S.37

File With

SECTION 131 FORM

Appeal No: ABP— 314487-22

Defer Re O/H:

To: SEO

Having considered the contents of the submission dated/received 26/09/2022 from Cllr. David Healy I recommend that section 131 of the Planning and Development Act, 2000 be/not be invoked at this stage for the following reason(s):

Signed: _____ Date: _____
EO

To: _____
EO

Section 131 not to be invoked at this stage. ☐

Section 131 to be invoked — allow 2/4 weeks for reply. ☐

Signed: _____ Date: _____
SEO

Signed: _____ Date: _____
SAO

M

Please prepare BP — Section 131 notice enclosing a copy of the attached submission.

To: _____ Task No: _____ Allow 2/3/4 weeks: BP

Signed: _____ Date: _____
EO

Signed: _____ Date: _____
AA

An Bord Pleanála

Planning Appeal Online Observation

Online Reference
NPA-OBS-001296

Online Observation Details

Contact Name	Lodgement Date	Case Number / Description
Cllr. David Healy	26/09/2022 17:22:37	314487

Payment Details

Payment Method	Cardholder Name	Payment Amount
Online Payment	David Healy	€50.00

Processing Section

S.131 Consideration Required

☐ Yes — P.T.O. ☐ N/A — Invalid

Signed

54, Páirc Éabhóra,
Beann Éadair,
Co. Bh.Á.C
D13 DY28
26th October 2022

An Bord Pleanála,
Marlborough St.,
Dublin 1

Submitted online

Observation on planning appeal 314487

A chairde,

I wish to make the following observations in relation to the above appeal.

The proposal for dredging and infill was the subject of a non-statutory public consultation to which I understand in excess of 50 responses were received by the deadline in April 2021. Please see https://www.gov.ie/en/consultation/8dad4-howth-harbour-dredging/

I attach the response I made to the public consultation and incorporate those observations as the core of this submission.

This website still says "Consultation is being reviewed" and to the best of my knowledge no results of the public consultation have been published.

However, the current planning application was made in July 2021. Despite making a submission to the non-statutory consultation and I was not notified of the planning application. I assume from the fact that only one observation was received that nobody else who had responded to the non-statutory consultation was notified either. I only became aware of the application after the Council's decision to grant permission as it was referred to in a report on our draft County Development Plan.

The dredging side of the application is clearly essential for the ongoing use of the harbour and appears to have been fully analysed. However, the infill proposal has not received the necessary attention.

Fingal's Parks Department's initial analysis recommended that the decision include the following condition:

> 1. Landscape Plan Prior to the commencement of site works a Landscape Plan with scaled section & elevation drawings prepared by a professional landscape architect to be submitted for the agreement of the Parks & Green Infrastructure Division showing the following:
>
> i. Details of proposed plant species to include planting specification sizes & densities. Omit species known to be potentially problematic e.g. Ulex, Rubus and Hippophae. Consider the screening of hard standing areas from the amenity areas with a suitable hedging species along the fence line.
>
> ii. Details of the proposed 'Natural Amenity Area' construction & planting in the form of a Method Statement in liaison with the project ecologist including the sourcing of plant & soil material, timing of works, natural regeneration or similar methods.

iii. Details of boundary treatments and street furniture including seating and large capacity litter bins. Given the potential use of this new open space, these features will be required.

iv. All paths to be hard surfaced rather than bounded gravel, in the interest of durability. Locate proposed storm water and petrol interceptors within hard surface areas, widen paths to accommodate if necessary.

v. Review the amount of public lighting and the potential use of ground level lights, to reduce the visual impact and maintenance issues of bollard lights.

vi. Landscape Design risk assessment – this may include railings to prevent falls (where rock armour is absent), sloping of mounds no greater than 1:5 to allow ride-on mower access and the location of life buoys.

vii. An item of public art sculpture with a local theme, to provide a sense of place. The Per Cent for Art Scheme should apply. Identify the location of the art sculpture and timeline for delivery.

viii. Landscape Maintenance Plan detailing the responsible agency, access arrangements/opening hours, maintenance duties and frequency, milestones & monitoring of the Natural Amenity Area.

ix. The Landscape Architect shall be engaged to supervise the landscape construction stage and to certify that the completed landscape works are completed within the first planting season following completion of construction works and to the agreed Landscape Plan details.

x. The Project Ecologist shall be engaged for the duration of the works as an Ecological Clerk of Works to monitor the impact of the works on the adjoining SAC and SPA areas, to liaise with the NPWS & Fingal's Biodiversity Officer and to ensure that all recommended ecology mitigation measures are implemented and effective.

These important issues in relation to the design and management of the area should have been raised in the initial application or at a minimum by way of an additional information request and should not be left over for consideration without public input under a condition of planning permission.

