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Naylor, MacArthur, Hampshire *et al.*
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Rock armour for birds and their prey: ecological enhancement of coastal engineering

Larissa A. Naylor
Lecturer, University of Glasgow, Glasgow, UK (corresponding author: larissa.naylor@glasgow.ac.uk)

Mairi MacArthur
Doctoral Research Student, University of Glasgow, Glasgow, UK

Stephanie Hampshire
Coastal Scientist, Mott MacDonald, Croydon, UK; currently at C2MH, Swindon, UK

Kieran Bostock
Principal Engineer, Hartlepool Borough Council, Hartlepool, UK

Martin A. Coombes
Lecturer, University of Oxford, Oxford, UK

Jim D. Hansom
Reader, University of Glasgow, Glasgow, UK

Rowan Byrne
Principal Marine Environmental Scientist, Mott MacDonald, Cambridge, UK

Tristan Folland
Senior Ecologist, Mott MacDonald, Cambridge, UK; currently at NIRAS Consulting Ltd, Cambridge, UK

The authors present key design, construction and ecological enhancement criteria for sustainable coastal defence structures at Hartlepool, UK, a high-energy wave climate. Such 'ecologically favourable' coastal defences fulfil the habitats directive and key engineering and cost criteria. Bird, rocky intertidal ecological and biogeomorphological data underpin recommendations for 'passive' enhancement mitigation to maximise ecological potential involving rock armour material choice (partially enhanced) and its smart positioning (enhanced). Within 12–18 months of installation, key intertidal species (e.g. limpets, barnacles, fucoid seaweeds) had successfully colonised the rock revetment, matching the initial baseline biotope. However, species abundance and overall mobile and sessile species were not significantly different between the two enhanced treatments after 12–18 months. Importantly, key prey species (the limpet, *Patella vulgata*) on enhanced rock armour showed statistically significant abundances similar to the baseline shore platform and significantly higher than partially enhanced rock armour. These preliminary data show that well-chosen rock armour material and boulder enhancement using positioning can match baseline biotope conditions in 12–18 months and that for some key prey species, positioning-enhanced rock armour rapidly matches baseline conditions. This facilitates rapid rock revetment colonisation, enabling good recruitment of food species and favourable conditions for internationally designated waterbird species.

1. Introduction

Increasing storminess, sea levels and coastal urbanisation is fuelling demand for hard defence infrastructure such as seawalls and revetments. Such structures must withstand harsh environmental conditions (e.g. storm waves and deteriorative salts) and typically require expensive, on-going maintenance. In parallel, there is a growing requirement from the government for grey infrastructure, including coastal defences, to be multi-functional, sustainable, resilient and to work with nature to provide ecosystem services (EA, 2012). However, urbanised coastlines often have lower biodiversity value than equivalent natural habitats and remain some of the least-studied ecosystems worldwide (Bulleri and Chapman, 2010).

A growing body of ecological and geomorphological research demonstrates that hard coastal infrastructure can be inexpensively designed to sustain greater biodiversity (e.g. Coombes *et al.*, 2015; EA, 2008; Firth *et al.*, 2014; Strain *et al.*, 2017). These 'ecological enhancements' improve structural engineering through the selection of ecologically favourable materials and/or niche habitat designs, yet also satisfy engineering performance requirements. Research worldwide shows the operational applications of these techniques to be successful – that is, the ecological goals of 'environmental friendly' structural engineering have been met without reduction in the protection capability of schemes. Yet, the adoption of these approaches into mainstream engineering practice remains limited to a handful of examples across Europe (Devon, Isle of Wight, the Mediterranean), in North America (Seattle, New York, Vancouver) and Australia (Sydney) (for a review, see Naylor *et al.* (2011)).

There also remains a need for best practice case studies and guidance on how assets that need to remain 'grey' for their primary function can be 'greened' (Naylor *et al.*, unpublished report, 2016). Such greening of hard maritime infrastructure (e.g. outfall pipes, ports, harbours, bridge footings) and estuarine and coastal protection structures are typically missing from green infrastructure policy and guidance. Similarly, the existing guidance for working with natural processes (also called nature-based solutions) typically focuses on soft materials such

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as sandscaping, the use of dredged material, saltmarsh creation and managed realignment (e.g. EA, 2012). Apart from Naylor *et al.* (2011), the government guidance on improving the ecological value of hard coastal infrastructure is scarce.

2. Aims

This paper reports the first known ecological enhancements of hard coastal structures in the UK that provide mitigation under the EU habitats directive (EC, 1992), to ensure that there are no adverse effects on the integrity of a Natura 2000 site designated for its internationally important waterbirds. The UK government's implementation of article 6(3) of the habitats directive to use habitat creation as mitigation within the Natura 2000 site, as in this project, may not be strictly compatible with the directive (see case C521/12 *Briels* v. *Minster of Infrastructuur en Milieu*). Nevertheless, this project aimed to mitigate the expected habitat and natural substrate loss associated with improving the standard of both new and pre-existing coastal defences within the Natura 2000 site. This mitigation also sought to minimise future habitat losses due to the sea-level rise and coastal squeeze.

To date, it is also the largest known operational ecological enhancement of hard coastal infrastructures in the UK (after Shaldon, Devon, Isle of Wight and Bournemouth) (Arc Consulting, 2016; Naylor *et al.*, 2012) and as such it provides an important 'proof of concept' demonstration of how ecological enhancement research and innovation has been operationalised in the UK (e.g. Coombes *et al.*, 2015; Evans *et al.*, 2016; Firth *et al.*, 2015; Naylor *et al.*, 2012).

The authors provide an appraisal of the rationale, approval process, design criteria and building phase considerations related to meeting the habitat mitigation requirements of the Hartlepool headland coastal protection scheme (the scheme) in Hartlepool, Teesside, UK. Currently under construction, the long-term (>1·5 years) colonisation patterns are not yet available but pre- and post-construction ecological data are available from the areas of rock revetment that have been installed to date. The authors highlight the lessons learned and discuss the wider application of such intervention.

3. Legislative imperatives for ecological enhancement

The headland foreshore coastal defence scheme at Hartlepool is within the Teesmouth and Cleveland Coast Natura 2000 site, designated under the EU birds directive (Council of the European Union, 1979) as a special protected area (SPA) for internationally important numbers of waterbirds (JNCC, 2016). Also designated for waterbirds under the Convention on Wetlands of International Importance (Ramsar convention), it is a Ramsar site (JNCC, 2008) and a site of special scientific interest (Natural England, 1997). Overwintering bird patterns along the Durham coastline show that the area impacted by this scheme represents some of the most important feeding sites for designated species (Cadwallender and Cadwallender, 2013), an environment also under threat from coastal squeeze under a 'hold the line' policy (Natural England, 2014). If intertidal invertebrate species on which the birds feed cannot adapt and migrate inland with future sea-level rise, then the locally available habitat they depend on will be reduced and/or lost in the future (Jackson and McIlvenny, 2011). This will impact negatively on the condition status of the qualifying features and consequently adversely affect site integrity. In England and Wales, the Conservation of Habitats and Species Regulations 2010 (as amended) (the 'Habitat Regulations'), article 6(3) of the EU habitats directive, requires that a project 'design appropriate mitigation measures that will cancel or minimise the adverse impacts' (EC, 2002). The scheme, within the Natura 2000 site, therefore had to consider the design implications of direct and indirect habitat loss on the qualifying features, alone and in combination with the climate change-related sea-level rise.

The approval process from the nature conservation body Natural England required any proposed mitigation to be signed off at the planning permission stage (the final design did not need the Natural England official sign off). The Natural England approved mitigation formed part of the approved planning permission for the scheme and as such was a delivery requirement. Any changes to the proposed design and/or mitigation plans would require a variation to the planning conditions, trigger a re-consultation with Natural England and objections if the scheme was not able to deliver the original mitigation.

