (Rabbits)	(3)	Historically very important (Ranwell, 1960; Baeyens and Martinez, 2004)	(3)	Dunes provided ideal conditions for warrens, but warrens also in other land use types
• (Asparagus)	(2)	Extensive asparagus cultivation in some areas (Jones *et al*., 1993)	(2)	Also provided by other agricultural land
• Wild food	1	Some wild food harvesting (mushrooms, berries, etc.)	2	Also provided by other habitats
• Rare breed cattle	1	Market in rare breed cattle is a potential growth area	1	Better provision from production agriculture
• Meat	(2) 1	Historically important in north-west Europe (van der Maarel *et al*., 1985). Subsistence stock rearing on machair	$1\sharp^{L}$	Commercial grazing persists in parts of north-west UK, but is provided better by other agricultural land. Subsistence stock-rearing is specific to machair landscape
• Miscellaneous crops	(2) 1	Historically important in north-west Europe. Subsistence crops on machair (Angus, 2001a), and small plots/gardens in Netherlands	$3\sharp^{L}$	Specific to machair landscape, and to Dutch cultural situation
Fibre and fuel (e.g. timber, wool, etc.)				
• Grass/reeds	(2)	Marram grass (and possibly *Phragmites*) was historically important for mats, basket-weaving and thatching (Carter, 1985; Christensen and Johnsen, 2001)	$(2\sharp^{L})$	Locally often the only source of material for thatching etc.
• Wool	1	Agricultural sheep grazing on some sites, but stock are also used for conservation grazing	1	Better provision from other agricultural land
• Timber	2	Commercial plantation forestry common on dunes across Europe (at present largely uneconomic), but forestry has formerly been used to stabilize dune systems across the world including for example in Scotland (Gauld, 1981; Comber *et al*., 1994) and New Zealand (Gadgil and Ede, 1999)	$1\sharp^{L}$	Locally very important, e.g. Les Landes, France, but generally low productivity and currently uneconomic. Better provision from other soil types
Genetic resources				
• Breeding stock	1	Potentially high due to characteristic biodiversity, though there is currently no direct exploitation of this. However, there is limited trade of brood stock of rare stock breeds. Wild populations of endangered species (e.g. sand lizard (Atkinson *et al*., 1993)) have been used for re-introductions to other sites	$2\sharp^{L}$	Endangered obligate sand dune species are by definition rare and therefore only of local occurrence
• Biochemicals, natural medicines, pharmaceuticals	1	Potentially high due to characteristic biodiversity. Some species are under research for biochemical/ pharmaceutical uses e.g. sea holly (*Eryngium maritimum*) (Küpeli *et al*., 2006; Meot-Duros *et al*., 2008). Historical use of medicinal leeches at some sites (http://www.ukbap.org.uk/ UKPlans.aspx?ID = 365)	2	Potentially a medium specificity score, due to specific biochemical properties of coastal plants
• Ornamental resources (e.g. shells, flowers, etc.)	0	Not thought significant in a European context	1	Potentially a low specificity score, depending on resources used which may be specific to dunes
Mineral extraction (*context-specific addition to MA set*)				
• Sand extraction	1 (2)	Sand extraction has been historically important at some sites for use in construction and industry (Jones *et al*., 1993), though it is arguably unsustainable if not balanced with sand input to the system. Now largely stopped on protected sites, but still continued elsewhere	$1\ (2\sharp^{L})$	Sand extraction generally replaced by off-shore sources

