Eco-engineering of artificial coastal structures to enhance biodiversity: An illustrated guide

Urban Research on Biodiversity on Artificial and Natural coastal Environments:
Enhancing biodiversity by sensitive design

Urbane

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This document was prepared by L.B. Firth, R.C. Thompson and S.J. Hawkins for the Esmée Fairbairn Foundation as part of the Urbane Project. Funding was provided by the Esmée Fairbairn Foundation and the EU-FP7 under the THESEUS project (contract number 244104: Innovative technologies for safer European coasts in a changing climate. Additional support was provided by the Seacams Partnership (www.seacams.ac.uk) in collaboration with Ruthin Precast Concrete (RPC).

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Front page image: Fish-tailed rock rubble groyne at West Shore, near Llandudno, North Wales

Factors affecting biodiversity

When considering the incorporation of biological enhancement into artificial coastal defence structures , there are some factors which are uncontrollable and context dependent, whilst other are controllable through careful design and planning.

Factors which are uncontrollable & context-dependent

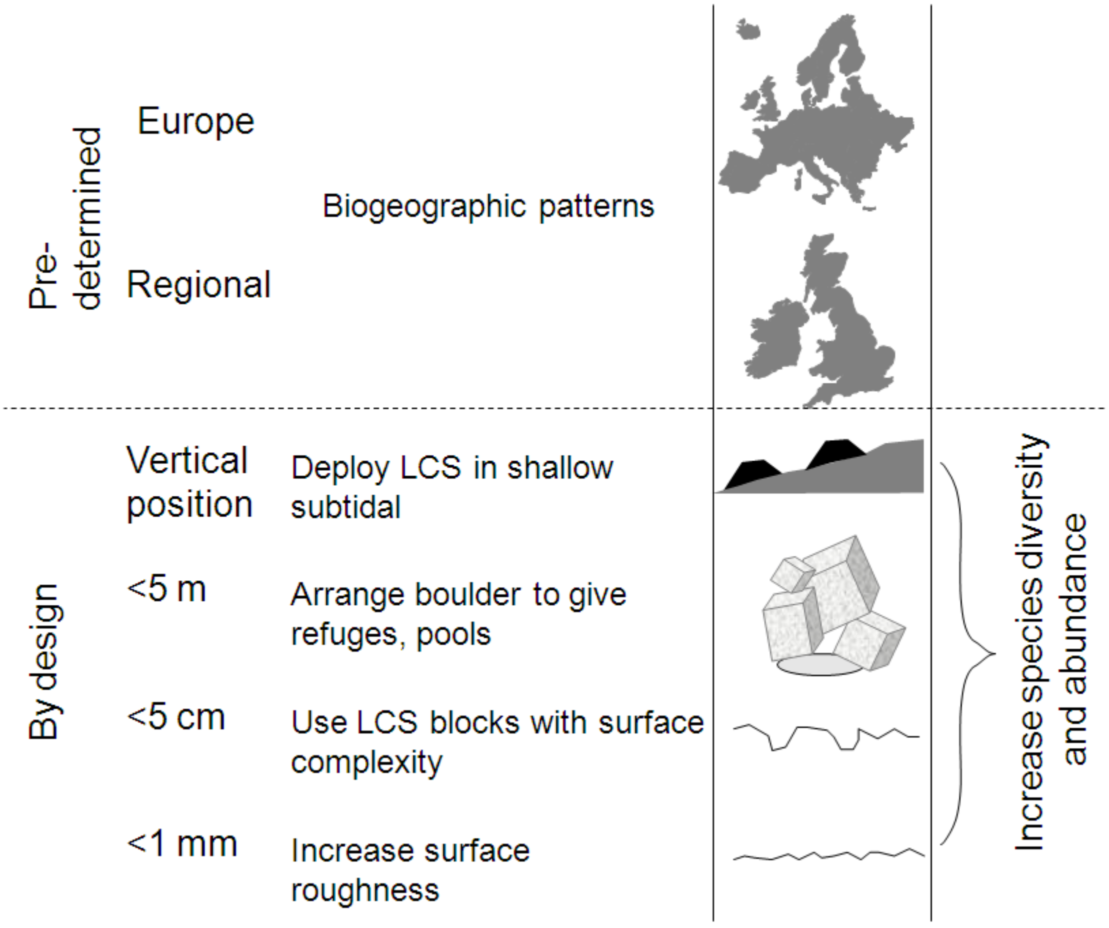
- Bio-geographic setting and potential species pool
- Larval recruitment regime
- Sediment supply and dynamics
- Wave action
- Tidal range
- Degree of maintenance required & therefore disturbance to epibiotic communities