4. Site description

The headland coastal defences at Hartlepool protect 562 residential and commercial properties, and key heritage features, including the Heugh gun battery scheduled monument (Figure 1). The defences consist of north-east facing vertical masonry and concrete walls, built over the last 150 years, and now in poor condition, being frequently overtopped during storms (e.g. significant damage during the winter 2013/2014 storms (Thorne, 2014)). Funded by way of the Project for Accelerated Growth Scheme, funding partners include the Environment Agency, Hartlepool Borough Council and PD Ports, with support from Natural England for ecological enhancement 'proof of concept'. The current defences are fronted predominately by a magnesian limestone intertidal shore platform, with limited areas overlain by perched beach deposits. The upper shore zone (0–10 m from the seawall) also displays considerable evidence of active abrasion with a reduced ecology (Naylor *et al.*, 2014).

The scheme aimed to upgrade the defences and 'hold the line' in accordance with the local shoreline management plan

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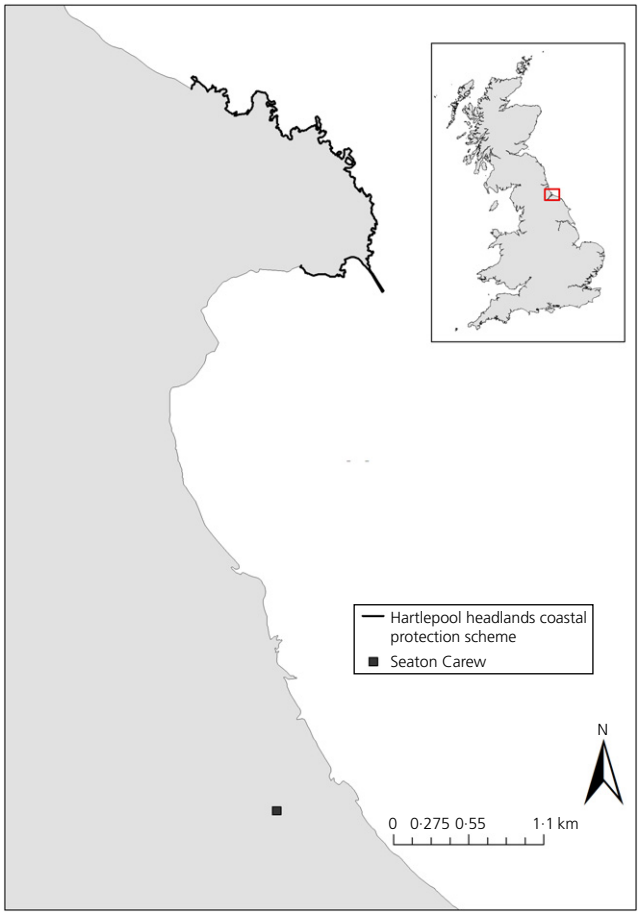

Figure 1. Study area location map including the comparison site Seaton Carew

(SMP) (Royal Haskoning, 2007). The SMP highlights the challenges of maintaining ecological conditions while adopting a hold the line policy: 'The SMP supports the natural development of this SPA and Ramsar designated coastal habitat. However, holding the line at Hartlepool Headland may result in the loss of habitat due to the provision of enhanced toe protection over the littoral rock sub-feature' and there is 'currently a danger of short-term coastal squeeze and subsequent net losses of SPA and Ramsar designated foreshore habitat' (Royal Haskoning, 2007: pp. 168 and 167). Public consultation on allowing part of the proposed area to naturally erode met with opposition; therefore, the decision to 'hold the line' required more focus on habitat mitigation than would be required with an adaptational policy decision, such as managed realignment.

4.1 Coastal defence scheme

The scheme aimed to provide: 'a coastal protection Scheme to reduce coastal erosion risk to the community and increase amenity value of the frontage over the next 100 years' (MM, 2012: p. 7). Phase 1 includes 800 m of low-level granite rock revetment to dissipate wave energy and protect the toe of deteriorated sections of existing seawall (Figure 2) and prevent damage to foundations. However, the scheme also aimed to 'provide the same ecological function for overwintering birds and as such there will be no overall loss of habitat function for Annex II bird species' (MM, 2014: p. 36) and other species within the waterbird assemblage. Phase 1 of the revetment works has been completed and phase 2 is currently underway (autumn 2016). Overall, the scheme will take 5 years to install.

5. Planning and mitigation design approval

5.1 Planning phase

Prior to the scheme planning application, the preferred options for the wider coastal defence strategy (the plan) were subjected to a habitats regulations assessment (HRA) (MM, 2012). The HRA concluded that the strategy, including this scheme, would not adversely affect the integrity of the Natura 2000 site if: (*a*) the shore platform height was enhanced to maintain its extent; (*b*) the rock revetment was placed on the shore platform to increase its elevation and allow potential habitat for birds to be exposed during the tide, accounting for a projected sea-level rise; (*c*) disturbance of qualifying features during construction is avoided; and (*d*) reflective wave energy dissipation is minimised by the placement of rock blocks. Building on the conclusions of the strategic HRA, an HRA specifically for the scheme was undertaken to support the planning application (MM, 2012). Hartlepool Borough Council and Mott MacDonald sought expert advice on the ecological enhancement design (Naylor *et al.*, 2014); this was instrumental in agreeing ecologically favourable design options with Natural England and thus securing planning approval for the scheme.

5.2 Ecological enhancement design criteria

5.2.1 Key design parameters

Previous research indicates that ecological enhancements can be designed to support the assemblages of marine invertebrates on which waterbirds might feed (Coombes *et al.*, 2015; Evans *et al.*, 2016; Firth *et al.*, 2014, 2015). These can be quite simple and inexpensive 'passive' techniques (e.g. choosing construction materials based on lithology and surface roughness (Coombes *et al.*, 2010, 2015)), or more 'active' multi-scale enhancements that seek to better mimic the geomorphological heterogeneity of natural rocky shores (e.g. Evans *et al.*, 2016). This can include rock and concrete blocks with fine-scale millimetre to centimetre textures, incorporation of sheltered and overhanging areas and in-built water-retaining features such as pools. To achieve a habitat outcome most closely mimicking the existing rocky shores at Hartlepool, and which offers feeding opportunities as the qualifying waterbird features, a combination of passive and active multi-scale enhancement

