Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design

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Abstract

Coastal defence structures to protect sedimentary coastlines from erosion and flooding are increasingly common throughout Europe. They will become more widespread over the next 10–30 years in response to rising and stormier seas and accelerating economic development of the coastal zone. Building coastal defences results in the loss and fragmentation of sedimentary habitats and their replacement by artificial rocky habitats that become colonised by algae and marine animals. The engineering design and construction of these structures have received considerable attention. However, the ecological consequences of coastal defences have been less extensively investigated. Furthermore, due to their rapid proliferation, there is a growing need to understand the role of these man-made habitats in the coastal ecosystems in order to implement impact minimisation and/or mitigation measures.

As part of the DELOS project, targeted studies were carried out throughout Europe to assess the ecological similarity of low-crested coastal defence structures (LCS) to natural rocky shores and to investigate the influence of LCS design features on the colonising marine epibiota. LCSs can be considered as a relatively poor surrogate of natural rocky shores. Epibiotic communities were qualitatively similar to those on natural rocky shores as both habitats are regulated by the same physical and biological factors. However, there were quantitative differences in the diversity and abundance of epibiota on artificial structures. Typically, epibiotic assemblages were less diverse than rocky shore communities. Also, LCSs offered less

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structurally complex habitats for colonisation and in some locations experienced higher disturbance than natural shores. We propose several criteria that can be integrated into the design and construction of LCSs to minimise ecological impacts and allow targeted management of diversity and natural living resources.

1. Introduction

The coasts of Europe and many other parts in the world are increasingly threatened by erosion and flooding, mainly due to sea level rise and greater storminess associated with climate change (IPCC, 2001a,b; Holman et al., 2002; Hulme et al., 2002). The need for coastal protection has therefore increased, particularly in developed areas. In the south of Europe tourism and other coastal recreational activities are often an additional driver for building coastal defence structures (e.g. to enhance sandy beaches or protect marinas). As a result, an increasing number of hard defence structures have been and are being built, as a rapid and cost-effective means of coastal protection. These consist of seawalls, jetties, offshore breakwaters and rock groynes. For example, in England 23% of eroding coastlines are already modified by man-made structures (MAFF, 1994) and this proportion is certain to increase in the near future, especially on the southern and eastern coasts which are most susceptible to sea level rise.

The proliferation of coastal defences has transformed sections of naturally dynamic, erosive and depositional soft-shores coastlines into artificially static, hard-substrates. These are colonised by epibiotic organisms such as algae and sessile marine invertebrates that are commonly found on natural rocky habitats as well as providing refuges and nursery grounds for fish and crustaceans (Duffy-Anderson et al., 2003). The epibiota of man-made coastal defence structures, has received little attention (but see Moore, 1939; Southward and Orton, 1954; Hawkins et al., 1983) until the last decade or so (Johannesson and Warmoes, 1990; Hawkins and Cashmore, 1993; Connell and Glasby, 1999; Bulleri et al., 2000; Connell, 2000; Russell, 2000; Chapman, 2003), including studies of shore parallel, low crested structures (e.g. Davis et al., 2002; Bacchiocchi and Airoldi, 2003).

The overall aim of this paper is to assess the extent to which the design of shore-parallel, low crested coastal defence structures (LCS) influences the abundance and composition of colonising epibiota. Studies were made on several shore-parallel LCSs located in Spain, Italy, Denmark and UK. Our specific objectives were: 1) to compare the abundance and composition of epibiotic assemblages with natural rocky shore communities; 2) to examine at a local scale the effect of selected LCS design features such as orientation, tidal elevation, surface and habitat complexity; 3) to synthesise results from DELOS with existing knowledge on rocky shores to identify the major natural processes determining distribution, abundance and diversity of epibiota; 4) to suggest simple qualitative design rules that minimise and mitigate the ecological impacts of LCS. Thus our paper seeks to inform engineers, coastal planners and other stakeholders to enable management of diversity and natural resources and sustainable development of coasts.

This overview paper is intended to inform a non-ecological target audience and summarises a diverse array of work which is being reported in more detail elsewhere (see www.delos.unibo.it). Subsets of data have been used to illustrate specific points of interest to the general reader. Extensive referencing has been used throughout, to provide access to key literature on this complex multidisciplinary topic.

2. Material and methods

2.1. Study sites and general methodological approach

Several coastal defence schemes were investigated in Italy, Spain, UK and Denmark. In this paper we show results from studies carried out on selected sites (summarised in Table 1). Unless otherwise stated, the coastal defence schemes considered consisted of shore-parallel, low-crested structures (LCS). Epibiotic

Table 1
Main features of coastal defence schemes investigated during the DELOS project and considered in these paper

Country	Location	Position on the coast	Tidal range	N of LCS
UK	Elmer (West Sussex)[1]	50°47′ N 0°35′ W	Macrotidal (6.3 m)	8
	Lyme Regis (Dorset)	50°43′ N 02°56′ W	Macrotidal (4 m)	
	Sea Palling (Norfolk coast)[2]	52°42′ N 01°41′ E	Mesotidal (2 m)	9
	Leasowe Bay (Wirral)[3]	53°26′ N 03°06′ W	Macrotidal (10 m)	2
	King's Parade (Wirral)[3]	53°26′ N 03°06′ W	Macrotidal (10 m)	1
	Rhos-on Sea (Welsh coast)	53°19′ N 03°42′ W	Macrotidal (8.4 m)	1
	Sidmouth (South Devon coast)	50°40′ N 03°14′ W	Macrotidal (4.2 m)	2
	Isle of Wight	50°36′ N 01°11′ W	Macrotidal (3.6 m)	1
	Milford-on-Sea	50°43′ N 01°35′ W	Mesotidal (2 m)	1
Denmark	Hirtshals	57°35′ N 09°56′ E	Mesotidal (1 m)	1
	Skagen	57°46′ N 10°39′ E	Microtidal (<0.5 m)	24
Italy	Lido di Savio	44°18′ N 12°20′ E	Microtidal (<0.5 m)	>10
	Cesenatico[4]	44°12′ N 12°24′ E	Microtidal (<0.5 m)	>10
	Gabicce	43°58′ N 12°45′ E	Microtidal (<0.5 m)	1
Spain	Cubelles	41°11′ N 01°38′ E	Microtidal (<0.5 m)	5
	Calonge	41°50 N 03°06′ E	Microtidal (<0.5 m)	3

Selected references: [1] King et al., 2000. [2] Thomalla and Vincent, 2003. [3] Davies, 1989. [4] Bacchiocchi and Airoldi, 2003.

communities were sampled using standard, non-destructive (where possible) methods for sampling rocky shore benthos (see Hawkins and Jones, 1992; Benedetti-Cecchi et al., 1996; Bianchi et al., 2004). Similar sampling design, wherever possible, were used across countries, with some tailoring to local conditions.

The abundance of epibiota was visually estimated as percentage cover of macroalgae and sessile fauna and the number of mobile species in quadrats (20×20 or 25×25 cm). Destructive samples and photographs were taken where visual sampling was technically difficult, for example subtidally. Details of specific methods are given in each section.