Factors which are controllable through design

- Size, shape, configuration, location (100 m – km)
- Position in the intertidal
- Block size, porosity, habitat complexity (1-10 m)
- Block composition (1 m)
- Surface roughness (< 1 cm)

What can coastal managers do to increase biodiversity on artificial structures?

The figure below is taken from Burcharth et al. (2007) and illustrates the various measures that coastal managers can take at a range of spatial scales in order to increase biodiversity in artificial coastal habitats.



Burcharth HF, Hawkins SJ, Zanuttigh B, Lamberti A. (2007) Environmental design guidelines for low crested coastal structures. Oxford, UK, Elsevier.

Natural rocky shores support greater diversity and abundance than artificial habitats

Artificial coastal structures make poor surrogates for natural rocky shores, often supporting lower species diversity but supporting higher densities of opportunistic species such as ephemeral green algae and barnacles. Artificial structures generally lack the environmental heterogeneity and surface roughness that is usually present on natural rocky shores, enabling them to support greater numbers of individuals and species. This will be discussed in more detail in the following pages.

A diverse natural boulder shore community at Niarbyl on the Isle of Man. Note the diverse and dense cover of algae.

A depauperate community on the concrete walls of the Harbour at Aberaeron, mid Wales. Note the presence only of ephemeral green algae and fucoids.

A depauperate community on the granite boulders of the breakwater at Rhos-on-Sea, North Wales. Note that the only species present are barnacles, limpets, mussels and ephemeral green algae at the base of the structure.

Geology and surface roughness can have a major effect on colonizing communities

The geology of the substratum can have a significant influence on the diversity and abundance of the colonizing community. In addition micro-scale surface roughness (< 1 mm) can also have a very important impact on community structure. In general, smooth, artificial substrates support less diverse and abundant communities, whilst rougher natural substrates favour more diverse assemblages.

Concrete

Granite

Limestone

The Universities of Exeter and Plymouth have experimented with the colonization and weathering of engineering materials by marine microorganisms. Experiments were carried out comparing the micro-scale biological growth features of Marine concrete, Cornish granite and Portland limestone blocks.

It was revealed that granite blocks supported the greatest micro-scale colonization in comparison to concrete and limestone blocks.

Coombes MA, Naylor LA, Thompson RC, Roast SD, Gómez-Pujol L, Fairhurst RJ. (2011) Colonization and weathering of engineering materials by marine microorganisms: an SEM study. Earth Surface Processes and Landforms 36: 582-593.

Environmental heterogeneity underpins greater biodiversity in natural habitats

Heterogeneity of the environment is essential for species co-existence, with structurally complex habitats offering a great variety of different microhabitats and niches, therefore allowing species to co-exist and is, therefore, an important mechanism in the maintenance of biological diversity. Environmental heterogeneity can operate on a range of spatial scales: surface roughness on microscales (< 1 cm); surface heterogeneity such as pits and depressions on small scales (< 5 cm); and refuges, crevices and rock pools on medium scales (< 5 m).

Small scale pits (< 5 cm): Small littorinids (*Littorina saxatilis* and *Melaraphe neritoides*) commonly occupy small pits and barnacle tests. Note that the winkles are only occupying the pits and not the surrounding emergent rock. The natural pits here were found in the upper shore of Port St. Mary Ledges on the Isle of Man.

Medium scale rock pools (< 5 m): Rock pools support more diverse floral and faunal communities than emergent rock. Note the diverse algal assemblages around the edges of the pool. Also not the presence of the invasive seaweed *Sargassum muticum*. The image was taken in the mid shore at West Looe, Cornwall, UK.

Medium scale rock crevices (< 5 m): Crevices are important on rocky shores as they provide a refuge for many benthic organisms from predation, desiccation and temperature stress. Note the abundance of algae and anemones in the crevice compared to the surrounding rock. The image was taken at Vigra, Norway.

