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Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures

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ABSTRACT

Coastal defence structures are proliferating as a result of rising sea levels and stormier seas. With the realisation that most coastal infrastructure cannot be lost or removed, research is required into ways that coastal defence structures can be built to meet engineering requirements, whilst also providing relevant ecosystem services—so-called ecological engineering. This approach requires an understanding of the types of assemblages and their functional roles that are desirable and feasible in these novel ecosystems. We review the major impacts coastal defence structures have on surrounding environments and recent experiments informing building coastal defences in a more ecologically sustainable manner. We summarise research carried out during the THESEUS project (2009–2014) which optimised the design of coastal defence structures with the aim to conserve or restore native species diversity. Native biodiversity could be manipulated on defence structures through various interventions: we created artificial rock pools, pits and crevices on breakwaters; we deployed a precast habitat enhancement unit in a coastal defence scheme; we tested the use of a mixture of stone sizes in gabion baskets; and we gardened native habitat-forming species, such as threatened canopy-forming algae on coastal defence structures. Finally, we outline guidelines and recommendations to provide multiple ecosystem services while maintaining engineering efficacy. This work demonstrated that simple enhancement methods can be cost-effective measures to manage local biodiversity. Care is required, however, in the wholesale implementation of these recommendations without full consideration of the desired effects and overall management goals.

1. Introduction: the problem and current knowledge

In recent years there has been much interest in ecologically sensitive design of coastal defence structures. This is in response to the growing realisation that rising sea levels and stormier seas (IPCC, 2007; Jackson and McIlvenny, 2011; Wang et al., 2012) will prompt proliferation of such structures (Dugan et al., 2011; Firth and Hawkins, 2011) where managed retreat or re-alignment is not an option because important infrastructure, industrial activities and residential property require protection. In this paper we review recent advances in this field since the DELOS project (www.delos.unibo.it) special issue of Coastal Engineering was published in 2005 (e.g. Airoldi et al., 2005; Martin et al., 2005; Moschella et al., 2005; Zanuttigh et al., 2005; see also Burcharth et al., 2007). We synthesise this work and integrate it with our own recent experimental and demonstration studies undertaken in the context of the THESEUS project (www.theseusproject.eu). In response to climate change related sea level rises, the THESEUS project (2009–2014), building on DELOS, examined the application of innovative adaptational technologies to enable safer development and use of the coast whilst ensuring the health of coastal habitats and continued delivery of their ecosystem goods and services. The primary

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objective was to provide an integrated methodology for planning sustainable defence strategies for the management of coastal erosion and flooding by integrating engineering, social, economic and environmental knowledge and practice.

There is a growing consensus that artificial systems are different to natural systems (Bulleri and Chapman, 2004; Chapman and Bulleri, 2003; Firth et al., 2013a; Gacia et al., 2007; Glasby, 1999; Glasby and Connell, 1999; Pister, 2009; Vaselli et al., 2008). The reduced environmental heterogeneity of artificial environments is thought to be one factor explaining the lower epibiotic diversity on artificial structures (Moschella et al., 2005). On a micro-scale (<1 cm), the geological origin of building materials and hence their composition and surface roughness has a significant effect on the structure and functioning of the colonising assemblages (Coombes et al., 2011; Green et al., 2012), whilst at small (<10 cm) to medium scales (1–10 m), crevices, pits and rock pools provide important refuges for many species (Bracewell et al., 2012; Cartwright and Williams, 2012; Chapman and Johnson, 1990; Firth and Crowe, 2008, 2010; Firth and Williams, 2009; Firth et al., 2009; Goss-Custard et al., 1979; Johnson et al., 1998; Skov et al., 2011). The artificial surfaces of most coastal defences lack many of these microhabitats that can be found on natural rocky shores (Firth et al., 2013a,b); thus many species that use these microhabitats are absent from seawalls (Chapman, 2003). Furthermore, when the material used to create the structure is different from that of the natural habitat, species settlement and survival will differ and may be reduced (Davis et al., 2002; Moreira et al., 2006; Coombes et al., 2011; Green et al., 2012). Also, artificial structures are usually characterised by unnaturally high levels of both natural (e.g. storms, sediment scour) and anthropogenic disturbance (e.g. harvesting, trampling, maintenance works). This often results in poor habitat quality and the dominance of opportunistic and invasive species (Airoldi and Bulleri, 2011; Airoldi et al., 2005; Bracewell et al., 2012, 2013; Bulleri and Airoldi, 2005; Bulleri et al., 2006; Firth et al., 2011). Furthermore, in areas where natural shores are gently-sloping, the steeper or vertical surfaces of most types of structure provide a much smaller extent of intertidal habitat, reducing the transition from low to high water from 10s of metres to only a few metres (Chapman, 2003). The number of species will reduce as an inevitable consequence of species–area relationships. When the resident species are more suited to living on gentle slopes, they may not be able to survive on vertical surfaces, especially where wave-action is high. Steeper intertidal slopes may therefore reduce habitat quality in addition to available area, resulting in differences in the composition of the associated communities (Glasby, 2000; Knott et al., 2004; Virgilio et al., 2006; Vaselli et al., 2008). Finally, the construction of artificial structures can alter connectivity of local populations by fragmentation (Goodsell et al., 2007, 2009) or providing stepping-stones, thereby having impacts at a landscape scale.