2.2. Comparison of diversity between low crested structures and natural rocky shores

The epibiota on coastal defence structures was compared with natural rocky shore communities in four locations: Lyme Regis (UK), Gabicce (Italy), Calonge and Cubelles (Spain). The LCSs in these sites were adjacent to a natural rocky habitat and made of similar rock type. Only the seaward side of the structures was sampled to standardise exposure to wave action between natural and artificial rocky habitats. Both abundance and number of species was recorded. The sampling design varied between countries according to the type of defence scheme and

environmental conditions. In the UK, 15 replicate quadrats (25×25 cm) were randomly sampled on a shore-parallel groyne and on the nearby rocky shore. In Italy, four random areas were randomly selected on LCSs and the adjacent natural rocky habitat; within each area, 10 replicate quadrats (20×20 cm) were sampled. At both sites in Spain, three replicate quadrats (20×20 cm) were sampled in each of 4 random areas located on LCSs and on the nearby rocky shore. Multivariate analysis (MDS, ANOSIM) was performed to test for differences between communities on natural shores and those on man-made structures.

2.3. Effects of LCS design features on epibiotic assemblages

2.3.1. Orientation

The effect of orientation of LCSs on the abundance and diversity of epibiota was investigated on two defence schemes in the UK (Elmer, Sea Palling), one in Italy (Lido di Savio) and one in Spain (Calonge). A common nested sampling design was adopted: orientation was the fixed factor with 2 levels (landward, seaward) while structure was a random factor with 3 levels nested within orientation. For the Spanish site, structure was substituted by area (4 levels), randomly selected along 4 structures. The sample size (UK: $n = 15$; Italy: $n = 10$; Spain: $n = 3$) was determined on the basis of pilot studies carried

out on each defence scheme. For the purpose of this paper, data collected for each taxa were aggregated under three broad groups: macroalgae (fucoids, turfs and ephemerals), filter feeders (mussels, oysters, barnacles) and grazers (limpets and littorinids) to standardise comparisons between countries as the number and identity of species vary considerably geographically. Data were analysed using two-way ANOVA.

Two separate experiments tested the relative importance of wave action and limpet grazing in limiting the distribution of fucoid algae on the seaward side of LCSs at Elmer. Here we report only a brief description, as more details on methods and statistics can be found in Jonsson et al. (submitted for publication). In the first experiment, a predictive model of maximum wave-induced forces was formulated based on wave theory and available time-series data on wave climate. The model was then validated against empirical measurements of relevant maximum wave forces on the LCSs. Additional field measurements determined the dislodgement (critical breaking stress) for periwinkles (*Littorina littorea*) and the brown alga *Fucus spiralis*. By combining modelled maximum wave forces with data on critical breaking stress it was possible to predict the expected distribution of the species on LCSs assuming wave forces to be the dominant controlling factor.

In the second experiment, the effect of grazing on establishment of macroalgae was investigated. Abundance of macroalgae was recorded bimonthly for over 1 year on stone blocks of the LCS (size approximately 1 m^3) from which limpets were either reduced in numbers or completely removed and on control blocks where limpets were left undisturbed. For each treatment three stone blocks were randomly chosen along two LCSs.

2.3.2. Location on the shore

The influence of tidal elevation on intertidal epibiotic assemblages was assessed on macrotidal shores in the UK by relating the total number of species on LCSs to the amount of structure that extended below mid tidal level (MTL). A total of 20 LCSs in six locations were investigated (The Wirral, Merseyside; Rhos-on-Sea, North Wales; Sidmouth, Devon; Isle of Wight and Milford-on-Sea, Hampshire; Elmer, West Sussex; Sea Palling, East Anglia). On each structure all epibiotic species were recorded. The height

between the sediment level surrounding the base of the structure and mid-tide level (MTL) was recorded at 4–6 different points located on the seaward and landward sides and roundheads of each structure and the values were then averaged.

On microtidal shores in Denmark the influence of water depth on the composition of subtidal epibiotic assemblages was investigated, by recording the total number of species at half meter depth intervals from the water surface to a depth of 2 m on 5 replicate vertical transects on LCSs in Skagen and Hirthshals.

2.3.3. Habitat complexity

The importance of habitat complexity in determining the abundance and diversity of epibiota was assessed at different spatial scales in three separate studies carried out at Elmer defence scheme in the UK. The effect of micro-crevices and fractures of the rock surface (less than a centimeter wide) on the epibiotic species was investigated by comparing the density of barnacles on areas of differing roughness. Barnacles were counted using 4 × 4 cm quadrats placed on five smooth and five fractured areas randomly chosen on the LCS blocks. In each area, surface roughness was measured using plasticine imprints of the rock surface. These were cut into 1 mm thick sections and the resulting topographic profile was photographed with a digital camera, and analysed with a computer routine (written in Matlab, Mathworks). First the roughness profile was run through a low-frequency filter, and then roughness height was calculated as the maximum height difference of the profile.

The extent to which artificially enhanced complexity at a scale of <10 cm could be used to enhance biodiversity of LCS was examined using 30 × 30 cm experimental concrete panels of differing complexity. These panels were used to assess the feasibility of casting complex features into the surface of concrete blocks that could be integrated in to LCSs. Four levels of complexity were chosen: smooth panels, which mimicked the surface of concrete LCS blocks (e.g. tetrapods); panels with 6 large pits (30 mm dia., 20 mm depth); panels with 13 small pits (15 mm dia., 20 mm depth) and panels with 4 large and 4 small pits. The number of pits was determined to standardise the total surface area available for settlement of species between panels of different complexity. Panels were

fixed at MTL to the horizontal and vertical surfaces of blocks on the seaward side of two structures. At each structure, four replicate panels were used for each treatment and for each orientation (vertical, horizontal). The diversity and abundance of species present on these panels were recorded at regular 2–3 monthly intervals. Here we show results for horizontal panels after 1 year of exposure to sea.

The influence of complexity on epibiota was further investigated at the scale of 10 to 100 cm by assessing the effect of rock pools on species diversity on LCSs. The number of species colonising pools that naturally formed at the base of the LCSs and on the adjacent blocks was compared. All pools on the seaward side of 8 LCSs were sampled and their dimensions (width, length and depth) measured. Pearson's correlation index was used to assess the effect of dimensions of pools on diversity.

2.3.4. Disturbance: structural stability and scouring of LCS

The effect of maintenance of LCSs on epibiotic assemblages was examined on the Cesenatico defence scheme in Italy. The epibiota was compared between two LCSs that had been just repaired and other two LCSs that had not been maintained for at least three

years. The abundance of epibiotic species were recorded in eight replicate quadrats (20×20 cm) randomly placed on the landward side of each structure. Data were analysed using ANOVA.

Qualitative observations were also made on various LCSs in the UK, Italy and Spain to assess the effect of scouring by sediment, variation in the sediment level and siltation on the epibiotic assemblages. Disturbance by sand scouring was preliminarily investigated at Elmer by recording the abundance of organisms on the surface of LCS blocks at increasing heights from the sediment level.