Ecological engineering of artificial habitats can be done during the construction phase or retrospectively

It is advantageous to incorporate any modifications during the construction phase. Modifications made at this time can be done on a larger scale, can be incorporated into the design of the structure and take advantage of heavy plant machinery that is present on the construction site. It will enable greater flexibility to work with contractors, local councils and agencies.

If it is not possible to incorporate modifications at the construction phase, there are many ways to engineer artificial habitats retrospectively. Typically these will be on a smaller scale.

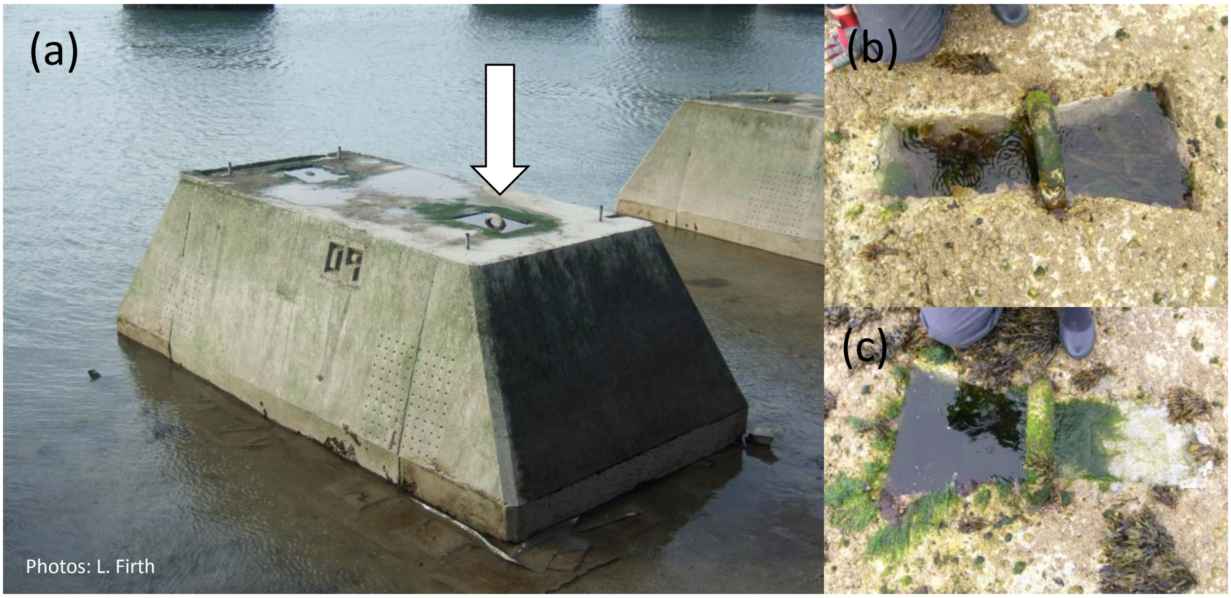
Construction of Twywn Breakwater: If possible, it is advantageous to incorporate modifications during the construction phase. The image shows the early stages of the construction of Tywyn breakwater, Wales in January 2010.

Deployment of BIOBLOCK during construction at Colwyn Bay: The URBANE team were able to take advantage of heavy plant machinery and incorporate a large-scale habitat enhancement unit into the newly constructed groyne at Colwyn Bay (see page 14 for more details).

The construction process can sometimes produce artefacts that function as favourable habitat types

Cast rock pools on sacrificial blocks on Plymouth Breakwater

Large concrete blocks (~100 tonne) are periodically placed on the seaward side of the Plymouth Breakwater. The purpose of these blocks is to dissipate wave energy. These blocks have depressions which are created to facilitate the placing of loops (a,b,c) to lift the blocks into place with a crane from a barge. Although purely an artefact of construction, these features retain water at low tide and create rockpool habitat, supporting diverse assemblages of flora and fauna.



The University of Plymouth (Juliette Jackson) has been carrying out surveys of the artificial rock pools on the surface of the blocks since 2004. The pools are quite deep (up to 40 cm) and support diverse assemblages of animals and algae, including large kelp.