Table 3. *Continued*

MA ecosystem services	Importance score (0–3)	Importance notes	Specificity score (0–3)	Specificity Notes
• Mineral extraction	2♯^{L}	Mining for minerals is important in some countries, e.g. for heavy metals in South Africa (Van Aarde *et al*., 2004)	3♯^{L}	Locally important sources suitable for large-scale exploitation
Landscape suitable for industrial use (*context-specific addition to MA set*)				
• Pipeline landfalls	2	Several sites used as landfall for gas/oil pipelines (Ritchie and Gimingham, 1989), or transatlantic cables. These activities are themselves pressures on ecosystems, but the suitability of the landscape units for this purpose may also be considered a service	2	Also provided by other soft-coasts such as saltmarshes
• Military use	2♯^{L}	Locally important resource for firing ranges, vehicle manoeuvres, etc. Many dunes used for military training in WW2 such as Braunton Burrows (Devon, UK). Several UK sites are still under Ministry of Defence ownership and management (Baker, 2001)	2	Also provided by other habitats
Regulating Services				
Air quality regulation	1	Dune slacks are a seasonal wetland so the net nitrogen fluxes are uncertain; canopy roughness of low-level grassland and scrub may be significant in particulate fallout and dry gaseous pollutant deposition (Sutton *et al*., 1993)	1	As with most other semi-natural habitats, dunes are a net sink for gaseous nitrogen and particulates
Climate regulation (local temperature/ precipitation, GHG sequestration, etc)	2	Carbon accumulation rate is high as this is an early successional habitat (Jones *et al*., 2008) although overall dune areas are low; carbon sequestration is greater in the dune slacks, however, these may also be a source of GHGs such as methane and nitrous oxide. There are also questions about the permanence of sequestration due to natural dynamics. (GHG emission from dune slacks is a major research gap)	2	Relatively few habitats with such high sequestration rates for soil carbon over decadal timescales
Water regulation (water storage)	3	Sand dunes form a shallow aquifer, useful for water storage under large dune systems (Heslenfeld *et al*., 2004)	3	Few other habitats provide such rapid recharge groundwater
Natural hazard regulation (i.e. storm protection)	3	Dunes have a significant role in buffering storms and other extreme natural events, providing a major coastal defence (McHarg, 1969; French, 2001), e.g. the Sefton coast which is the largest area of dunes protecting an urban area in the UK	3	Can be replaced by artificial structures, but at significant cost
Pest regulation	1	Dunes are likely to harbour natural predators of crop and stock pests, though this is not well studied. Importance depends on patterns of coastal land use. (Research gap)	1	Provided better by other habitats
Disease regulation	1	Dune slacks typically flood in winter, so are out of synchrony with the life cycles of most disease vectors. i.e. Provides wetland diversity but without promoting disease vectors	1	Also provided by other winter-flooded habitats
Erosion regulation	0	Not important in the context of soil erosion on slopes		
Water purification and waste treatment				
• For drinking water	2♯^{L}	In the Netherlands, water from the River Meuse is infiltrated into dune systems for purification	3♯^{L}	Unique to sand dunes, but only local examples
• Purification of groundwater	2	Dunes are highly likely to purify groundwater and run-off, protecting the marine environment, but this is not studied. (This is a major research gap)	3	Few other coast types purify groundwater, most land-use types are a nutrient source to the marine environment, or act as neutral conduit
Pollination	1	Dunes harbour natural pollinators, including many hymenopterans (Howe *et al*., in press); their specificity for crop pollination has not been studied, but coastal arable fields often border dunes. Importance depends on patterns of coastal land use. (Research gap)	1	Provided by other semi-natural habitats

Table 3. *Continued*

MA ecosystem services	Importance score (0–3)	Importance notes	Specificity score (0–3)	Specificity Notes
Cultural Services				
Cultural heritage	2♯[L]	Sand dunes provide characteristic 'wild' landscapes but also generate local complaints about sand blow, with historical fears about sand inundating fields and villages (Steers, 1937); Long history of human occupation, going back to Mesolithic (Provoost *et al.*, in press). Blown sand can preserve archaeological remains e.g. Skara Brae in the Orkney Islands, UK (Hansom, 2001), but mobility can also destroy archaeological context. (Research gap, particularly for modern cultural role.)	2	As with most habitats, dunes provide a very distinctive unique cultural memory. Machair is a cultural landscape
Recreation and tourism	2	Sand dunes are a major tourist attraction. The Sefton coast receives 4.6 million visits, providing £62.7m revenue, with 26% of visitors specifically visiting the beach (Stewerd, 2001).In the Netherlands, roughly 1 million people per year visit the Meijendel Dunes (Van der Meulen *et al.*, 2004). Amenity uses include walking, cycling, horse riding. Golf courses comprise a major recreational use of (heavily modified) dune habitat in the UK, being both a significant pressure on the dune resource, but also providing some conservation of later successional habitats, if carefully managed (Simpson *et al.*, 2001)	3♯[L]	Much of the appeal is due to the unique character of sand dunes
Aesthetic value	2	Evidence of the popularity of sand dunes in photographs/adverts shows how popular sand dunes are with the public	3♯[L]	Much of the appeal is due to the unique character of sand dunes
Spiritual and religious value	?	Unknown. (Research gap, particularly for modern use)	?	
Inspiration of art, folklore, architecture, etc.	1	Poems inspired by dunes include works by Robert Frost (1874–1963), Carl Sandburg (1878–1967). Paintings by many Dutch artists feature dune landscapes	3	Much of the appeal is due to the unique character of sand dunes
Social relations (e.g. fishing, grazing or cropping communities)				
• Machair	1	Machair landscape maintained by community-level low-intensity traditional management (Angus, 2001b; Owen *et al.*, 2000)	3♯[L]	Highly specific to machair cultural situation
• General other	2	A focus for local nature groups, photographers, bird watchers, etc.	2	Attractions are frequently habitat specific, although other habitats provide different interest
Educational resource (context-specific addition to MA set)	1	Coastal sand dunes can represent an important educational resource (Huddart, 1993)	3	Provides unique examples for teaching concepts such as 'succession theory' (Clements, 1916; Connell and Slatyer, 1977; Cowles, 1899), soil processes etc.
Supporting Services				
Soil formation	2	Sand dunes are successional habitats, accreting soil in both dry and wet habitats (Jones *et al.*, 2008; Sevink, 1991)	2	Common to most habitats
Primary production	1	Generally low-productivity systems, despite a high standing crop (Willis and Yemm, 1961)	1	Common to most habitats
Nutrient cycling	2	Most nitrogen and phosphorus is retained in the system. There are high rates of biological nitrogen fixation	2	Common to most habitats
Water recycling	1	Slacks and taller marram and scrub/reed vegetation are active in recycling water	2	Common to most habitats
Photosynthesis (production of atmospheric oxygen)	1	Generally low-productivity systems	1	Common to most habitats