The Department of the Marine has handed over responsibility for both the day to day maintenance of the green areas within the Harbour, and the development and renovation of the areas, including new playgrounds, exercise equipment, planting, hard surfacing etc. to Fingal County Council, and this relationship has worked well over the years. There are strong arguments in favour of the Council similarly taking responsibility for this new open space and biodiversity area. I have verified that this issue hasn't even been discussed with the Parks Department. If that is not to happen, clear maintenance responsibility should be set out in the application and not left to a condition.

In essence the design presented, even amended in response to the conservation architect's input, is simply an outline design. The important issues of amenity, particularly water-based amenity and biodiversity simply haven't been addressed.

It is very understandable that the Department of the Marine should focus on the dredging side of the application, but the permission sought is for both dredging and infill. It is vital that a full design for the infill area is presented.

The proposal to have a one-way road and potentially thereby increase motor vehicle traffic on the pier is not consistent with proper planning and development and would significantly damage the existing amenity of the West Pier as well as damaging the potential for amenity on the infill area. The plan for the harbour should be to manage the car parking rather than increase the area of car parking.

I am also concerned that the impact of the infill on the erosion and sedimentation processes on Claremont and Burrow Beaches has not been adequately addressed in the application and additional information.

Thank you for considering the above observations.

Best regards,

David Healy

Comhairle Contae Fhine Gall | **An Roinn Gnóthaí Corparáideacha**
Fingal County Council | Corporate Affairs Department

Harbourmaster's Office
West Pier,
Howth,
Co. Dublin D13 A3Y0

By email: howthengineering@agriculture.gov.ie

9th April 2021

Cllr. David Healy
Green Party
Mayor of Fingal
2020/2021

County Hall,
Swords,
Fingal,
Co. Dublin

Áras an Chontae,
Sord,
Fine Gall,
Contae Átha Cliath

Telephone
01 890 5025
Mobile
087-6178852
Email
David.Healy@cllrs.fingal.ie

Observations on Howth Harbour Dredging and infill project

Dear Harbourmaster and Department of Agriculture, Food and the Marine,

Please find my observations below in response to the public consultation.

General
The siltation within the harbour is severe and the need for dredging is clear. The dredged material is contaminated and therefore not suited for dumping at sea. Fingal identified the area behind the West Pier as a potential infill location some time ago. Subject to the implementation of the necessary environmental protection measures this infill proposal is likely to be the best option.

In this sensitive location, such a major intervention brings both risks and opportunities.

Protect sea and land from contamination.
It is vital that the dredged material is safely encased to prevent the movement of contaminants into the marine environment both during construction and subsequently. The Environmental Impact Assessment must address this protection in detail so that the proposals can be fully examined by the public and by relevant authorities including EPA and NPWS.

Maximise biodiversity benefits
Artificial structures in the coastal environment such as this proposed infill should be designed in line with an eco-engineering approach, with objectives including maximising biodiversity and ecosystem services. For an overview of design options please see the attached article and supplementary material.[1]

[1] O'Shaughnessy, K.A., Hawkins, S.J., Evans, A.J. *et al.* Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users. *Urban Ecosyst* **23,** 431–443 (2020). https://doi.org/10.1007/s11252-019-00924-z

This should include consideration of the potential for the provision of locations where reef ecosystems could develop, taking into account the conservation objectives for the nearby Rockabill to Dalkey Island SAC which include increasing the area and the distribution of reefs.[2]

Similarly, the elements of the proposal above the high water line should also be designed with a view to protecting and maximising coastal biodiversity.

Provide for swimming, kayaking, windsurfing and other watersports
Howth is a busy location for swimming and other watersports with large numbers visiting to access the water in Howth especially in the summer. Claremont and Burrow Beaches are very shallow, so suited to some forms of bathing but not others. Balscadden Beach is busy with people swimming. The provision of a coastal pool as part of the infill would be a very welcome additional amenity and this proposal provides an excellent opportunity to include such an amenity in the design.

Provide space for enjoying the evening sun and the sunset
The views west over Baldoyle Estuary from the location of the infill are particularly fine in the evenings and this amenity area will undoubtedly be a place of public resort on summer evenings. The design should facilitate cafes and dining areas both indoors and outdoors to take advantage of the views as well as open public space with built-in seating areas and benches for open non-commercial use.

Do not provide extra space for car parking
The harbour area already has extensive areas of car parking, more than enough for everyday demand. The only time when parking is scarce is when large numbers of visitors come (typically summer weekends) and the problem of road congestion at those times is a much greater inconvenience than the scarcity of car parking spaces. Providing extra spaces for the peak demand only risks worsening the problem of traffic congestion.

Provide for secure bicycle parking
Large numbers of visitors come by bicycle and it would be of great benefit to have secure bicycle parking at this location.