3. Results

3.1. Epibiota of LCSs versus rocky shore communities

In each region epibiotic assemblages on LCSs included the species that were most commonly found on natural rocky shores nearby. This was observed throughout the DELOS project in addition to sites reported here. In the UK, mid-shore species such as barnacles (mainly *Elminius modestus* and *Semibalanus balanoides* and some *Chthamalus* spp. on the south and west coasts), limpets (mainly *Patella*
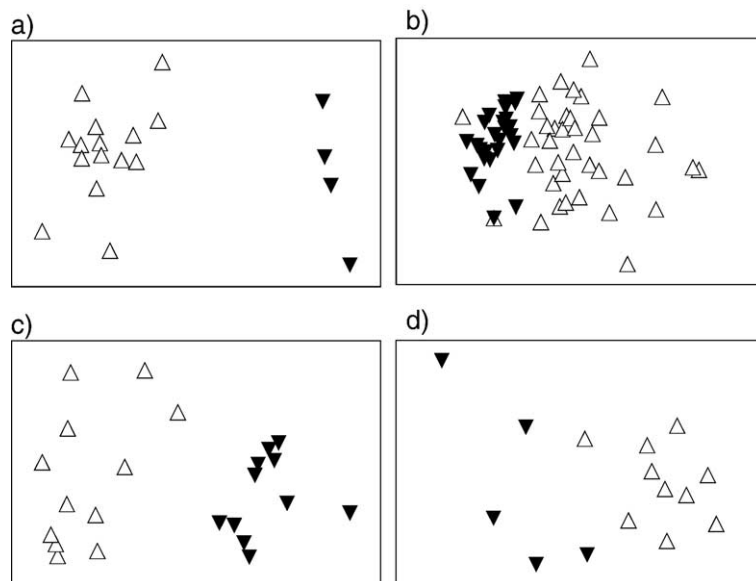

Fig. 1. Non metric MDS based on presence/absence of epibiotic species showing differences between artificial (black triangles) and natural (white triangles) habitats in four locations: (a) Lyme Regis; UK; (b) Gabicce, Italy; (c) Calonge, Spain; (d) Cubelles, Spain.

vulgata) and fucoid algae (mainly *F. spiralis* and *F. vesiculosus*) were recorded on virtually all the LCSs.

Similar patterns were observed in the Mediterranean Sea. In Italy, the dominant species on LCSs were the ephemeral green algae (*Ulva* spp.), mussels (mainly *Mytilus* spp.), oysters (*Ostrea edulis* and *Crassotrea gigas*), barnacles (*Chthamalus* spp., *Balanus perforatus*) and limpets (*Patella caerulea*)—all of which are common on the Italian rocky shores. In Spain, assemblages on structures were dominated by the algae *Corallina elongata* and *Lithophyllum incrustans* and the mussel *Mytilus* sp.

Despite similarities in the presence of these common species, the composition of epibiotic assemblages differed significantly from rocky shore communities in the UK (ANOSIM, $R = 0.987$, $p = 0.001$, Fig. 1a), Italy (ANOSIM $R = 0.719$, $p = 0.03$, Fig. 1b) and Spain (ANOSIM: Calonge, $R = 1$, $p = 0.03$; Cubelles, $R = 1$, $p = 0.03$, Fig. 1c, d). Also, within each region, areas in each habitat had very low dissimilarity (Italy, $R = 0.13$; Calonge, $R = 0.164$; Cubelles, $R = 0.164$). The total number of species recorded on the structures was generally lower than on the adjacent rocky shores (Fig. 2). The number of shared species was also low, regardless of differences in total species richness.

In the UK, species that are frequently found in rock pools and crevices or lower on the shore such as kelps (*Laminaria digitata*, *L. saccharina*) and other large seaweeds (*F. serratus*, *Himanthalia elongata*), algal turfs (*Corallina officinalis*, *Chondrus crispus*, *Mastocarpus stellatus*), algal crusts (*Lithothamnia*, *Verrucaria* spp.), sponges (*Halichondria panicea*), sea anemones (*Actinia equina*) and bryozoans (*Membra-*

nipora membranacea, *Electra pilosa*) were only occasionally recorded on LCSs. The lower diversity of epibiota on the Spanish LCSs was mainly due to the absence of the brown canopy forming algae *Cystoseira* spp. and to the scarcity of other algae, including *Ulva* spp., *Hypnea* sp. and *Ceramium* sp. On the Adriatic coast of Italy artificial and natural assemblages differed in the abundance of certain taxa. For example, encrusting algae were more abundant on natural than artificial habitats, while the opposite pattern was observed for oysters, mussels and limpets. Similarly, a greater abundance of limpets on artificial structures was observed on LCSs in the UK.

Although no formal comparison was possible due to the lack of nearby natural rocky shores, epibiotic communities on LCSs in Denmark also appeared to have low diversity.

3.2. Effects of LCS design features on epibiota

3.2.1. Orientation

There were clear differences in the abundance and composition of epibiota between the landward and the seaward sides of the structures at all locations on the Atlantic and Mediterranean coasts. These differences, however, were not consistent between geographical locations (Fig. 3). In the UK (Fig. 3a,b), the abundance of algae (fucoids) was significantly higher on the landward side of structures at both Elmer (Landward $F_{1,84} = 1025.1$, $p < 0.0001$) and Sea Palling ($F_{1,84} = 72.39$, $p < 0.005$). Abundance of filter feeders (barnacles) was greater on the seaward side of Elmer LCSs ($F_{1,84} = 34.9$, $p < 0.005$), whilst the opposite was observed in Sea Palling ($F_{1,84} = 49.49$, $p < 0.005$). The
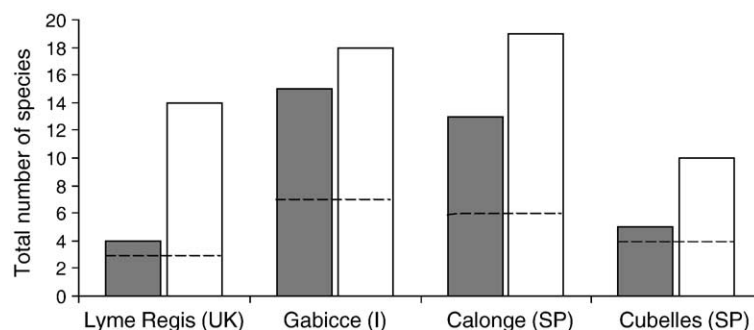

Fig. 2. Species richness on artificial (grey bars) and natural (white bars) habitats in four location: Lyme Regis; UK; Gabicce, Italy; Calonge, Spain; Cubelles, Spain. Dashed lines indicate number of shared species between artificial and natural habitats.
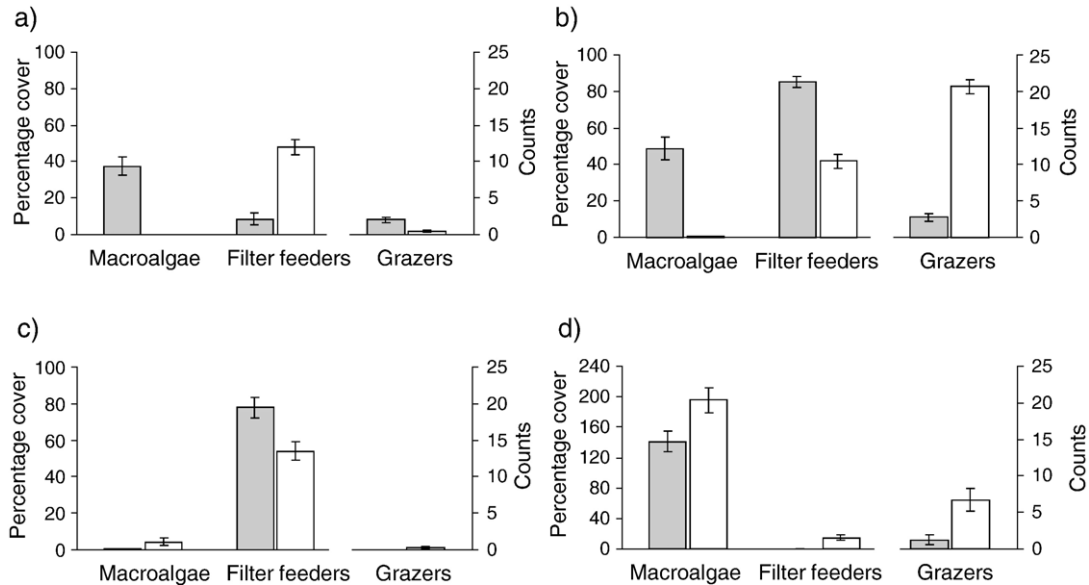
Fig. 3. Differences in the abundance of macroalgae, filter feeders and grazers between the landward (grey bars) and the seaward (white bars) sides of LCS along European coasts. Abundance of macroalgae and filter feeders is expressed as mean percentage cover (Y axis on the left) whilst abundance of grazers is expressed as mean number of individuals per quadrat (Y axis on the right). Locations: a) Elmer (UK), b) Sea Palling (UK), c) Lido di Savio (Italy), d) Calonge (Spain). Standard errors are indicated.