Table 3. *Continued*

MA ecosystem services	Importance score (0–3)	Importance notes	Specificity score (0–3)	Specificity Notes
Provision of habitat	3	Sand dune systems support a disproportionately large compliment of endangered species, as well as a high diversity of species in part due to the variety of early/late successional, wet/dry, acid/calcareous niches (Atkinson *et al*., 1993; Grootjans *et al*., 2004)	$3\sharp^{L}$	Highly specific for obligate sand dune species and 'refugee' species

Importance score at national/international level, on a per-unit area basis (0–3): 0-Not important, 1-Low importance, 2-Medium importance, 3-High importance. Specificity score, the extent to which a service provided by sand dunes is unique to sand dunes, or whether it is better provided by other habitats or land-use types: (0–3): 0-Sand dunes do not provide this service, 1-Sand dunes can provide it but other habitats provide it better, 2-Service provision by sand dunes is of equal quality to other habitats, 3-Only sand dunes can provide this service, or they are among the best providers of this service. $\sharp^{L}$ In addition, each score can be qualified denoting high importance locally, or that sand dunes uniquely provide that service locally for cultural/historical reasons, but that may not apply to other areas. Significant historical uses given in parentheses.

assessed at a present value of £374 000, yet were only a small proportion of the damage avoided from downstream flooding (assigned a present value of £265 million). Therefore, wetland creation in the upper Derwent, largely restoring lost habitat and its associated ecosystem services, efficiently offsets property damage currently resulting from flooding, with additional 'environmental benefits'. The analysis further excludes valuation of water quality and carbon oxidization benefits so, for various other reasons, can be treated as a substantial underestimate of the true benefits of the wetland re-creation initiative. However, the study does endorse the principle of context dependence, as dependent upon location, flood risk management benefits can be dominant or, alternatively, inconsequential.

From a systemic perspective, the perceived value of ecosystem-derived benefits accruing in the fields of flood risk management (Everard *et al*., 2009), freshwater fisheries (Cowx and Gerdeaux, 2004) and nature conservation has resulted in substantial changes in management policies compared with those implemented under former reductive and generally exploitative paradigms. This is observed for sand dunes in the form of growing recognition of their role in regulation of tidal, wind and wave energy. The same shift from narrow to increasingly systemic (including ecosystem services) perspectives reveals that the societal values derived from sand dunes are substantial compared with those reflected from a narrower emphasis of provisioning services, or recognition of elements of biodiversity alone, notwithstanding a longer-term recognition of the importance of some sand dune services including coastal defence and tourism.

Threats to the biodiversity and geomorphological values of sand dunes discussed earlier are generally well understood. However, since the wider significance of dune systems is only beginning to be appreciated, the potential impact of these drivers on the provision of ecosystem services from dunes, and on the interactions between them, is far from clear. This paper outlines the main societal benefits of sand dunes, but it is also worth mentioning briefly some threats to the provision of those ecosystem services. Generally, any factor which diminishes the remaining area of dunes will most probably have a negative effect on the services they provide, and such loss should be avoided. One example is sea-level rise which, unless society is willing to consider roll-back options where dune systems are allowed to migrate inland in a manner analogous to managed realignment schemes operating for saltmarsh, is likely to result in the erosion of the frontal edge and coastal squeeze and a diminution of their sea defence role and other ecosystem services. In the case of saltmarshes, and it is assumed also for sand dunes where the same principles apply, this will result in degradation of the wide range of ecosystem services that they provide and which are of considerable cumulative value to society (Everard, 2009b).