Design in harmony with the existing Harbour
The distinctive features of the existing West and East Piers include the local sandstone they are built of and the cut granite finishes. Without necessarily replicating either material, it would be important to design and finish the new amenity area in keeping with the existing Harbour.

Thank you for considering the above.

Best regards,

David Healy

---

[2] NPWS, 2013, Rockabill to Dalkey Island SAC (site code: 3000) Conservation objectives supporting document - Marine Habitats and Species
https://www.npws.ie/sites/default/files/publications/pdf/003000_Rockabill%20to%20Dalkey%20Island%20SAC%20Marine%20Supporting%20Doc_V1.pdf

Urban Ecosystems (2020) 23:431–443
https://doi.org/10.1007/s11252-019-00924-z

Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users

Kathryn A. O'Shaughnessy[1] · Stephen J. Hawkins[2,3] · Ally J. Evans[2,3,4] · Mick E. Hanley[5] · Paul Lunt[1] · Richard C. Thompson[5] · Robert A. Francis[6] · Simon P. G. Hoggart[7] · Pippa J. Moore[4] · Gregorio Iglesias[8] · David Simmonds[8] · James Ducker[5] · Louise B. Firth[5]

Published online: 28 December 2019

Abstract

Coastal urbanisation, energy extraction, food production, shipping and transportation have led to the global proliferation of artificial structures within the coastal and marine environments (sensu "ocean sprawl"), with subsequent loss of natural habitats and biodiversity. To mitigate and compensate impacts of ocean sprawl, the practice of eco-engineering of artificial structures has been developed over the past decade. Eco-engineering aims to create sustainable ecosystems that integrate human society with the natural environment for the benefit of both. The science of eco-engineering has grown markedly, yet synthesis of research into a user-friendly and practitioner-focused format is lacking. Feedback from stakeholders has repeatedly stated that a "photo user guide" or "manual" covering the range of eco-engineering options available for artificial structures would be beneficial. However, a detailed and structured "user guide" for eco-engineering in coastal and marine environments is not yet possible; therefore we present an accessible review and catalogue of trialled eco-engineering options and a summary of guidance for a range of different structures tailored for stakeholders and end-users as the first step towards a structured manual. This work can thus serve as a potential template for future eco-engineering guides. Here we provide suggestions for potential eco-engineering designs to enhance biodiversity and ecosystem functioning and services of coastal artificial structures with the following structures covered: (1) rock revetment, breakwaters and groynes composed of armour stones or concrete units; (2) vertical and sloping seawalls; (3) over-water structures (i.e., piers) and associated support structures; and (4) tidal river walls.

Keywords Biodiversity · Coastal management · Ecological engineering · Green infrastructure · Ocean sprawl · Nature-based solutions

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11252-019-00924-z) contains supplementary material, which is available to authorized users.

✉ Kathryn A. O'Shaughnessy
kathryn.oshaughnessy@plymouth.ac.uk

[1] School of Geography, Earth and Environmental Science, University of Plymouth, Plymouth PL4 8AA, UK

[2] Ocean and Earth Science, University of Southampton, National Oceanography Centre Southampton, Southampton SO17 3ZH, UK

[3] The Marine Biological Association of the UK, The Laboratory, Citadel Hill, Plymouth PL1 2PB, UK

[4] Institute of Biological, Environmental and Rural Sciences, Aberystwyth University, Aberystwyth SY23 3DA, UK

[5] School of Biological and Marine Sciences, University of Plymouth, Plymouth PL4 8AA, UK

[6] Department of Geography, King's College London, Strand, London WC2R 2LS, UK

[7] British Ecological Society, Charles Darwin House, London WC1N 2JU, UK

[8] School of Engineering, University of Plymouth, Plymouth PL4 8AA, UK

Introduction

Coastlines worldwide are becoming increasingly vulnerable to flooding, erosion and degradation due to rising sea level, stormier seas and increased coastal urbanisation (McGranahan et al. 2007; Halpern et al. 2008; Tessler et al. 2015). The human population within 100 km of the coastline is disproportionally higher compared to inland areas (Small and Nicholls 2003; McGranahan et al. 2007), with much of this population concentrated in densely packed urban areas (Firth et al. 2016a; Todd et al. 2019). Consequently, coastlines globally have been developed to support human activity, resulting in the drastic and irreversible modification of natural systems (Vitousek et al. 1997; Halpern et al. 2008; Knights et al. 2015). Human activities focused along the coast, such as shipping and transportation, residential and commercial development, as well as the creation of hard artificial defence structures (i.e., seawalls, breakwaters, groynes) to protect valuable urban infrastructure (i.e., utilities, roads, buildings) from rising and stormier seas, have contributed to "ocean sprawl." Ocean sprawl (sensu Duarte et al. 2012) describes the proliferation of artificial structures in marine and coastal environments, and the subsequent modification and loss of natural substrata (Duarte et al. 2012; Firth et al. 2016a; Bishop et al. 2017; Heery et al. 2017). For example, 14% of coastal United States is composed of hard urban structures (Popkin 2015), 10% of the Great Barrier Reef World Heritage Area in Australia is armoured (Waltham and Sheaves 2015) and 60% of the natural coastline in China has been replaced by seawalls (Ma et al. 2014).