number of grazers (limpets, littorinids) did not differ between landward and seaward on the Elmer defence scheme, whilst in Sea Palling, the abundance of limpets was markedly greater on the exposed side of LCSs ($F_{1,84}=503.91$, $p<0.0001$). On LCSs at Lido di Savio (Italy), the main space-occupying filter feeders (oysters and mussels) were significantly more abundant on the landward side ($F_{1,42}=12.86$, $p<0.05$, Fig. 3c). Mussels (*Mytilus* spp.), however, were generally more abundant on the seaward side. The abundance of algal species and grazers did not differ significantly between landward and seaward sides, whilst great spatial variability was observed within each landward and seaward side. On the Calonge defence scheme in Spain (Fig. 3d), the abundance of algae ($F_{1,16}=11.85$, $p<0.05$), filter feeders ($F_{1,16}=42.37$, $p<0.001$) and grazers ($F_{1,16}=28.72$, $p<0.01$) was significantly greater on the seaward side. Within the algal group, articulated-coralline and encrusting algae were more abundant on the seaward side, whilst fast growing algal turfs such as *Herposyphonia tenella* were more common on the landward side. The filter feeder *Mytilus* and the grazer *Patella* were significantly more abundant on the exposed seaward side.

Experiments to determine the effects of wave exposure and grazing on epibiotic communities at Elmer in the UK (reported in more detail in Jonsson et al., submitted for publication) showed that both factors were important in determining the relative abundance of algae and grazers on landward and seaward sides of LCSs. The maximum flow speed of breaking waves on the seaward side of the LCSs at Elmer exceeded 7 m s^{-1}. The total force acting on epibiota ranged from 1 N for a small snail to over 50 N for larger macro-algae. The critical breaking stress for different sizes of *F. spiralis* (Fig. 4) suggests that on the seaward side most of the larger plants are likely to be dislodged by maximum wave-induced forces, while almost all plants are expected to remain on the landward side. These predictions correspond well with the observed distribution of the fucoid algae on LCSs.

On the seaward side of LCSs, growth of ephemeral algae and *F. spiralis* occurred on rocks where limpets were removed, but was limited to areas that were partially sheltered by other boulders and so not directly exposed to the full force of the incoming waves, (Fig. 5). This suggests that on the exposed side of LCSs recruitment and settlement of perennial species such as *F. spiralis* is possible if grazing pressure
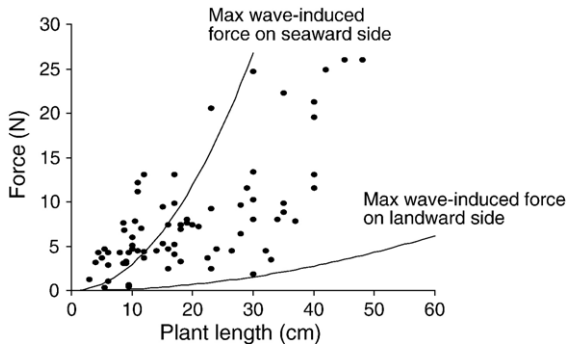
Fig. 4. Critical breaking stress of the seaweed *F. spiralis* as a function of plant size. Also shown are the predicted maximum wave-induced forces acting on *F. spiralis* based on empirical measurements and hydrodynamic theory. The steep and flat curves reflect predicted maximum forces on the seaward and landward sides, respectively. Data were collected at Elmer in West Sussex, UK.

is relatively low, but the persistence of these algae strongly depends on wave exposure. In the UK, natural densities of limpets on LCSs, once established, are sufficient to keep the substratum clear of macroalgae, particularly on the exposed seaward sides.

3.2.2. Location on the shore (tidal height)

On macrotidal coasts, LCSs are generally located in the intertidal, and their position with respect to mid tide level varies, in part depending on local tidal range. The number of species significantly increased on LCSs that had a larger portion of the structure below mid tidal level, as a consequence of being built lower on the shore (Pearson's $R = 0.48$, $p < 0.001$,

Fig. 6). As on natural rocky shores, diversity is greater on the lower shore where desiccation and thermal stresses are reduced due to shorter emersion periods.

On micro- and mesotidal shores, where epibiota occur mainly subtidally, diversity was higher on parts of LCSs located at greater depths. In Denmark, the total number of epibiotic species at 2 m depth was more than three times higher than at 0.5 m depth at both Skagen and Hirthshals. The increase in diversity with depth was probably related to less disturbed conditions in comparison to the wave-swept zone.

3.2.3. Habitat complexity

Design features determining habitat complexity influenced the diversity and abundance of epibiota at all spatial scales examined. At a scale of <1 cm, there was clear evidence that barnacles were more abundant in small crevices on rougher surfaces than on adjacent smooth areas (*t* test $p < 0.001$, Fig. 7a). At a scale of <10 cm, diversity also significantly increased with higher surface complexity. For example, after a year the average number of species on panels with small pits (16 mm diameter) was more than twice that of smooth panels (Fig. 7b).