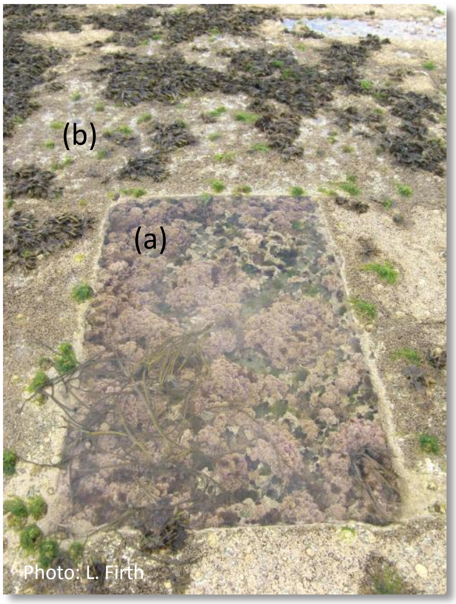
It is possible to test hypotheses about biodiversity relating to different pool area and volume by filling in sections with concrete (a, b).

Griffin JN, Noël LML, Crowe TP, Burrows MT, Hawkins SJ (2010) Consumer effects on ecosystem functioning in rock pools: roles of species richness and composition. Marine Ecology Progress Series. 420: 45–56

The construction process can sometimes produce artefacts that function as favourable habitat types

Weathered rock pools on main structure of Plymouth Breakwater

The central structure of Plymouth Breakwater is constructed of mixture of both limestone and granite block interspersed among each other. Carbonate rocks such as limestone weather faster than igneous rocks such as granite, becoming rougher after few years, with shallow pools, crevices, pits and deep fractures forming additional habitats. Surface complexity on carbonate rocks can further increase due to bioerosion by grazers and rock boring organisms that make deep holes and galleries



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.

A small rock pool (< 10 cm diameter) that has formed in a pit that has eroded away on a limestone block on Plymouth Breakwater. Note that there are at least 5 species of algae, 2 species of anemone and 1 species of limpet found in such a small pool. This is in contrast to the species poor adjacent emergent rock.

Moschella PS, Abbiati M, Åberg P, Airoldi L, Anderson JM, Bacchiocchi F, Bulleri F, Dinesen GE, Frost M, Gacia E, Granhag L, Jonsson PR, Satta MP., Sundelöf A, Thompson RC, Hawkins SJ. (2005). Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design. Coastal Engineering 52: 1053-1071.

The construction process can sometimes produce artefacts that function as favourable habitat types

Blast lines on Tywyn Breakwater

Sometimes boulders on coastal defences can have parallel longitudinal depressions along the length of the rock. These depressions are an artefact of the quarry blasting process and add an extra layer of surface heterogeneity to the structure. The depressions can provide a valuable refuge for many organisms.

Photo: L. Firth

Photo: L. Firth

The image above is of a boulder on Tywyn Breakwater, Wales approximately 12 months after construction. Note the presence of mussels only in the longitudinal depressions but not on the surrounding boulder. Although, mussels later covered many of the boulders, it is possible that the blast lines provided a favourable habitat for early settling mussels which then facilitated the further settlement of individuals.

The construction process can sometimes produce artefacts that function as favourable habitat types

Rock pools at the base of Elmer breakwaters

Elmer coastal defence scheme was constructed between 1991 and 1993.
The breakwater scheme comprises a system of 8 shore-parallel offshore breakwaters extending along 1.75 km of coastline between Little Hampton and Bognor Regis in West Sussex. Water is retained between the boulders at the base of some of these structures, creating an additional rockpool habitat to the boulder structure.

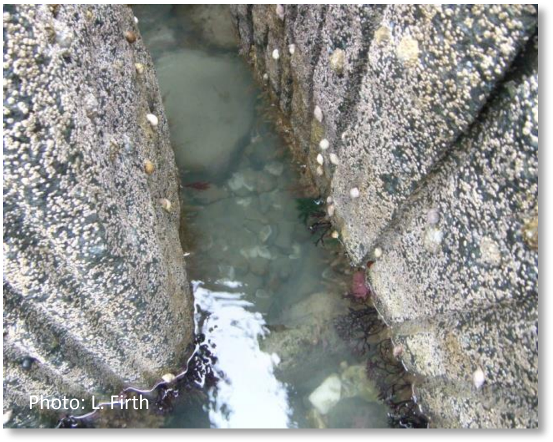


Photo: L. Firth

Photo: L. Firth

Surveys of the biodiversity in these rock pool habitats have found that a greater diversity of flora and fauna inhabit the rock pools in comparison to the adjacent rock. The pool habitats are particularly important for red algae which are are not present on the emergent rock.