More complex are factors that diminish the quality of dunes as a resource, where the implications for provision of some of these ecosystem services are not yet evaluated. For example, atmospheric nitrogen deposition is widely regarded as a threat to dune biodiversity (Kooijman *et al*., 1998; Jones *et al*., 2004; van den Berg *et al*., 2005), but the resulting increased stability of dune systems may actually benefit regulatory services such as climate control through greater carbon accumulation as vegetative successions occur building up the sequestered carbon content of the dune system. Its effects on cultural services may be mixed, with some positive impacts by reducing the perceived hazard of blowing sand, but with negative impacts on the character of the traditional dune landscapes which provide aesthetic and cultural significance to society. The way dune systems are managed may also have an impact on the provision of ecosystem services and the relative balance between them. Management techniques are usually developed in order to counteract specific threats to biodiversity, generally with little or no consideration of related ecosystem services nor of the wider biodiversity consequences of maintaining sand dunes in particular successional states. Destabilization is increasingly recommended as a technique to re-create an element of mobility on dune systems regarded as over-stable (Arens and Geelen, 2006; Jones *et al*., in press a). However, it is perceived by some, rightly or wrongly, as reducing the ability of sand dunes to provide a coastal defence role (Sefton Coast Partnership, 1999). Thus, trade-offs between the level of provision of different ecosystem services may be a necessary consideration when discussing management options at a site.

There do not always have to be trade-offs, and some situations may boost the provision of all major services. The larger the site, generally, the greater the variety of biodiversity and geomorphological features it supports, but it will also have a greater flood defence role by reducing exposure of the hinterlands to natural hazards, and is more likely to support other ecosystem services owing to its greater visibility to society and potential for greater internal heterogeneity. Larger sites therefore have a greater resilience both in terms of biological adaptation and in the human benefits they provide.

There is clearly work to be done examining the competing or conflicting requirements of ecosystem services within a site, and how different management options might increase or decrease the wider societal benefits provided by sand dunes. A societal dialogue is required to address the balance of advantages and costs of different management options across stakeholder groups using different services provided by dune systems.

A substantial proportion of the UK coast is in the ownership of Government Departments/Agencies or voluntary conservation bodies, though the degree of influence over management is variable because of legal complexities. Statutory instruments may therefore serve to institute some protection through compulsions and duties to consider the functional role of sand dunes, but economic measures that better reflect the value to society of the services that they support may provide further stimuli for their protection.

Many ecosystem services provided by sand dunes are not subject to trade in a market, nevertheless they provide benefits to a wide range of stakeholders. Often, the services are public or club goods and, frequently, beneficiaries may not even be aware of their gain from the existence of the service. This means that the community as a whole have no way of appreciating the loss when the habitat is under threat from coastal squeeze, development encroachment or other pressures. Thus, the absence of markets for these services means that the owners and people who exercise control of these habitats, comprising 'service providers' whether recognized as such or not, lack an incentive to either safeguard or increase the habitat and the associated services that it provides. Development of regulations and subsidies across the UK and Europe throughout the 20th century to institute development planning controls, nature conservation, water resource management and land uses that are favourable to societal wellbeing, often constraining the freedoms of private land-owners formerly permitted to act solely in self-interest, can be seen as a progressive recognition and safeguarding of these beneficial ecosystem services from habitats and landscapes regardless of land patterns (Everard and Appleby, 2009). As we have seen with the rapid evolution of carbon markets in the past decade, not to mention evolution of 'paying for ecosystem services' schemes across the world often related to catchment management to yield fresh water of benefit to sometimes remote downstream communities (Everard, 2009a), markets can rapidly be created when the societal importance of ecosystem services becomes recognized and, eventually, established in policy priorities. This progressive trend towards recognition of, and reward for, beneficial ecosystem services suggests that the many services provided by coastal sand dune systems may, or at least should, become better internalized in markets and public priorities.

This discussion and the supporting evidence suggest that recognition of the societal value of sand dunes and associated protective measures are not proportionate to the range of benefits that they confer upon society. National protection is almost solely founded on biodiversity considerations, backed up by some recognition of local functional importance such as on the Sefton coast (Simpson *et al.*, 2001). In particular, the crucial role that coastal sand dunes may play in coastal flood and storm protection indicates that far greater recognition is due to safeguard these valued coastal defence services. Hence, for inherent reasons as well as in consideration of the multiple beneficial services that they provide to society, sand dunes are due greater recognition and protection than they currently enjoy. This study has also highlighted some important research gaps in the benefits sand dunes provide to society. These include the net balance of greenhouse gas emissions from dune slacks, whether invertebrate predators control pests in nearby agricultural fields, water purification of groundwater entering the marine environment, and the cultural values assigned to sand dunes by modern day society, compared with their historical benefits or heritage value.

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