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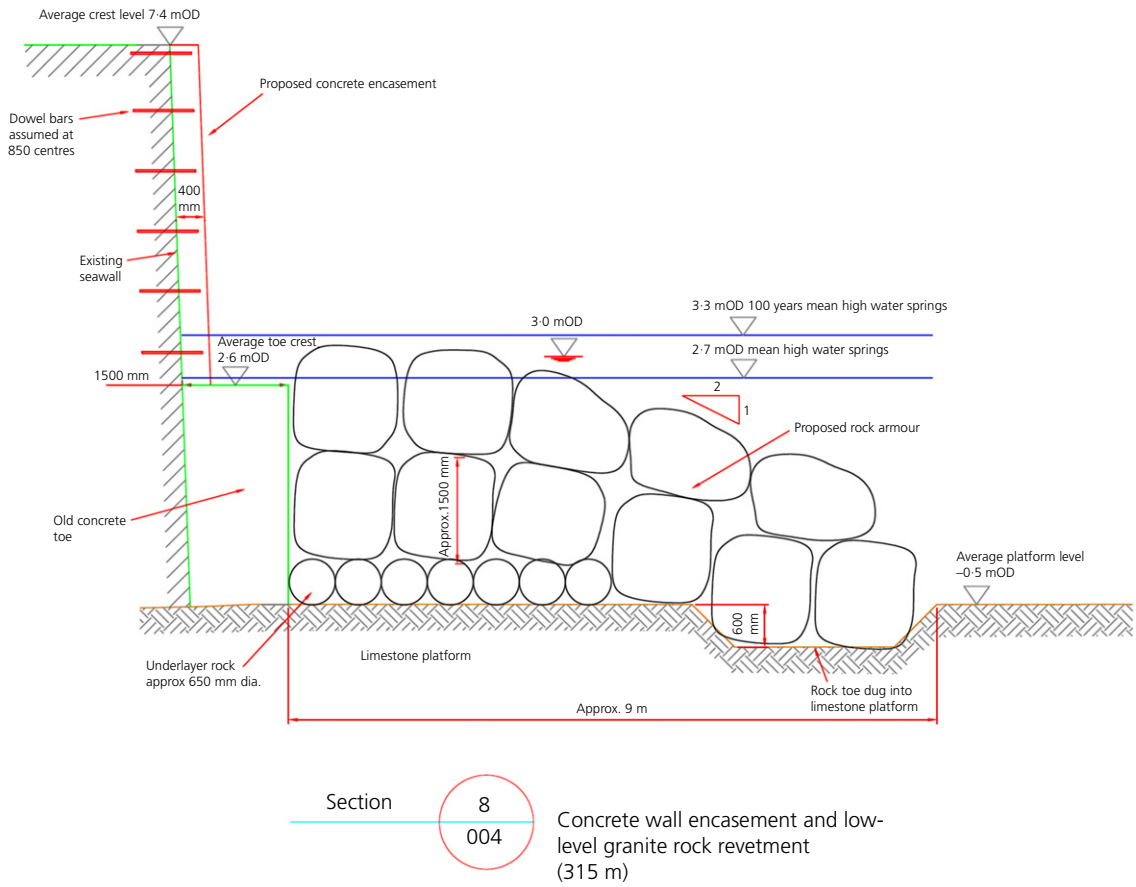

Figure 2. Schematic diagram depicting the encased seawall and rock revetment design used for the Hartlepool Headlands area of the scheme

was considered. The design needed to be cost-effective and use structurally acceptable engineering materials; these engineering and cost constraints favoured passive enhancement over active enhancement for the rock revetment. However, it resulted in granite being used instead of the more ecologically preferable (but expensive) local limestone. Recommendations also influenced the design of a proposed concrete step revetment and concrete wall casing to optimise post-construction colonisation (Naylor *et al.*, 2014; Perkol-Finkel and Sella, 2015). The contractors used Reckli formliners (Yukon design) for the concrete wall casing to mimic natural rock and provide enhanced texture (up to 27 mm deep) and improve the structural complexity of the wall, compared with plain cast concrete. The encased wall and rock revetment is currently under construction, while the stepped revetment is part of a later phase of construction. This paper reports solely on the rock revetment element of the scheme currently being deployed (during construction years 1–3) (Figures 1 and 4). Details of the recommended rock revetment mitigation are provided in Sections 5.2.4 and 6.

5.2.2 Baseline ecological surveys

Prior to any enhancement recommendations, a series of baseline ecological assessments included: 14 repeated bird surveys by Hartlepool Borough Council; a JNCC phase 1 habitat survey by Mott MacDonald of the existing defences and foreshore; and a phase 1 habitat survey by Mott MacDonald of a comparable, recent (2002) rock revetment scheme ~2 km from the current scheme. These surveys helped to develop an understanding of how bird species used the intertidal habitat likely to be affected by the scheme (Table 1) and informed both the engineering design recommendations (Naylor *et al.*, 2014) and the ecological mitigation required by the HRA (MM, 2012).

5.2.2.1 BASELINE BIRD SURVEYS

The scheme area has international designations for internationally important bird species and the habitat (including food sources) that supports them (Table 2). Rocky shore habitats typically provide refuge and overwintering sites for these bird species (Cadwallender and Cadwallender, 2013;

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Table 1. Summary of baseline habitat mitigation data needs, data collection methods and key findings

Question	Data collected	Key findings
Which parts of the foreshore do birds use most and for what purpose (e.g. foraging, roosting)?	■ Fourteen repeat winter bird surveys between November 2010 and January 2014 ■ Bird species counts and use (e.g. foraging, roosting) maps	■ Birds preferentially used the lower intertidal zone ■ Oystercatchers were more prevalent higher up the shore than other species
Which of the key food species for waterbirds are present and where on the shore are they located?	■ Phase 1 habitat mapping (February 2014)	■ More species of key food for birds (e.g. mussel spat) are found lower on the shore ■ Higher on the shore, the number of species providing food for waterbirds decreases, although some molluscs, isopods and gastropods are found on the shore platform
Is the ecology of rock armour[a] comparable to the current shore platform biotopes found in the wider scheme area?	■ Phase 1 habitat mapping (February 2014)	■ Similar biotopes were found on the rock armour at Seaton Carew and the natural rocky shore in the upper intertidal zone of the scheme area

[a]Placed nearby in the upper intertidal zone

Table 2. Summary of internationally important bird species and their key rocky intertidal prey species (after Cramp *et al*., 2004; Rehfisch *et al*., 1993)

	Key rocky intertidal prey species		
Bird species	Molluscs	Crustaceans	Other
Oystercatcher (*Haematopus ostralegus*)	Bivalves (especially mussels *Mytilus edulis*), limpets (*Patella vulgata*)		
Redshank (*Tringa totanus*)	Periwinkles (*Littorina* spp.),		
Turnstone (*Arenaria interpres*)	Periwinkles (*Littorina* spp.), mussels (*Mytilus edulis*)	Crabs (*Carcinus maenas*), barnacles	
Red knot (*Calidris canutus*)	Periwinkles (*Littorina* spp.), mussels (*Mytilus edulis*)	Crabs (*Carcinus maenas*), barnacles	Green seaweed (*Ulva* spp.)
Purple sandpiper (*Calidris maritima*)	Molluscs (especially *Littorina* spp.)	Some crustaceans	
Curlew (*Numenius arquata*)	Mussels (*Mytilus edulis*)	Crabs (*Carcinus maenas*)	
Ringed Plover (*Charadrius hiaticula*)	Molluscs (*Littorina* spp.)		
Sanderling (*Calidris alba*)	Dead storm-damaged molluscs (*Mytilus edulis*)	Crabs (*Carcinus maenas*)	
Dunlin (*Calidris alpina*)			

Rehfisch *et al*., 1993). Fourteen repeat winter intertidal bird surveys were carried out between 2010 and 2014 to determine the number of species, number of individuals and bird usage (e.g. foraging or roosting) across all areas of the proposed scheme.

The results show the highest density of individuals across the entire intertidal zone surveyed (Figure 3) are for oystercatchers, redshanks, turnstones and knots, and these also have a much higher abundance in the upper intertidal zones most affected by the scheme. Purple sandpipers were found in low numbers across all the shore zones sampled, and bird species abundance increased with distance from the seawall (nine taxa occurred beyond 20 m from the seawall, compared with four taxa at 0–10 m). These results are supported by the bird usage data summary map (Figure 4) showing feeding and roosting activities taking place seaward of the zone directly impacted by the scheme (0–10 m) and the 10–20 m buffer zone.

5.2.2.2 PHASE I HABITAT SURVEYS: WHICH OF THE KEY FOOD SPECIES FOR WATERBIRDS ARE PRESENT AND WHERE ON THE SHORE ARE THEY LOCATED?