The pools at the base of the structure vay in depth with some being up to 1 m deep whilst others are very shallow (< 10cm). Surveys have revealed that diversity of flora and fauna in these pools also increases with depth.

Diamond drill-cored rock pools on Tywyn Breakwater

In 2010 a £6m coastal defence scheme was completed at Tywyn, Gwynedd, Wales. As part of the scheme both the existing rock and timer groynes were replaced in addition to the construction of a new rock breakwater in front of the slipway.

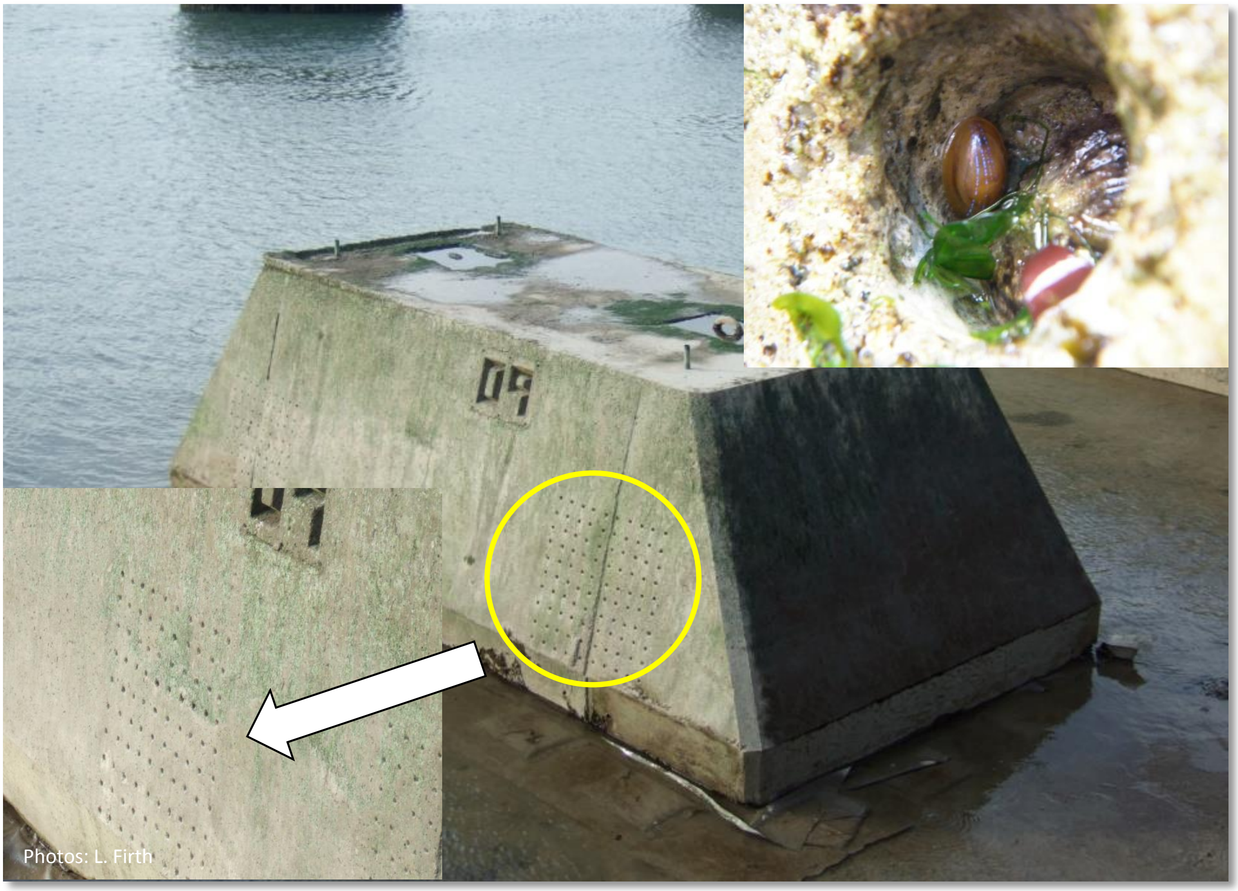
Photos: L. Firth

In collaboration with Gwynedd Council and SMS Wales, Bangor University explored to opportunity of habitat enhancement by the incorporation of rock pools onto the horizontal surfaces of some of the boulders around the base of the structure. A total of 18 pools with two different depths (5 cm and 15 cm) have been drilled with a diamond tipped corer in October 2011.

It is expected that long-term monitoring over the coming months to years will reveal that diversity of flora and fauna will be higher in the pool habitats than on the surrounding rock. Furthermore, it is expected that diversity will be higher in the deeper pools than in the shallow pools.

Drilled pits on sacrificial blocks on Plymouth Breakwater

The artificial creation of small pits and depressions is a very cheap and effective way of increasing surface heterogeneity of small spatial scales (< 5 cm). Prior to positioning on the Plymouth Breakwater, the large concrete blocks can be modified by drilling pits of varying diameter, depth and spacing distance. Such a large number of large pits (2.5 cm) requires a drill that is either driven by petrol or a generator. These pits provide unique habitat for a range of different floral and faunal species.



Photos: L. Firth

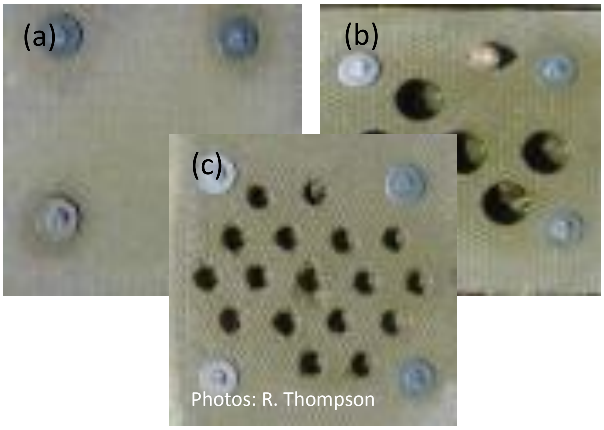
In collaboration with the Ministry of Defence and SERCO, The University of Plymouth has explored opportunities for habitat enhancement by drilling pit of varying diameter and spacing distance on the concrete blocks prior to positioning on the Plymouth Breakwater.