Rock pools (scales of 10–100 cm) had on average twice the number of species found on adjacent, freely draining parts of the LCSs (Fig. 7c). This difference was mainly determined by the absence, on open rock, of organisms such as sponges, hydroids, ascidians, small fish and prawns, which are very sensitive to
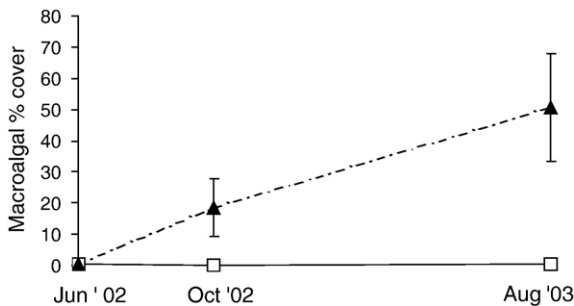

Fig. 5. Effect of removal of grazers on macroalgal growth on the seaward side of LCSs at Elmer, UK. Percentage cover of macroalgae (ephemerals, fucoids) recorded on the seaward side of LCS blocks where limpets (*P. vulgata*) were removed (▲) and on control, blocks where limpets were not removed (□). $n = 3$. Standard error is indicated.
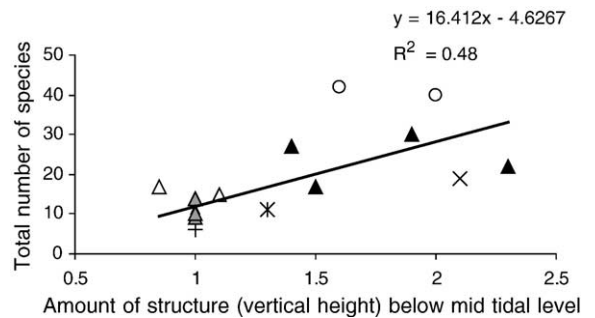

Fig. 6. Increase in diversity (expressed as total number of species) with location of LCS on the shore on macrotidal shores in the UK. Correlation between total number of species and position of LCSs on the shore (expressed as amount of structure below mean tidal level). Each data point represents one structure. Different symbols were used to indicate structures from different locations: ▲ Elmer; Δ Wirral; ▲ Sea Palling; + Isle of Wight; × Milford-on-Sea; * Rhos-on-Sea; ○ Sidmouth. $n = 20$.
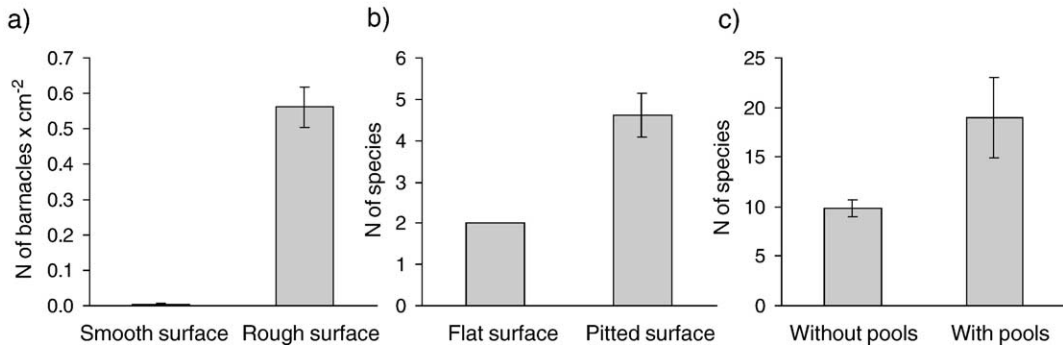
Fig. 7. Effects of surface complexity on epibiota at different spatial scales on LCSs at Elmer. (a) Scale of mm: mean abundance of barnacles on smooth and rough surface areas (4×4 cm) of blocks. (b) Scale of cm: total number of species on smooth and pitted panels (30×30 cm) after one year. (c) Scale of m: total number of species of epibiota in rock pools (1 m^2 on average) and adjacent blocks. Standard errors are indicated.

desiccation stresses. Diversity was positively correlated with pool depth and hence the volume of the rock pools (Pearson's $R = 0.64$, $p < 0.01$, Fig. 8) but not with the total surface area of the pools.

The building material used for LCS construction can also indirectly affect the epibiota, primarily through its surface complexity, which in turn depends on the intrinsic physical and chemical properties of the material. For example, epibiotic assemblages on sand bags or smooth concrete units were generally less diverse than on natural rock. Carbonate rocks such as limestone weather faster than igneous rocks, becoming rougher after few years, with crevices, pits and deep fractures forming (Fig. 9). Surface complexity on carbonate rocks can further increase due to bioerosion by grazers and rock boring organisms such as *Lithophaga lithophaga* that make deep holes and galleries (Kleeman, 1973).
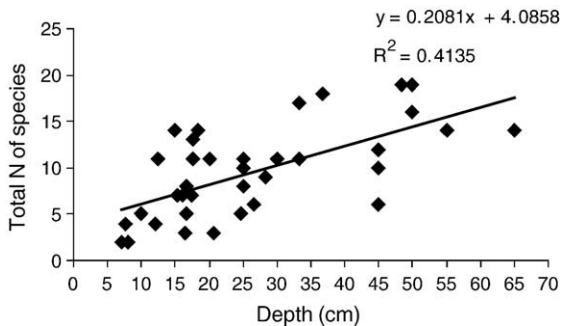
3.2.4. Disturbance: structural stability and scouring

The effect of regular maintenance of LCSs through the addition of new building material to compensate for storm damage or sinking had dramatic effects on epibiotic communities on LCSs in the Adriatic coast. In Cesenatico, epibiota on structures that had just been repaired was much less diverse than on structures that had not been maintained for three or more years (Fig. 10). In particular, the abundance of filter feeders, mainly mussels, was significantly reduced ($F_{1,28} = 43.31$, $p < 0.05$) on recently maintained LCSs, whilst filamentous green algae increased ($F_{1,28} = 48.56$, $p < 0.05$). On heavily maintained LCSs, epibiotic assemblages seemed to be reset

Fig. 8. Diversity in rock pools located at the base of LCSs at Elmer. Correlation between number of species and depth of rock pools. $n = 37$.
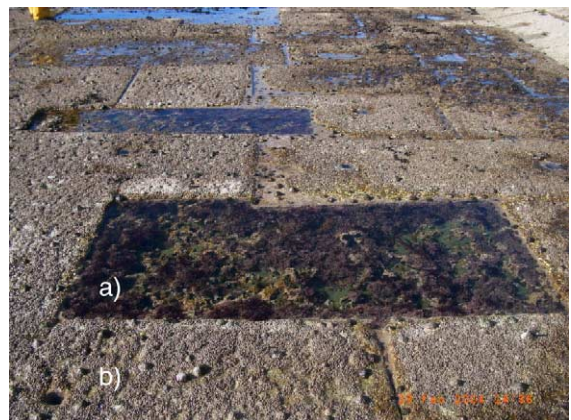

Fig. 9. Limestone (a) and granite (b) blocks on Plymouth breakwater, showing different levels of erosion. Eroded limestone blocks formed highly diverse rock pools, whilst granite blocks are colonised by few species only, mainly barnacles and limpets.
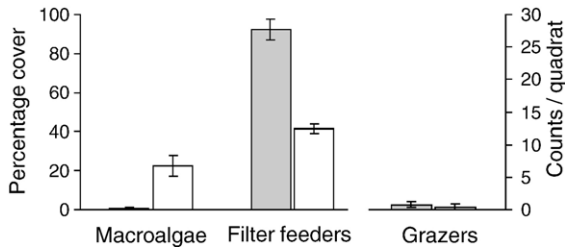
Fig. 10. Effects of maintenance works on epibiotic communities: mean abundance of macroalgae, filter feeders and grazers on the landward side of LCSs at Cesenatico (Adriatic coast, Italy) not maintained for at least 3 years (grey bars) and just maintained (white bars). Standard error is indicated ($n = 16$).

to early stages of colonisation characterised by few dominant pioneer species such as *Ulva* spp.

Scouring and sediment deposition can also be important causes of disturbance to rocky shores communities (Fig. 11a, b). At Elmer, preliminary observations showed that sand scouring at the base of LCSs resulted in a zone of bare rock that extended to 30 cm above the sediment, followed by a zone with sparse juvenile barnacles and ephemeral algae. Mature assemblages, consisting of adult barnacles, grazers and macroalgae, were observed from 50 cm above the sediment. Thus, sand scouring kills organisms settling at the base of the structure. This effect is further amplified by sand burial, as a consequence of changes in the sediment level, especially after storms.