The rocky intertidal prey species listed in Table 2 respond to passive and active ecological enhancements elsewhere in the UK (including Elmer, West Sussex and Lyme Regis, Dorset (Moschella *et al*., 2005); Colwyn Bay and Penthyn Bay (Firth *et al*., 2014); Porthleven and Zennor (Coombes *et al*., 2015)). Baseline ecological surveys were undertaken to identify key species and their location relative to the proposed footprint of the scheme. Surveys involved a combination of desk-based

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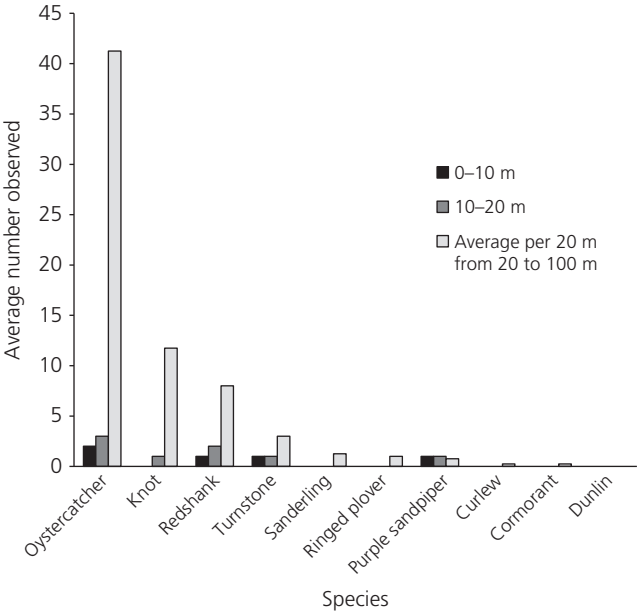

Figure 3. Average bird species count across the proposed scheme footprint (0–10 m), the adjacent 10–20 m likely to be impacted during construction and an average 20 m width value for the remaining mid-to-lower intertidal areas surveyed

analysis of previous surveys (2003, 2010 by BMT Cordah) and new baseline phase I habitat mapping surveys conducted by Mott MacDonald in January–February 2014.

Established phase I mapping protocols were followed (Wyn, 2000) and rocky shore ecology communities were mapped and their biotopes assessed as feeding resources for waterbirds. Fourteen systematic-random selected transects were surveyed at ~500 m spacing along the shore platform, four in Block Sands and ten in North Headland areas, and the biotopes present were mapped over 20 m intervals up to 100 m across the intertidal zone. The presence of key rocky intertidal species (Table 2) as possible prey sources was also recorded along each transect. Transects were geo-referenced to facilitate future re-survey work and, where possible, transects were positioned to overlap with previous surveys by BMT Cordah in 2003 and 2010. The 2014 data are presented here.

Across the intertidal zone, species assemblages known to provide food for overwintering bird species were found, including mussel spat, gastropods and molluscs, marine isopods and crustaceans (Cramp *et al.*, 2004; Rehfisch *et al.*, 1993). These findings are consistent with that expected for a relatively exposed, high-energy North Sea coastline and the substrate and morphological features of each transect (BMT Cordah, 2004). The whole intertidal zone supports feeding habitats for qualifying waterbirds including red knot, oystercatchers and redshanks (Figure 4).

Eleven biotopes were recorded across all transects. However, the upper intertidal (0–20 m from the seawall) zone had only one biotope across all 14 transects (ephemeral green seaweeds, LR.FLR.Eph.Ent, Connor *et al.*, 2004; Figure 5). The upper intertidal zone (0–20 m) data were consistent across the entire length of the proposed scheme, providing only limited food species for birds (e.g. barnacles, limpets and periwinkles) and containing fewer prey species of interest (e.g. marine isopods (*Jaera albifrons*), limpets (*Patella vulgata*) and periwinkles (*Littorina* spp.). The total number of biotopes supporting prey species of interest was greater lower down the shore (Figure 5) where the number of biotopes increased to 3–5 across the mid- to lower intertidal zone. This zone also had increased numbers and density of prey species for shore birds of interest (e.g. LR.MLR.MusF biotope containing substantive colonies of mussels (*Mytilus edulis*) and mussel spat).

Food availability was more prevalent in the lower intertidal zone where birds have been documented more often (Figure 4) suggesting that birds favour the lower intertidal zone, probably due to food availability, open sightlines and less disturbance than near the seawall (Cadwallender and Cadwallender, 2013).

5.2.3 Seaton Carew defences comparison

To evaluate the local feasibility of colonisation of rocks at the seawall–land boundary in the upper intertidal zone, a nearby comparison with similar wave exposure and aspect was required. Seaton Carew, ~2 km from the scheme, provided the comparison of a rock revetment installed in 2002 on the upper intertidal zone at the seawall toe (Figure 1). Visited on 1 February 2014, the rock revetment rests on a red Triassic sandstone rocky shore platform and sandy beach, where fucoid seaweeds and mussels (*M. edulis*) were found. Importantly, the upper intertidal biotope (ephemeral green seaweed communities, on unstable upper eulittoral rock (FLR.Eph.Ent), Connor *et al.*, 2004) observed on the rock revetment at Seaton Carew was the same as that found on the upper intertidal shore platforms at Hartlepool (Figure 5). Foraging species were present and coastal birds (oystercatchers, *Haematopus ostralegus*) were observed interacting with the coastal protection structure during surveys conducted by the authors, suggesting that rock armour can be colonised in a similar manner to the upper intertidal zone of natural rocky shores in this area (see (MM, 2012) for more details).

5.2.4 Design goals and parameters

The mitigation sought to maintain the extent of key habitat sub-features through ecological enhancement of the proposed

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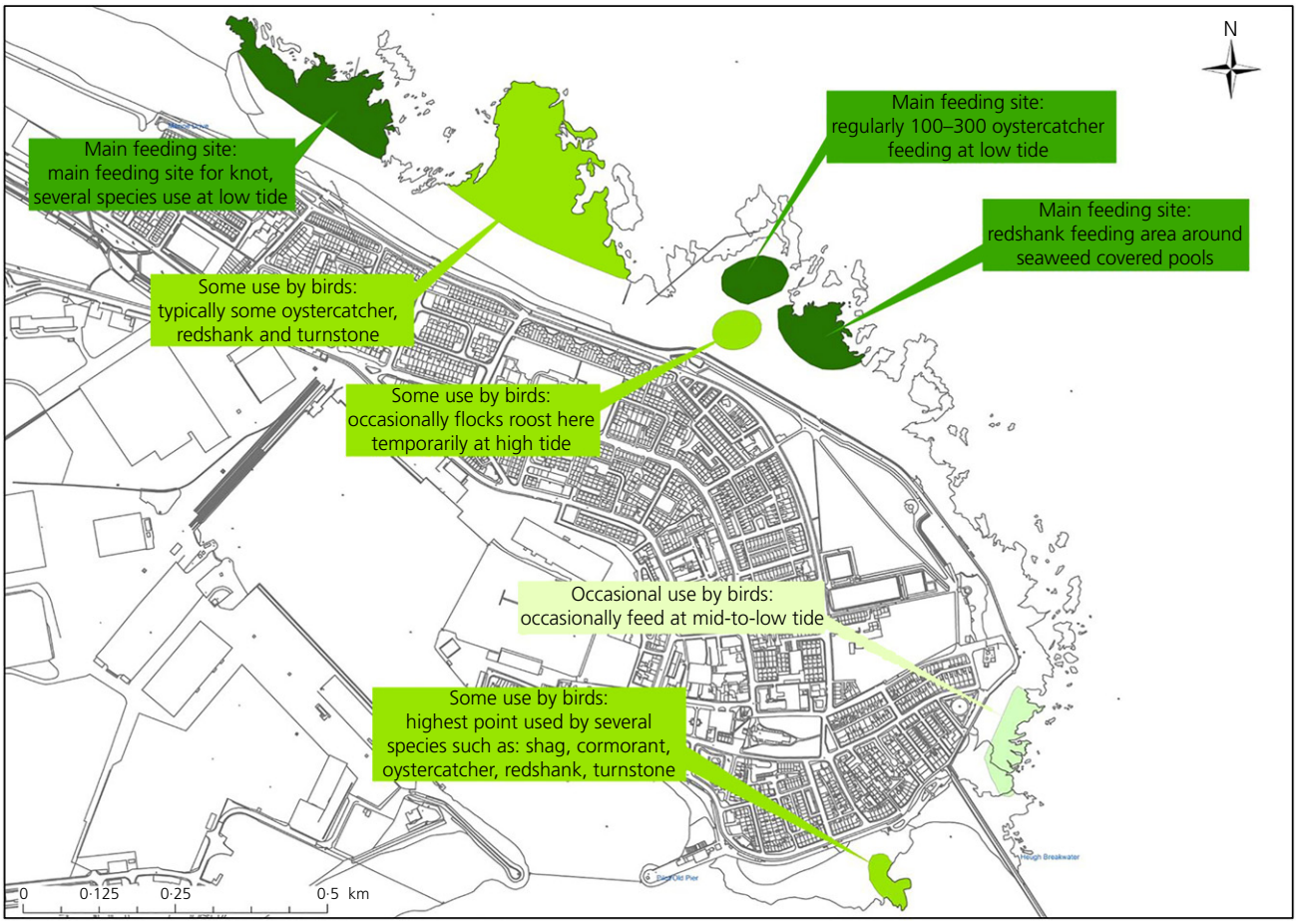