Over time these pits become colonised by species that would be otherwise unable to inhabit the smooth surface of the concrete block, such as red algae and blue rayed limpets (inset).

Ecological enhancements can be incorporated retrospectively

Drilled pits on panels on Elmer breakwaters

At Elmer, West Sussex, an alternative method of incorporating the addition to pits to artificial structures was trialed by affixing tiles with pre-drilled holes. This method meant that habitat enhancements could be carried out using a cordless, battery-driven drill rather than a power-driven drill. The method would enable that locations that are difficult to access or do not have a power source may be enhanced.



(a) Panels with no pits, (b) few large (32 mm) pits and (c) many small (14 mm) pits were affixed on both horizontal and vertical rock surfaces on the boulders of Elmer breakwaters. After 5 months, diversity of flora and fauna was greatest in panels with many small pits than the other two, with only very low numbers on species being recorded on the smooth panels.

Note the winkle, algae and limpet occupying the pits and only barnacles can be seen on the smooth surface of the panel.

Witt MJ, Sheehan EV, Bearhop S, Broderick AC, Conley DC, Cotterell SP, Crow E, Grecian WJ, Halsband C, Hodgson DJ, Hosegood P, Inger R, Miller PI, Sims DW, Thompson RC, Vanstaen K, Votier SC, Attrill MJ, Godley BJ (2012) Assessing the biodiversity impacts of wave energy: the Wave Hub experience. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 370: 502-529 (see Appendix A)

New habitat niches in estuary wall at Shaldon

The Shaldon and Ringmore £6.5 million tidal defence scheme was built in 2010/2011 to provide flood protection to the homes and businesses of the villages in Devon, UK. Funding was provided by Defra with approval from the South West Regional Flood Defence Committee.