The negative effect of sediment deposition has been widely documented in natural habitats (reviewed

by Airoldi, 2003), but preliminary studies and qualitative observations carried out in the UK, Italy and Spain during DELOS indicated that this process is exacerbated on LCSs. For example, in Spain, high sedimentation rates were detected using sediment traps located 0.5 m from the seabed on the seaward and landward side of the LCS. Very high deposition rates were found on natural soft-bottom areas; this was particularly the case during storm conditions on the landward side, probably due to the advection of sediment material from a nourished beach nearby. This could also explain the scarcity of organisms sensitive to siltation such as filter feeders. In contrast, fast growing finely branched and sheet-like algae, which are less sensitive to siltation, dominated the landward side.

4. Discussion

4.1. Can LCSs be viewed as artificial rocky shores?

LCSs share similar ecological attributes with natural rocky shores (summarised in Table 2). This was clear from previous work on Atlantic shores (Southward and Orton, 1954; Hawkins et al., 1983), the Mediterranean (Bacchiocchi and Airoldi, 2003; Bulleri and Chapman, 2004) and investigations from the DELOS project summarised here.

Biogeographic differences in the abundance and composition of epibiotic assemblages seem to reflect those observed on natural rocky shores and are mainly
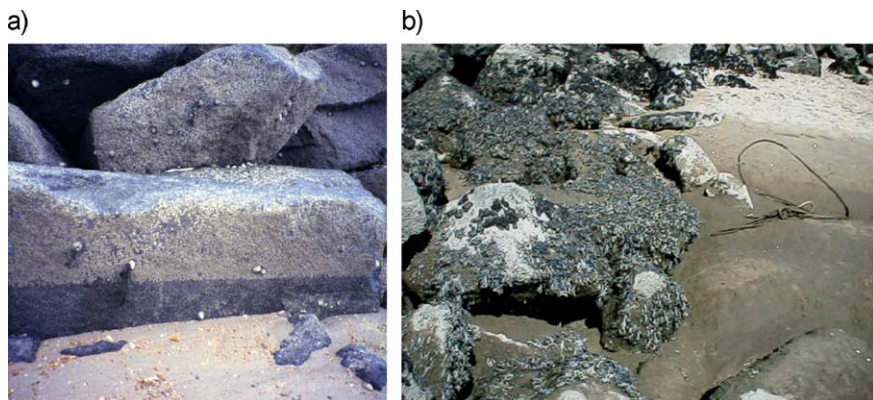

Fig. 11. (a) sediment scouring at the base of breakwater at Elmer, West Sussex; (b) sand burial of fucoid algae and barnacles at the base of Leasowe Bay coastal defence structure, on the Wirral.

Table 2
Summary of major ecological features and engineering aspects of LCS design affecting the abundance and diversity of epibiota

	Main effects on epibiota	Knowledge		Confidence in predicting the effect	Control of effect through LCS design	General references
		DELOS (LCS)	Background (rocky shores)			
Biogeographic patterns						
—At European scale	Changes in diversity and abundance	Extensive	Moderate	Moderate	None	(Lewis, 1964; Stephenson and Stephenson, 1972)
—At regional scale	Changes in diversity and abundance	Extensive	Extensive	High	None	(Lewis, 1964; Raffaelli and Hawkins, 1996)
Temporal changes						
—Initial colonisation and succession	Changes in diversity	High	Extensive	High	None	(Sousa, 1979b; Raffaelli and Hawkins, 1996)
—Seasonal variability	Changes in abundance	High	Extensive	Moderate	None	(Raffaelli and Hawkins, 1996)
—Long-term fluctuations	Changes in diversity and abundance	Moderate	Limited	Moderate	None	(Connell and Slatyer, 1977; Raffaelli and Hawkins, 1996)
Biological interactions	Changes in species composition and distribution; establishment of species.	High	Extensive	Moderate	Low	(Lubchenco and Gaines, 1981; Hawkins et al., 1992; Raffaelli and Hawkins, 1996)
Orientation/exposure	Changes in diversity and abundance	Extensive	Extensive	High	Low	(Ballantine, 1961; Lewis, 1964; Raffaelli and Hawkins, 1996)
Elevation of the shore	Changes in diversity	Moderate	Extensive	High	Moderate	(Lewis, 1964; Raffaelli and Hawkins, 1996)
Surface complexity						
—Rock pools and gullies (10–100 cm)	Changes in diversity and recruitment	Very high	Extensive	Very high	High	(Metaxas and Scheibling, 1993)
—Crevices ad pits (1–10 cm)	Changes in diversity and recruitment	Very high	Extensive	Very high	High	(Johnson et al., 2003)
—Roughness (<1cm)	Changes in abundance and recruitment	High	Extensive	Very high	High	(Kostylev and Erlandsson, 2001)
Disturbance						(Sousa, 1979b, 2001) (Airoldi, 2003)
—Scour	Changes in mortality	Limited	Moderate	High	Low	
—Sedimentation	Changes in diversity and morality	Limited	Moderate	Moderate	Low	(Airoldi, 2003)
—Maintenance works	Colonisation and succession	High	N/A	Very high	High	(Kostylev and Erlandsson, 2001)

determined by the climate and the species pool in a region (Lewis, 1964; Stephenson and Stephenson, 1972; Raffaelli and Hawkins, 1996). At a regional scale, other natural factors also contribute to the composition of epibiotic assemblages, including tidal range, wave and current regimes (Stephenson and Stephenson, 1972; Branch and Branch, 1981; Bustamante and Branch, 1996), salinity (Raffaelli and Hawkins, 1996) and larval supply (Gaines and Roughgarden, 1985; Bourget et al., 1994; Menge et al., 1997).

The composition of epibiotic assemblages is also highly variable with time. Results from DELOS and previous studies (Moore, 1939; Southward and Orton, 1954; Hawkins et al., 1983) have shown marked similarities in colonisation sequences on LCSs and natural rocky shores. The exact successional sequence of species can vary according to time, particularly season (Hawkins, 1981; Hawkins and Hartnoll, 1983b; Dayton et al., 1992), location (Raffaelli and Hawkins, 1996), intensity and frequency of disturbance (Sousa, 2001) and biological interactions (Connell and Slatyer, 1977; Sousa and Connell, 1992). However, the type of community that will first colonize a new structure can be reliably predicted. Early colonisation will be characterised by a few pioneer species, consisting of biofilms (mainly diatoms and cyanobacteria) and fast-growing ephemeral algae (*Blidingia*, *Ulva* and *Porphyra* spp.); these will be subsequently replaced by later colonisers, typically barnacles, limpets, mussels and foliose algae. Larval recruitment variability and seasonal changes in the abundance of species contribute to generate further spatial and temporal variability in the abundance and composition of epibiotic assemblages (Bowman and Lewis, 1977; Hawkins and Hartnoll, 1982; Hartnoll and Hawkins, 1985; Gaines and Bertness, 1992; Underwood, 1999).