Figure 4. Bird usage map derived from 14 individual bird usage surveys between 2010 and 2014, where type (feeding or roosting), location and indicative intensity of use is classified as: main = dark green (dark grey), moderate = mid-green (medium grey) and low use = light green (light grey). Contains OS data © Crown copyright Edina Digimap subscription. A full-colour version of this figure can be found on the ICE Virtual Library (www.icevirtuallibrary.com)

structures. The aim of these enhanced habitat surfaces and characteristics was to facilitate colonisation and establishment of breeding populations of prey species favoured by SPA birds. Although 'quantitative predictions of the effects [of hard defences] on individual species and assemblages at any particular location are more difficult…' (Airoldi *et al*., 2005: p. 1075) and the ecological outcomes of any design are uncertain, the enhancement measures recommended for this scheme were informed by the best available scientific evidence.

The key engineering and ecological enhancement design recommendations for the rock revetment are summarised in Table 3 (after MM, 2012; Naylor *et al*., 2014). Ensuring mitigation did not adversely affect the primary coastal protection performance of the scheme required close communication between the Mott MacDonald design team and the lead Hartlepool Borough Council engineer.

To satisfy the mitigation requirements for Natural England, the scheme was required to provide the same ecological function for over-wintering birds and ensure no overall loss of habitat function for Annex II bird species. Pre-construction surveys (Section 5.2.2) found little evidence of roosting by overwintering birds in this area of the SPA, allowing mitigation measures to focus on ensuring that opportunities for feeding are improved where possible.

As stated in Sections 3 and 4, although the scheme fulfils the current 'hold the line' SMP policy, it does limit the capacity for intertidal species to respond to coastal squeeze by moving inland. Although ~10 m of intertidal foreshore habitat was to be lost to the rock revetment, the revetment was designed to mitigate some of this loss (Figure 2). The passively enhanced rock revetment provides a much larger habitat surface area than the existing shore platform, including large numbers of

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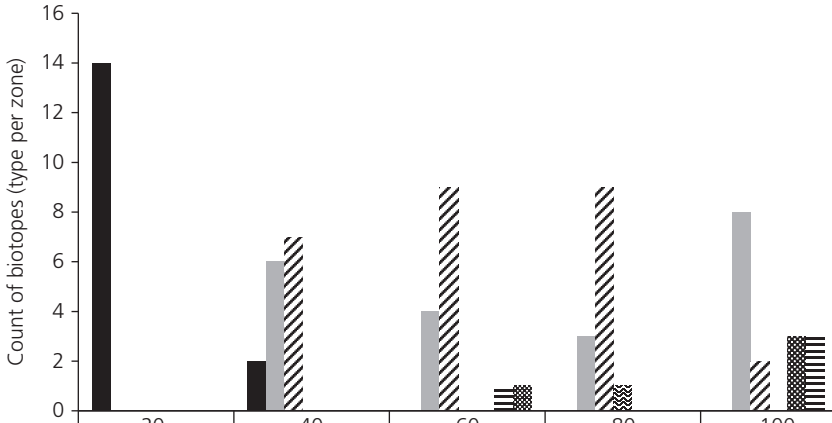

	20	40	60	80	100
FLR.Eph.Ent (2 var.)	14	2			
FLR.Rkp.Cor		6	4	3	8
LLR.F.Fves. (2 var.)		7	9	9	2
LLR.Fves/HLR.MusB				1	
MLR.MusF.MytFR					3
FLR.Rkp.FK/MLR.BF.Fser			1		3
LLR.MusF.MytFR			1		

Biotope zone in 20 m intervals (= m from current seawall)

Figure 5. Graph and table summarising the phase I intertidal biotope mapping data collected in 2014

cryptic spaces that provide important intertidal habitat for prey species (Sherrard *et al*., 2016). The revetment also increases the range of tidal elevations for species colonisation, providing physical space to allow species to adapt to sea-level rise. Without the revetment, there would be limited vertical space on the seawall and unsuitable habitat (lack of shade, water-retaining features, void spaces) for species to colonise on sea-level rise. Carboniferous limestone rock armour was added into the upper areas of the revetment to create the necessary engineering void ratio and a more ecologically favourable substrate than granite over the short term (e.g. Coombes *et al*., 2011) and long term (e.g. Plymouth breakwater). The revetment design allows additional layers of rock armour to be added on top as sea levels rise, allowing the scheme (and the species it supports) to adapt to climate change. Within a 'hold the line' policy, these design features help mitigate the risks of coastal squeeze.

6. Building phase

6.1 Ecologically sensitive construction considerations

Foreshore operations at Hartlepool required careful management given the sensitive nature of the environment (i.e. soft limestone platform supporting internationally important habitat) and working in a dynamic tidal zone with limited access (Basford *et al*., 2016). The key considerations included the engineering and biogeomorphology design criteria outlined in Table 3 as well as sensitive construction techniques on site, including timing, toe design and contractor instructions. Work on the foreshore was allowed only between April and September to minimise adverse impacts on the qualifying waterbird species, although work was permitted on the seawall from overhead during this period to help improve efficiency and reduce construction costs. To minimise the footprint of the works and ensure its durability, the rock revetment was toed into the limestone platform to stabilise the structure and ensure it met the design criteria. Intertidal limestone removed during this process was used as the core material (i.e. laid on top of the platform to aid machinery) or, where sufficiently large, added to the rock revetment.

6.2 Contractor instructions

This is the first known project worldwide aiming to employ 'passive' ecological enhancement techniques on a rock revetment and deliver a simple, cost-effective deployment methodology. However, the original detailed design criteria (Naylor *et al*., 2014) were made without consultation with contractors (who had not yet been appointed). This original design suggested interspersing areas of passively enhanced rock armour (i.e. placed and oriented to optimise the ecological

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Table 3. Outline of the recommended engineering and biogeomorphology design criteria for rock revetment element of the scheme

Design type	Detailed type	Rationale	Detailed criteria/recommendations
Engineering	Crest level of the revetment	Position crest of the revetment in the tidal zone (mean high water springs – mean high water neaps)	To maintain the extent of intertidal habitat
Engineering	Top of revetment	Allowance for sea-level rise	Designed to allow more rock to be added during the design life, if required
Engineering	Slope of revetment	Designed with a 1 in 2 slope at the seaward edge (Figure 2)	To provide transitional environmental conditions and therefore act to at least maintain baseline species richness
Biogeomorphology	Passive: specification of granite[a]	To improve ecological suitability (within available granite)	Light-coloured, coarse-grained granite with naturally topographically complex features (mm–cm scale) was preferred to optimise the potential for granite to serve as an ecologically favourable substrate
Biogeomorphology	Passive: core and void space infill material	Carboniferous limestone and intertidal magnesian limestone from construction was used	Limestone rocks have been shown to provide improved ecological suitability (e.g. Coombes *et al*., 2011) and are what the natural shore is composed of. Using limestone for the core and void space fill will aid ecological colonisation of the scheme
Biogeomorphology	Passive: rock selection	Where practical, select rocks with complex features, tooling and quarry marks	To provide greater range of topographic complexity (i.e. cm scale) to improve establishment of rocky intertidal communities
Biogeomorphology	Passive: rock positioning	To improve water-holding habitat	Position/orientation of topographically suitable features (e.g. concavities): these were placed facing upwards on the top of the structure to enable water holding to mimic rock pools while maintaining the void ratio required
Biogeomorphology	Active: modify rocks	To improve water-holding habitat	Retrofit additional holes to improve habitat provision[b]