Photos: L. Firth

The Universities of Plymouth and Exeter explored opportunities for ecological enhancement during the design phase of Shaldon & Ringmore tidal defence scheme. A trial was designed to test different enhancement options on two adjacent vertical concrete walls faced with local stone and mortar jointing. This involved manipulating areas of mortar (~15 x 15 cm) between blocks in four different ways:

Grooves: Mortar was roughened by 'drawing' grooves (mm in size) in the wet mortar during construction

Holes: Holes (1.5 cm diameter) were made in wet mortar using a broom handle to create shaded, water retaining features.

Pools: Recessed areas were created by occasionally leaving out blocks in the wall.

Control: Areas of mortar were left as-used for the rest of the wall.

Ecological enhancements can be incorporated during construction

BIOBLOCKS at Colwyn Bay

In 2011 a £6m coastal defence scheme is being constructed in Colwyn Bay. As part of the scheme the promenade has been extended seawards and a rock armour revetment and groyne have been constructed using 80,000 tonnes of imported materials.

Photo: J. Sharp

In collaboration with Conwy Council, the SEACAMS partnership and Ruthin Precast Concrete (RPC), Bangor University have developed a large-scale habitat-enhancement unit called the 'BIOBLOCK' which can be incorporated into rock armour breakwaters, groynes and revetments at the construction stage. The objective of the BIOBLOCK is to provide additional habitat types that would not be present on the rock armour structure.

The precast BIOBLOCK measures 1.5 x 1.5 x 1.1 m, weighs approximately 6 tonnes and has been designed in such a way that it has multiple habitat-types on the different faces of the block:

Rock pools of different depths and diameters on the horizontal surface.

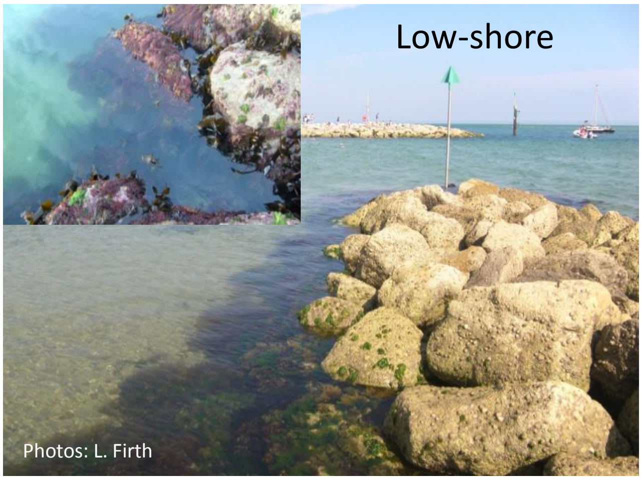
Circular pits of different depths on the vertical sides

Longitudinal depressions also on the vertical sides.

The positioning of a structure in relation to tidal height can have a significant effect on the colonizing community

Structures that are constructed at the mid tidal level or higher tend to have lower biodiversity and abundance than structures that are constructed in the lower shore. Manipulations incorporated at different tidal heights can have variable effects on the colonizing community. Those incorporated high on the shore provide refuge from desiccation and predators may only facilitate the survival of a small number of species that can live higher in the intertidal. Conversely, conditions lower down in the intertidal or shallow subtidal may be sufficiently benign that a greater proportion of space is occupied irrespective of manipulations. There appears to be a trade-off between tidal height and maximum benefit of manipulations, but it is not yet known which tidal height yields the most pronounced results.

Sandbanks coastal defence scheme in Dorset is located at the low tidal level with much of the structures covered by seawater even on a low spring tide. The base of these structures is coved with algae, sponges and other encrusting species.



Elmer coastal defence scheme in West Sussex is located at the mid tidal level and supports very few species on the emergent rock habitat, even at the base of the structure

Exposure to wave action can have a significant effect on the colonizing community

Structures that comprise both exposed and sheltered components are likely to provide a greater diversity of exposure regimes and therefore habitats for a wider range of species with differing environmental tolerances.