At a local scale, the same horizontal and vertical gradients that operate on rocky shores seem to determine the distribution of species on LCSs. Wave exposure plays a major role in the composition of rocky littoral and sub-littoral communities, on both LCSs (Southward and Orton, 1954) and natural rocky shores (Lewis, 1964; Hiscock, 1983; Raffaelli and Hawkins, 1996). On the exposed sides of LCSs, benthic organisms experience greater wave-induced forces and con-

sequently face a higher risk of dislodgement. Conversely, on the sheltered sides of the structures, reduced water movement is generally associated with greater siltation of the rock substratum. Species respond differently to this stress gradient (Denny et al., 1988; Denny, 1995); some organisms thrive in wave swept conditions (e.g. mussels and barnacles), whilst others are adapted to more sheltered conditions (e.g. the macroalga *Ascophyllum nodosum* and the gastropod *Osilinus lineatus*).

In the intertidal, the increase in diversity observed on LCSs located lower on shore reflects the vertical gradient of species richness found on rocky shores (Lewis, 1964; Raffaelli and Hawkins, 1996). Physiological tolerance to emersion and desiccation stress varies between and within species but in general a higher number of species can survive environmental conditions lower on the shore (Lewis, 1964; Newell, 1979; Raffaelli and Hawkins, 1996; Spicer and Gaston, 2000). This pattern is particularly evident on macrotidal shores, where epibiotic assemblages differed markedly between different tidal levels.

The abundance and diversity of epibiotic communities are not only influenced by physical factors. Interactions between species such as grazing (Jones, 1948; Southward, 1964; Southward and Southward, 1978; Lubchenco and Gaines, 1981; Hawkins and Hartnoll, 1983a; Branch et al., 1992) and competition (Connell, 1961; Paine, 1974; Lubchenco, 1980) are known to be key factors in determining the structure of rocky shore communities (Hawkins et al., 1992; Boaventura et al., 2002b,a). Similarly, these factors seem to control the development of epibiotic assemblages on LCSs. In the UK, for example, large seaweeds were prevented from establishment on the exposed side of LCSs by limpet grazing. In the absence of limpet grazing, fucoids tolerant to wave action (e.g. the short bladderless *Fucus vesiculosus evesiculosus*) seem to be able colonise the seaward side of LCS but eventually disappear as grazing pressure increases (Southward, 1964; Southward and Southward, 1978; Hawkins et al., 1983). Biological interactions, however, vary over both time (Southward and Southward, 1978; Sousa, 1979a; Hawkins and Hartnoll, 1983b) and space (Lively et al., 1993; Underwood and Chapman, 1998; Benedetti-Cecchi,

2001), reflecting both assemblage composition and environmental context.

Despite similarities between assemblages on LCSs and natural rocky shores, there are some marked quantitative dissimilarities between these two habitats. Disturbance on LCSs tends to be greater in intensity and frequency than on natural bedrock. LCSs can be compared, to a certain extent, to a natural boulder field or reef adjacent to a sandy beach (Bally et al., 1984). The main cause of disturbance to epibiotic assemblages is sedimentation and scouring by sand that surrounds LCSs, leading to changes in species composition and distribution, increased mortality and reduced settlement/recruitment. Thus the effects of disturbance by scouring and sedimentation on LCSs are the same as on rocky shores (Shanks, 1995; Airoldi, 2003), but the intensity and frequency of disturbance events are greater.

Human activities probably represent the second major cause of disturbance on LCSs especially in the Mediterranean. There is good evidence that frequent maintenance to reinforce and/or re-stabilise the structures has a significant negative impact on epibiotic communities (Bacchiocchi and Airoldi, 2003). Shellfish harvesting and recreational use of LCSs can also lead to disturbance through removal and trampling, particularly in summer (Airoldi et al., unpublished data). These activities are likely to affect the persistence, growth and abundance of more vulnerable species, thus leading to changes in diversity and dynamics of the whole assemblage, as largely documented on rocky shores (reviewed in Thompson et al., 2002). In particular, high levels of disturbance will retard successional processes that generally lead to greater diversity and more complex communities (Sousa and Connell, 1992; Sousa, 2001). On LCSs where disturbance is continuous or frequent, succession will not proceed beyond the stage characterised by a few pioneer species such as ephemeral algae (*Ulva* spp., *Porphyra* spp.).

LCSs also show lower overall species richness than rocky shores. In comparison to natural rocky shores, LCSs lack of habitat complexity, have a small spatial extent and are of relatively young age. Surface and habitat complexity enhances settlement and distribution of several species in both intertidal (Luther, 1976; Johnson, 1994; Kostylev, 1996; Hill and Thomason, 1998; Johnson et al.,

2003) and subtidal (Dobretsov and Railkin, 1996; Koehler et al., 1999; Choi et al., 2002) habitats, although this can vary depending on the geographical location and local environmental factors (Bourget et al., 1994; Johnson et al., 2003). The building units of most LCSs are characterised by a relatively homogenous surface, especially those made of cast concrete or machine cut rock. Crevices, small fractures, as well as pits and holes, which offer important habitats for marine life, are often absent on LCSs. On macrotidal shores, the lack of such features is of major importance in determining the epibiotic assemblages on LCSs, especially those located above mean tidal level, as only a limited number of species is able to cope on free draining rock at low tide, due to the longer exposure to desiccation and insolation stresses (Raffaelli and Hughes, 1978; Mak and Williams, 1999; Chapman, 2003). Topographic features also provide shelter from wave action and refuges from predation (Fretter and Manly, 1977; Underwood and Chapman, 1998). The presence of gullies and rock pools increases the variety of habitats, creating suitable conditions for a wider number of species, including crustaceans and small fish.

LCSs, as well as other types of coastal defence structures, differ from natural rocky habitats in other aspects. They have a limited spatial extent both horizontally and vertically and are generally located along sedimentary coastlines. The substrate available for colonisation and recruitment of new species is therefore limited. Increasing the size and number of structures enhances connectivity between these rocky habitats, which can lead to greater opportunities of colonization by species. At the same time, however, such increased connectivity will disrupt the natural barriers to species dispersal and facilitate the spread of non-native species (Bulleri et al., in press), with potential negative effects on natural assemblages and will also cause impacts on the surrounding sediments (Martin et al., 2005—this issue).

The lifetime of most structures is generally not greater than 70 years, during which LCSs are subject to renovation works. Large coastal structures that have been in place for many years (e.g. Plymouth Breakwater—since 1830s) are virtually indistinguishable from adjacent rocky shores (Southward and Orton, 1954). This is partly due to the weathering process

that makes rock surfaces rougher and more complex, particularly on limestone blocks.

4.2. Influence of engineering design on epibiota: what can and cannot be modified

Most natural processes and factors that affect the abundance and diversity of epibiota are pre-determined and cannot be avoided or controlled by any engineering intervention. They include physical factors such as wave and current regime, tidal range and salinity gradients, as well as biological factors such as the species pool, recruitment fluctuations and biological interactions.

Some ecological attributes of epibiota, however, can be controlled by modifying the relevant habitat features; hence target ecological effects can be achieved through engineering intervention on LCS design (see examples in Fig. 12). The following suggestions for modification of LCS design features to achieve target effects on habitats and species provide only general guidelines that need to be tailored on the basis of the desired management goals and on the specificity of the system considered (Airoldi et al., 2005—this issue).