[a]No other rock types were cost effective nor could they yield the large rock blocks needed
[b]To be carried out if preliminary ecology surveys suggest further enhancements are needed

potential of topographical complexity) with those that were deployed using conventional techniques. This required contractors to separate the rock armour based on its suitability for passive enhancement (i.e. physically complex surfaces) from unsuitable, smooth, featureless surfaces, and then alternating each load deployed. This proposal was focused on developing an optimal 'proof of concept' design to measure colonisation success. However, the contractors devised a more efficient and cost-effective method of delivering the enhancement within the timescale and working space constraints. The partially enhanced rock armour was deployed on the lower (i.e. buried) layers of the rock revetment, and the passively enhanced rock armour was placed on the top surface of the rock revetment and positioned as per Table 3. The rock revetment was thus a mixture of treatment types where the core structure comprised normal (partially enhanced) rock armour and the top surface was a combination of passively enhanced or normal (partially enhanced) rock armour (Figure 6). The top surface of a rock revetment has more challenging ecological conditions for intertidal species and is thus where the enhancement need is the greatest (Sherrard *et al*., 2016). This was further supplemented by adding limestone rock armour to the top surface, to create the required void space ratio and further optimise passive enhancement by including more ecologically favourable rock types (after Coombes *et al*., 2011).

7. Ecological colonisation of phase I of the scheme

7.1 Methods

Three different natural and artificial habitats (hereafter, treatments) were sampled along the length of the new scheme in Hartlepool: natural shore platforms (baseline); optimally selected rock revetment (based on material choice only; hereafter termed partially enhanced); and enhanced rock revetment (based on material choice plus further enhancement using smart positioning). Access and funding constraints at the design and pre-build phase, and the rapid construction of a timetable, precluded ecological monitoring of the shore platforms and walls prior to construction year 1 and most of year 2. All sampling thus occurred at the upper tidal levels (0–10 m from the seawall) in August and September 2016. Exposed shore platform surfaces, not yet covered by the new scheme or damaged by machinery, were used to collect quantitative baseline ecological data as control data for comparison with the newly installed rock revetment.

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Figure 6. Passive enhancement of rock armour compared with partially enhanced rocks. (a) Positioning of a passively enhanced rock so that depressions are face-up. (b) Water-retaining capacity of passively enhanced rock. (c) Partially enhanced rock, with smooth, featureless surface and (d) rock revetment with two passively enhanced rocks in the foreground/centre (black arrows) separated by partially enhanced rocks. The rock shown in part (a) was installed during 2015 (colonisation data included in this paper) and the rocks shown in parts (b), (c) and (d) were installed during 2016, showing differences in ecological colonisation

At each baseline plot ($n = 5$), five quadrats (25×25 cm) were randomly placed, leaving at least 50 cm between adjacent quadrats (Chapman and Bulleri, 2003; Firth *et al*., 2013; Moreira *et al*., 2006). Four quadrats (25×25 cm) were randomly sampled on enhanced and partially enhanced areas of the new rock revetment ($n = 1$ plot per treatment). Data collected consisted of visual estimates of percentage cover for sessile invertebrates and algae, and counts and life stage (adult or juvenile) of the mobile organisms within each quadrat (after Chapman and Bulleri, 2003). Quadrats were searched with plants and animals identified to species level where possible. Some stretches of shore platform habitat were relatively short (e.g. <20 m long); as such, each sampling area was between 5 and 8 m long and spaced 10 m apart (after Chapman and Bulleri, 2003, Moreira *et al*., 2006) with shore platform 3 sub-divided into wet and dry areas ($n = 5$ quadrats per type). The results from five sampling areas ($n = 25$ quadrats) on the horizontal shore platform were used as the control baseline against which the new rock revetment was compared. A preliminary survey of the newly colonised (12–18 months post-deployment) rock revetment was made, where one sampling area ($n = 4$ quadrats) was surveyed for passively enhanced and partially enhanced (traditionally deployed) surfaces. More intensive monitoring surveys will take place in autumn 2017 and 2018.

Post-construction bird surveys will assess bird use of the structure, although anecdotal evidence from engineers and contractors shows that birds are using the new revetment during the construction phase.

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7.2 Results and discussion

The presence of species and the density were first compared between the baseline and the rock revetment types (enhanced and partially enhanced), followed by a comparison of enhanced with partially enhanced areas of the rock revetment. This allowed the assessment of how the rock revetment (as a whole) compares with the baseline, and whether enhanced areas of the revetment show differences in colonisation compared with partially enhanced areas (representing conventional installation practice) of the revetment where both treatments use the most ecologically suitable granite available.

7.3 Baseline compared with rock revetment treatments

A one-way analysis of variance (Anova) of species richness on enhanced and partially enhanced rocks and shore platforms was significant, $F(2,9) = 6{\cdot}726$, $p = 0{\cdot}016$. A Student–Newman–Keuls post-hoc test indicated that the mean species richness was significantly greater for the baseline condition (natural horizontal rocky shore platforms) than for either artificial rock revetment type (enhanced and partially enhanced) 18 months after colonisation. A total of 19 taxa were recorded across the surveyed shore platform and rock revetment, with nine taxa unique to the natural shore platforms and only *Porphyra umbilicalis* unique to the rock revetment (Figure 7). Adults and juvenile animals were recorded in each treatment type, suggesting that breeding populations had successfully colonised the new rock revetment within 18 months of deployment. The lower species richness on the rock revetment indicates more time is needed to establish whether and how rapidly the rock revetment matches baseline species richness.

Species abundance was also compared between treatment types. Common limpets, *P. vulgata*, an important prey species for birds (Table 2), were recorded in the highest densities on the five shore platforms surveyed, with an average of eight individuals compared with an average of six individuals for the combined rock revetment data. In comparison, *P. vulgata* averaged 12 individuals on the enhanced rock revetment but only one on the partially enhanced rock revetment, suggesting that enhanced rock armour offers more comparable habitat quality to the natural rocky shore baseline. Paired two-tail *t*-tests also show that limpet abundance on enhanced boulders is statistically similar ($p = 0{\cdot}56$) to the shore platforms surveyed, while the partially enhanced boulders have significantly fewer ($p = 0{\cdot}04$) limpets compared with those found on the surveyed shore platforms. *P. vulgata, Anurida maritima* (seashore springtail) and *Littorina saxatilis* (periwinkle) had the next highest abundances and densities (m^2), with baseline areas outperforming the newly colonising rock revetment (Figure 8 and Table 4). However, the species density varied by the plot. For example, *A. maritima* numbers were highest on shore platform 1 (average of five individuals), shore platform 2 ($n = 10$) and the enhanced revetment ($n = 7{\cdot}5$). Similarly, *L. saxatilis* were recorded on shore platforms 1–3 and on two of the enhanced revetment quadrats, with the greatest averages per quadrat on shore platform 1 ($n = 1{\cdot}6$), wet quadrats on shore platform 3 ($n = 4{\cdot}4$) and on enhanced rock revetment quadrats ($n = 3$). In comparison, dry quadrats on shore platform 3 only averaged 0·8 per quadrat, with no individuals recorded on partially enhanced rocks, suggesting that the absence of water-retaining features is a key determinant of species density, as observed elsewhere (e.g. Evans *et al.*, 2016).