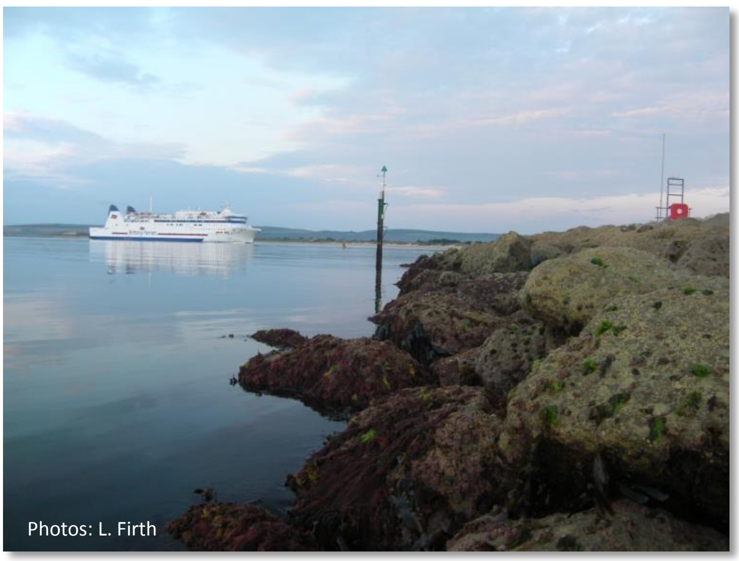
Both of these images are taken of the same structure on the same day. The top image is the seaward side of the structure and the bottom picture is the landward side of the structure.

Note the paucity of algae on the seaward side compared to the landward side.

Jonsson PR, Granhag L, Moschella PS, Åberg P, Hawkins SJ, Thompson RC (2006) Interactions between wave action and grazing control the distribution of intertidal macroalgae. Ecology 87:1169-1178

Proximity to a source of invasive species can have a significant effect on the colonizing community

Artificial structures have the potential to support greater numbers of invasive species than natural habitats as they are often constructed in highly disturbed environments that favour the establishment of opportunistic species. When multiple artificial structures are built relatively close to one another, along stretches of coast comprising predominantly soft sediments, these structures can sometimes function as pathways or stepping stones, facilitating the spread and connectivity of both native and non-native marine species.



Photos: L. Firth

Poole Harbour is an international ferry port with services to northern France and the Channel Islands. Poole Harbour has been the site of introduction for a number of non-native species in the past.

A network of artificial structures are constructed immediately outside the mouth of the harbour. The portions of these structures that remain submerged support a wide range of invasive species.

Undaria pinnatifida

Sargassum muticum

Crassostrea gigas

Crepidula fornicata

Routine maintenance of structures can have a significant effect on the colonizing community

Coastal structures are vulnerable to scouring, undermining, outflanking, overtopping, and battering by storm waves. Thus, there is an ongoing need for repair and maintenance during the lifetime of the structure. A study in the Mediterranean found that maintenance caused a marked decrease in the cover of dominant space occupiers, such as mussels and oysters, and a significant increase in opportunistic and invasive forms, such as biofilm and macroalgae. It is important to consider the level of maintenance works that may be required at a given site before manipulations are undertaken, in order to assess if they are worth while, or whether the level of maintenance will mask the effects of the manipulations.


Photo: L. Airoldi

View of a breakwater under maintenance at Cesenatico, along the Italian shores of the north Adriatic Sea.

Airoldi L, Bulleri F (2011) Anthropogenic Disturbance Can Determine the Magnitude of Opportunistic Species Responses on Marine Urban Infrastructures. PLoS ONE 6(8): e22985.

How can coastal managers influence the diversity of colonizing epibiota?

Vertical position in the intertidal zone, surface roughness, habitat heterogeneity (including water-retaining features) are important factors determining the diversity of colonizing epibiota on artificial structures. Many of these factors can be taken into account at the construction phase by locating the actual structure lower in the intertidal zone (if possible), choosing a suitable rock type and boulders with surface complexity. Boulders can be placed together, such that they retain water at the base. If a boulder has a natural depression, it can be placed with depression-side up, thus creating a water-retaining feature.

If it is not possible to consider some of these factors at the construction phase, artificial enhancements can be retro-fitted, after construction as discussed in the examples given in this document.