Differences in composition and abundance of epibiotic assemblages between the landward and seaward sides of LCSs can be controlled by modification of the freeboard height (effect on overtopping frequency), the total length of LCS (effect on diffracted waves around the round heads) or porosity (effect on water transmission through the structure). For example, on macrotidal shores, increasing water movement on the landward side could suppress growth of certain seaweeds (e.g. *Ascophyllum*, *Fucus* spp.) whilst promoting filter feeders such as mussels and barnacles.

The location of LCSs on the shore can be particularly important on macrotidal coasts. This will determine the periods of emersion/submersion of the structure and therefore the associated species composition. LCSs located lower on the shore will have a larger portion of structure below mean tidal level, hence a higher number of species will be able to settle and persist over time; diversity and biomass will therefore increase. In contrast, LCSs located at higher tidal levels will be colonised by fewer species, mainly ephemeral algae and barnacles. On microtidal coasts, these effects are less evident, although LCSs located in deeper waters will have greater species richness.

More diverse communities can be achieved by minimising disturbance. For example, scouring can be reduced by building a berm or platform in front
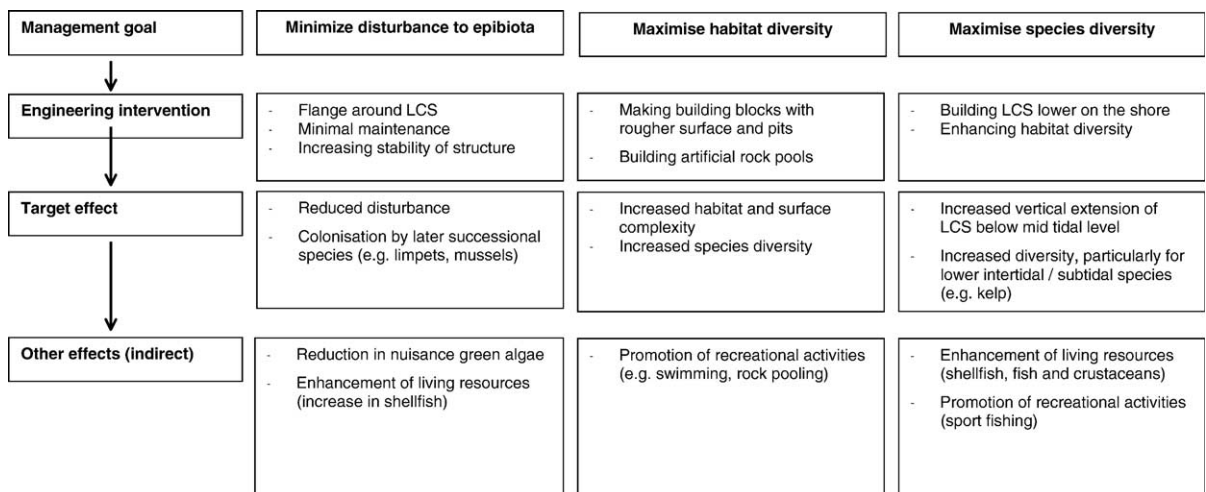

Fig. 12. Examples to illustrate how target effects on epibiota could be obtained via intervention/modification of LCS design. For example, engineering intervention can influence diversity and abundance of epibiotic species by increasing surface and habitat complexity or locating the structures lower on the shore. These modifications can also lead to indirect effects, such as promotion of natural resources (shellfish and fish) and recreational activities.

of the structures. More complex surfaces will provide protection for sessile species from scouring and sedimentation. Periodical maintenance of LCSs should be adapted to minimise disturbance. Unless maintenance is reduced to the minimum, there is little point in introducing additional features to promote species diversity, as colonisation and succession of species will be re-set to initial stages.

The scope for intervention for targeted outcomes is greatest at the smaller scale (1–100s cm), through manipulation of habitats and microhabitats. For example, if greater species richness is desired to promote recreational use of LCSs, this can be achieved by increasing the surface and habitat complexity, which provides protection from wave exposure, predation and grazing. The surface of LCS blocks can be made rougher by chiselling grooves or drilling small pits and deeper holes. The choice of building material can also significantly contribute to increase diversity of microhabitats. Rough or complex surfaces can be easily cast in concrete units, although similar features can be naturally created by weathering and bioerosion when using limestone blocks. Much more time (5–10 years), however, is needed to obtain complex and heterogeneous surfaces on natural rock.

Rock pools can also be incorporated into design of LCSs, to increase diversity on blocks located above mean tidal level and to provide suitable habitats for recruitment and settlement of species such as limpets, winkles (littorinids) and crabs. Promoting settlement of limpets can be a very useful, cost-effective and environmentally sensitive tool for drastically reducing the abundance of nuisance green algae that generally flourish on disturbed habitats such as frequently maintained man-made structures or slipways.

In addition, the size, packing of blocks, and consequently the porosity of the LCS, can all be modified to provide a variety of habitats such as gullies and small caves. This approach has been successfully used in the design of artificial reefs, that are specifically built to attract fish and crustaceans (Collins et al., 1994; Jensen et al., 1994a, b).

These features need not be built throughout the structure to achieve the desired management goals but could be incorporated in selected areas of the structures. However, it is important to consider that

engineering intervention used to control epibiota is also likely to produce indirect effects on the surrounding environment, such as changes on sediment infauna and water quality (Martin et al., 2005—this issue). Any modification made to the design of a LCS and the consequent effect on epibiota, needs therefore to be carefully evaluated, depending on the desired outcome and potential ecological impacts that this could indirectly cause (Airoldi et al., 2005—this issue). A comprehensive knowledge of the ecology of the coastal cell where the LCS will be built and site-specific pre- and post-construction studies are therefore essential for the evaluation and prediction of effects on epibiota and in order to implement appropriate mitigation measures.

5. Conclusions

Results from DELOS show that low-crested coastal defence structures are analogous to natural rocky shores, but in essence are a poor imitation—*ersatz* rocky shores. There is also no doubt that colonisation by species typical of rocky shores will occur on any new LCS and this process cannot be prevented by human intervention. This also implies that LCSs can modify the natural limits of distribution of hard-substrate species as well as facilitate the spread of invasive species with detrimental effects for the identity of native benthic assemblages (see Airoldi et al., 2005—this issue). The first ecological consideration is therefore to avoid overengineering and build LCSs only where it is strictly necessary.

Results from DELOS indicate that the structural design of LCSs can be modified to influence the abundance and species composition of epibiota to achieve desired management goals such as controlling growth of nuisance algae or promoting diversity of habitats and species for recreational activities. The choice of specific engineering interventions on structural design to obtain target ecological effects, however, is not universally applicable and will depend on the environmental setting. For example, there is no gain in modifying design features of LCSs to promote settlement of mussels in a region where recruitment of this species is very low (e.g. south coast of England). It is therefore important to perform scoping studies and accurate environmental assessments

to obtain a full ecological characterisation of a site before decisions on the preferred design of LCSs are made.

Moreover, there is no absolute judgement upon which the type of engineering interventions and the associated ecological effects can be regarded as positive or negative. This will depend on the managerial goals which should take account of both local and regional environmental impacts as well as socio-economic needs. Also, they should reflect cultural differences, such as the appreciation of marine life in the UK and shellfish collecting in Italy (Airoldi et al., 2005—this issue). Nevertheless, design criteria should always aim to promote integration of LCSs and other man-made structures in the coastal system, by minimising changes to the nature and identity of the surrounding environment.

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