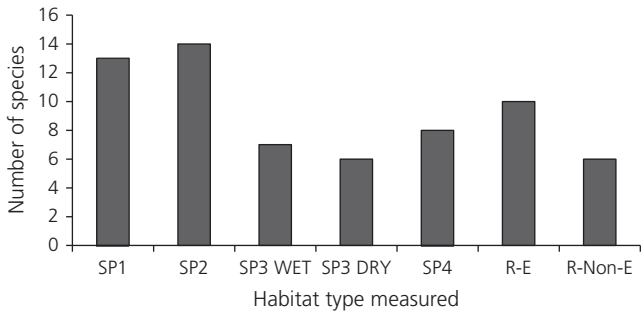

Figure 7. Species richness recorded on shore platforms (SP) and enhanced and partially enhanced boulders (R-E/R-PE, respectively)

A separate one-way Anova of mobile and sessile species abundance was performed on enhanced and partially enhanced rocks and shore platforms. The results showed that there was no difference between the three habitat types for mobile and sessile abundance after 18 months $F(2,9) = 1{\cdot}423$, $p = 0{\cdot}290$ (mobile) and $F(2,9) = 3{\cdot}100$, $p = 0{\cdot}095$ (sessile).

For individual mobile prey species, a series of one-way Anova comparisons was made between the three different habitat types. These results were significant only for *P. vulgata*, $F(2,9) = 8{\cdot}640$, $p = 0{\cdot}008$, with Student–Newman–Keuls (SNK) tests indicating that enhanced rocks were as suitable for *P. vulgata* as the shore platform. Both the natural shore platform and enhanced rocks had significantly higher limpet abundances than on partially enhanced rocks when $p = 0{\cdot}05$. At $p = 0{\cdot}01$, enhanced rocks outperformed partially enhanced rocks for limpet abundance. These results indicate that the enhanced rock revetment supports similar abundances of a key prey species, *P. vulgata*, as the baseline natural rock after 18 months and significantly higher abundance than found on the partially enhanced rocks.

Higher percentage covers of algal species were recorded in the baseline horizontal shore platforms (*Fucus vesiculosus*, *Rhodothamniella floridula*), whereas filamentous green algae were equally abundant on the rock revetment and the natural

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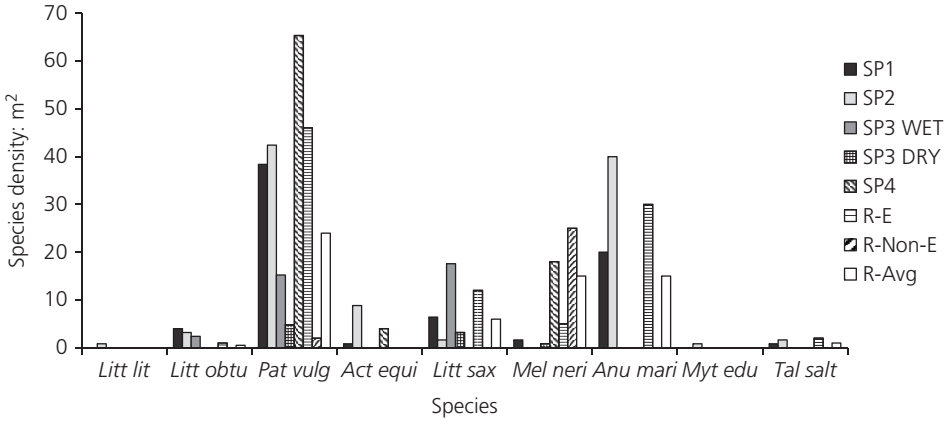

Figure 8. Species density (m^2) of motile species taken as an average from $n = 5$ quadrats on horizontal shore platforms and $n = 4$ quadrats on surveyed enhanced and partially enhanced rock armour

Table 4. Species richness and density for enhanced and partially enhanced rock armour areas surveyed

Species	Enhanced (R-E)				Partially enhanced (R-PE)				Average number of species		Density: m^2	
Rock number	R1-EA	R1-EB	R2-E	R3-E	R1-PE	R2-PE	R3-PEA	R3-PEB	R-E avg (±SE)	R-NE avg (±SE)	R-E	R-NE
Litt obtu	0	0	1	0	0	0	0	0	0·3 ± 0·3	0·0 ± 0·0	1	0
Pat vulg	12	8	11	15	1	0	1	0	11·5 ± 1·4	0·5 ± 0·3	46	2
Litt sax	0	1	0	11	0	0	0	0	3·0 ± 2·7	0·0 ± 0·0	12	0
Mel neri	5	0	0	0	17	8	0	0	1·3 ± 1·3	6·3 ± 4·0	5	25
Tal salt	0	2	0	0	0	0	0	0	0·5 ± 0·5	0·0 ± 0·0	2	0
Anu mari	0	0	30	0	0	0	0	0	7·5 ± 7·5	0·0 ± 0·0	30	0

shore platforms, with an average cover of 24·2 and 24·4%, respectively. However, *P. umbilicalis* was unique to the rock revetment and is indicative of an early succession, post-disturbance species (Imrie *et al.*, 1989).

For sessile species, a series of one-way Anova comparisons was made between the three different habitat types (enhanced and partially enhanced rocks and shore platform). Barnacle (predominately *Semibalanus balanoides*) abundance was significantly different between the three habitat areas, $F(2,9) = 26{\cdot}456$, $p = 0{\cdot}0002$. The SNK tests indicated that at $p = 0{\cdot}05$, enhanced rocks were significantly greater than both partially enhanced and platform abundances. At $p = 0{\cdot}001$, enhanced rocks performed similarly to partially enhanced rocks but still had significantly higher barnacle abundances than on shore platforms. Barnacle (predominately *Semibalanus balanoides*) abundance was greater on the artificial rock armour than on the natural platforms – this is likely to be attributable, in part, to greater surface roughness (Coombes *et al.*, 2015) of the coarse-grained, crystalline, granite revetment compared with the eroded, fine-grained, magnesian limestone shore platform. Importantly, key rocky intertidal prey species (e.g. *S. balanoides, P. vulgata* and *L. saxatilis*) showed similar, or higher, species densities on the enhanced rock revetment compared with the baseline (Figures 8 and 9).

7.4 Comparison between rock revetment treatments

The mean species richness for enhanced and partially enhanced areas was 10 and 6, respectively. At the individual quadrat level, enhanced rock revetment quadrats had 33% more species on average than partially enhanced rock revetment quadrats (Figure 10). Only *Melarhaphe neritoides* had higher counts (79% higher) in partially enhanced areas. A two-tailed *t*-test for rock revetment treatments (enhanced and partially enhanced) showed limpet abundance was significantly greater on enhanced than partially enhanced rocks, $p = 0{\cdot}005$. Although not statistically significant, *A. maritima, L. saxatilis* and *Littorina obtusata* had higher abundances on enhanced areas of the revetment (7·5, 3 and 0·3, respectively) compared with partially enhanced areas. *A. maritima* and periwinkles (*L. saxatilis* and *L. obtusata*) were also unique to the enhanced areas (Figures 10 and 11). Overall there was a 96% higher abundance of limpets in the enhanced areas compared with partially enhanced areas of rock revetment. A two-tailed *t*-test comparing the abundance of