The above-mentioned differences between artificial and natural rocky shores result in pronounced differences in biological factors such as settlement and recruitment (Bulleri, 2005), competition and predation (Iveša et al., 2010; Marzinelli et al., 2011). Grazing pressure also seems to be consistently higher on artificial than on natural substrates (Ferrario, 2013; Perkol-Finkel et al., 2012). The colonising epibiota (e.g. fucoids, mussels, sabellariid worms) can provide biogenic habitat for small mobile invertebrates, facilitating biodiversity by increasing complexity and heterogeneity of primary substrata (Thompson et al., 1996). Complexity encompasses the absolute abundance of individual structural components that are distinct physical elements of a habitat, per unit area or per unit volume, and heterogeneity encompasses variation in habitat structure attributable to variation in the relative abundance of different structural components (McCoy and Bell, 1991). To date, little research has been carried out investigating the differential importance of biogenic habitats in artificial and natural environments.

The ecological value of shorelines which have been altered to create new hard substrata therefore appears to be lower and the expansion of artificial structures can even lead to genetic diversity loss at regional scales, even if the underlying mechanisms are not yet fully clear (Fauvelot et al., 2009, 2012). Below, we outline simple measures that are intended to redress these differences synthesizing cumulative collective expertise, past research and new studies.

Ecological engineering is a relatively new concept which integrates ecological, economic and social needs into the design of man-made ecosystems. Several studies have shown the effectiveness of simple ecological engineering methods that result in the enhancement of native biodiversity on artificial structures (see Firth et al., 2013a for more details). Habitats of varying complexity (surface roughness, grooves and pits) and configuration (vertical/horizontal) can be easily deployed at different tidal levels (low, mid, high) to the blocks on breakwaters (Borsje et al., 2011; Thompson et al. illustrated in appendix A of Witt et al., 2012). Slabs at lower tidal heights and with greater surface complexity were found to support higher biodiversity (Borsje et al., 2011). Artificial rock pools are easily created in newly constructed seawalls by omitting large sandstone blocks (Chapman and Blockley, 2009) or by fitting habitat enhancement units (custom-made flowerpots) retrospectively to existing seawalls (Browne and Chapman, 2011). These approaches rely on the general consideration that greater habitat complexity leads to greater species richness. The modification of artificial environments can also be implemented to sustain species of conservation or commercial importance. For example, the addition of pits into seawalls resulted in an increase in the commercially exploited limpet *Patella candei*, due to higher microhabitat complexity (Martins et al., 2010). More detail on the various ecological engineering methods can be found in a recent review by Firth et al. (2013a).

In this paper we summarise recent experimental work carried out during the THESEUS project in which we: i) tested the effectiveness of simple physical interventions such as the creation of pits, crevices and rock pools on the colonising biota; ii) present demonstration projects of a prototype habitat enhancement unit ("BIOBLOCK") that can be prefabricated and deployed during construction of coastal defence structures or retrospectively post-construction; iii) describe experimental studies to develop techniques to 'garden' native canopy-forming algae of high ecological and conservation value on coastal defence structures; iv) summarise the costs of these interventions; and finally v) outline simple guidelines for achieving particular management goals. We emphasise throughout the need to formulate clear management aims and anticipated outcomes at the design stage of any structure.

2. Physical interventions

2.1. Experimental physical manipulation of the substratum

2.1.1. The creation of artificial rock pools on Tywyn Breakwater, Wales

The construction of a new detached breakwater on the beach at Tywyn, Wales (52°34′N, 04°05′ W) was completed in 2010. In August 2011 artificial rock pools of two different depths were created on the boulders around the base of the new breakwater (Fig. S1a). The purpose of the artificial pools was to provide novel habitat that would not normally be present on the boulders of the breakwater. It was hypothesised that the pools would become colonised by a number of species that were not found on the surrounding boulders. Eighteen artificial pools were created in the horizontal surfaces of the granite boulders using a diamond-tipped drill corer (Fig. S1a), randomly assigned to two treatments (deep and shallow) with nine replicates of each treatment. Deep and shallow pools measured 12 cm and 5 cm deep respectively and 15 cm in diameter. Permanent horizontal and vertical plots of comparable area to the surfaces of the drilled pools were marked on open freely draining rock with drilled holes on the adjacent boulders. In March 2012, all experimental surfaces (emergent rock and pools) were scraped clear and burnt with a flame gun to ensure that substrata were devoid of epibiota (including biofilm).

All colonising animals and algae were identified and counted monthly in the pools and on the adjacent emergent substrata plots for ten months. Due to differences in surface area between deep (742 cm^2) and shallow