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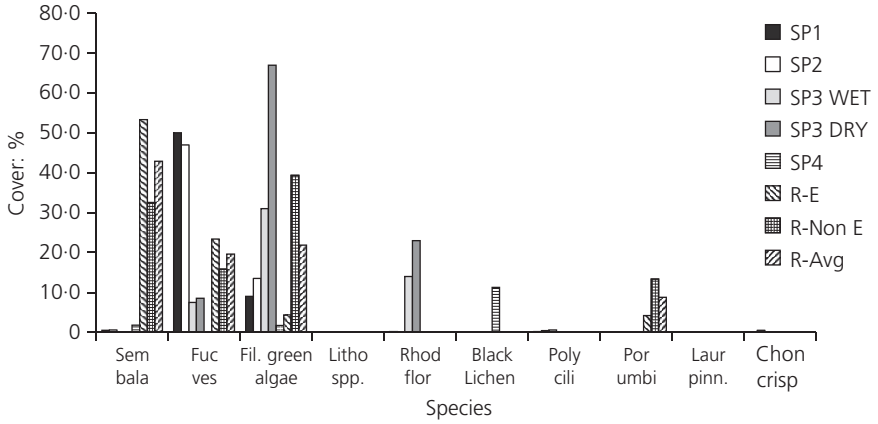

Figure 9. Percentage cover of colonial invertebrate and algal species on all treatment types

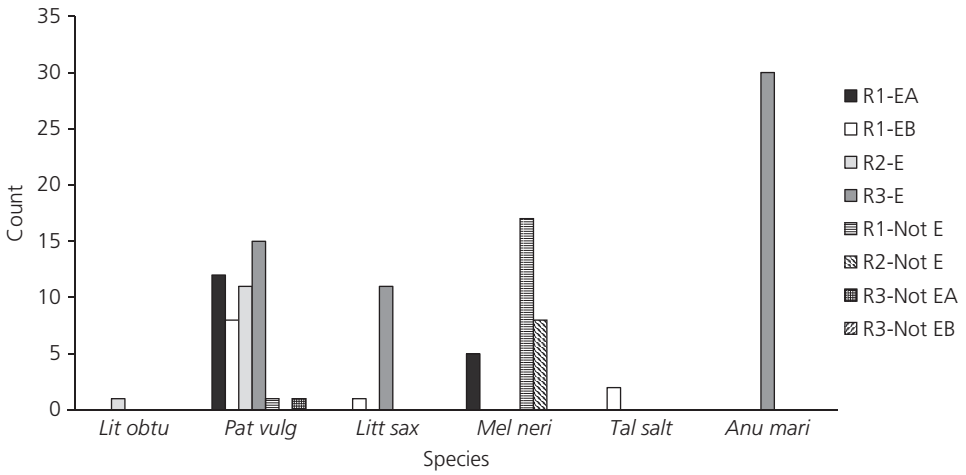

Figure 10. Species richness on enhanced and partially enhanced rock armour

P. vulgata, a key prey species, between enhanced and partially enhanced rock armour after 1 year was statistically significant ($p = 0{\cdot}0050$).

For the sessile organisms recorded (algae and invertebrates), only the colonial invertebrates (*S. balanoides*) had a greater percentage cover on enhanced rock armour (53·3%). Filamentous green algae were observed in notably higher abundances on partially enhanced rock armour (44·6%) in contrast to enhanced rocks (3·8% cover), an indicator of swifter succession (Cruz, 2007).

These preliminary data from 12 to 18 months after deployment show that both rock revetment treatments have species characterising the *Entromorpha* spp. on freshwater-influenced and/or unstable upper eulittoral rock (LR.FLR.Eph.Ent) biotope characteristic of all 14 phase 1 biotope survey points from 0 to 20 m (Figure 5), indicating that early post-deployment colonisation appears to favour similar ecological communities to those that have been replaced. For example, characteristic species of this biotope (e.g. *S. balanoides*, *P. vulgata, Ulva* spp. and *F. vesiculosus*) are already present on both rock revetment treatment types. Furthermore, after only 18 months, rock revetment chosen for its favourable physical complexity (passive enhancement) is already performing more similarly to the baseline than less physically complex alternatives (i.e. partially enhanced boulders). Understanding the colonisation and evolution of the ecological communities requires on-going monitoring to assess how quickly food species of the qualifying features colonise the revetment structure and whether birds feed on this part of the scheme.

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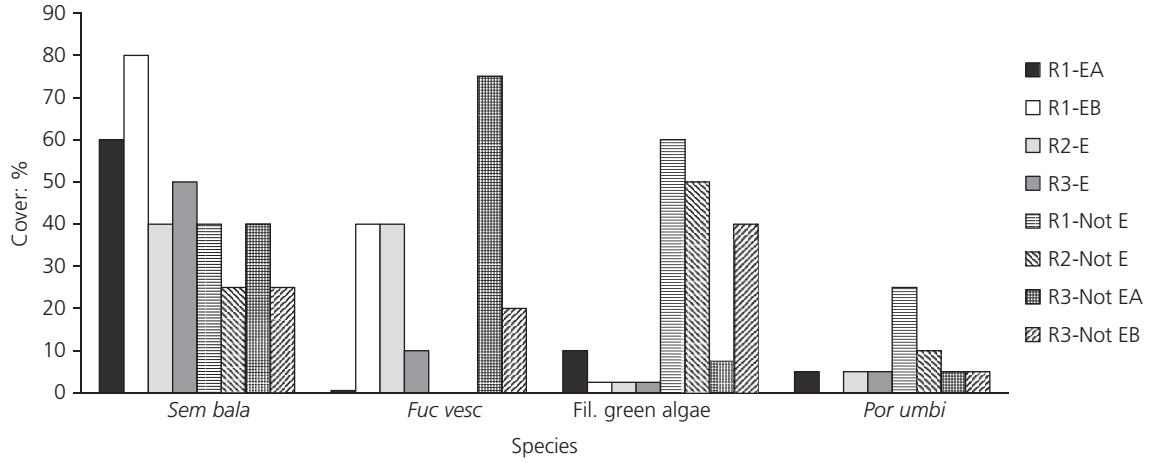

Figure 11. Percentage cover of species on enhanced and partially enhanced rock armour

8. Conclusions and lessons learnt

Several useful engineering, ecological and practical insights emerge from this innovative project that may inform future coastal defence schemes.

- Communication: Essential to the success of the mitigation plans was co-designing with the engineering team, academic experts and Natural England (Naylor *et al.*, 2012) to ensure the scheme was approved in a timely manner. During planning and design, face-to-face visits on site with all parties involved were necessary to identify potential ecological mitigation opportunities and issues within cost and engineering constraints.
- Ecological mitigation: Natural England approval of the ecological mitigation was critical to the approval of the coastal protection scheme.
- Climate change: As the hold the line policy strategy prevented any landward realignment of the foreshore, coastal squeeze risks to the rocky intertidal habitat on sea-level rise will emerge regardless of the scheme design. Nevertheless, the scheme design partly addresses this issue by using adaptive management principles to minimise future flood risks and provide habitat mitigation. A flexible design was created with ecological mitigation, aiming to at least maintain baseline conditions for surfaces affected by the scheme (the present-day mitigation) but also allow a degree of 'future-proofing' as sea-level rises.
- During the construction phase: Collaborative working with both the contractors and the council engineering team (client) ensured that methods for deploying the ecological mitigation were practical, cost effective and minimised damage to the Natura 2000 site, yet did not affect engineering performance.
- Ecological outcomes: Preliminary results suggest that the new 'passively' enhanced rock revetment (involving informed selection and placement of armour units to maximise the physical complexity of the structure) produces the same biotope as the baseline natural shore platform. Importantly, the enhanced areas had higher species densities of key prey species for birds (e.g. limpet abundance) than the partially enhanced areas. The enhanced areas also appear to support quicker succession and have species densities more similar to baseline conditions than partially enhanced areas of the revetment. These preliminary data suggest that passive ecological enhancement approaches can help mitigate ecological impacts of new rock revetments in designated Natura 2000 sites, over timescales as short as 18 months. Monitoring of the scheme is on-going through a University–local government collaborative project, and will provide valuable longer-term data on ecological performance.
- Habitats directive: This project demonstrates that mitigation of the ecological impacts of hard coastal structures to satisfy aspects of the habitats directive is achievable.

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