Urban infrastructure alters the physical, chemical and biological environment of the receiving ecosystem (Dugan et al. 2011; Firth et al. 2016a; Todd et al. 2019). Hard artificial defence structures (hereafter 'artificial structures') directly replace natural habitats (Airoldi and Beck 2007; Govarets and Lauwaert 2009), resulting in habitat fragmentation (Krauss et al. 2010) and disruption of ecological connectivity (Firth et al. 2016a; Bishop et al. 2017). Additionally, urban infrastructure changes the geomorphology and hydrodynamics of the surrounding habitats (Dugan et al. 2008; Nordstrom 2014). For example, in sandy bottom habitats, artificial structures alter normal wave activity and subsequently affect longshore transport and sediment deposition, modifying the morphology of the coastline (Dugan et al. 2011; Del Río et al. 2013; Nordstrom 2014). Impermeable surfaces that are a common feature of urban systems, such as roads and buildings, increase runoff into the adjacent body of water (Arnold Jr and Gibbons 1996; Barnes et al. 2001), often facilitating increased input of nutrients and pollutants (e.g., agricultural fertilizers, heavy metals; Arnold Jr and Gibbons 1996; Wicke et al. 2012). Fewer organisms in terms of numbers and abundances of species (i.e., biodiversity) colonise coastal urban infrastructure compared to natural habitats in similar environmental settings (Connell 2001; Bulleri and Chapman 2004; Moschella et al. 2005; Lai et al. 2018). This is attributed to the steep profiles and reduced surface area and topographic complexity of urban artificial structures (Knott et al. 2004; Moschella et al. 2005; Chapman and Underwood 2011; Lai et al. 2018). Many artificial structures are dominated by invasive species (organisms that are not native to the ecosystem) and opportunistic species (organisms that make up the initial stages of succession) compared to natural habitats (Glasby et al. 2007; Dafforn et al. 2009, 2012). As a result, the ecological functioning (i.e., biotic processes such as water filtration and primary productivity) of artificial structures is often different to comparable natural habitats (Mayer-Pinto et al. 2018a; b). Changes in ecological functioning can have detrimental knock-on effects on the provision of 'ecosystem services' – desirable secondary benefits to both society and nature, such as improvement in water quality, increase in carbon sequestration and more space for outdoor recreational activities (Fig. 1).

Regardless of the specific ecological impacts, it is clear that human actions are leading to the development of new habitats and ecosystems without natural analogues ('novel ecosystems'; Hobbs et al. 2006; Morse et al. 2014). In response, some ecologists are considering how to manage these new

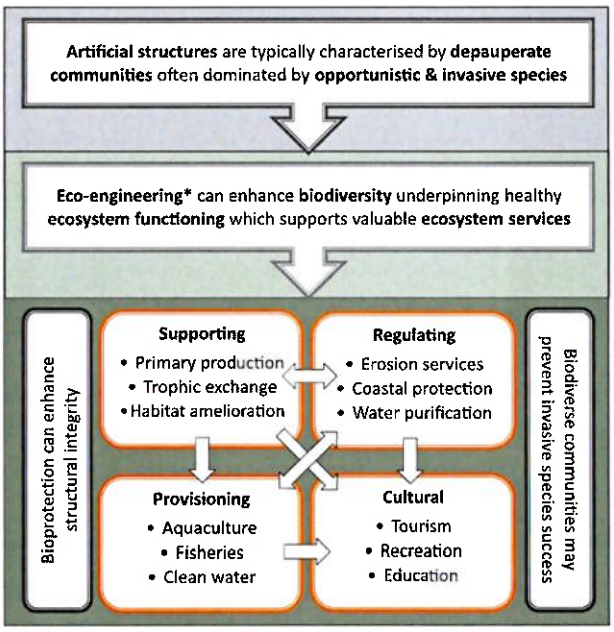

Fig. 1 Typical characteristics of artificial structures and how eco-engineering optimises the potential ecosystem services as outlined by the Millennium Ecosystem Assessment (red boxes) (Millennium Ecosystem Assessment 2005; Everard 2017). The arrows show the potential linkages and feedbacks between services (e.g., improved fisheries [provisioning service] can have beneficial knock-on effects to recreational fishing and tourism [cultural service]). Other potential desirable outcomes of eco-engineering are highlighted in black boxes. *Eco-engineering enhances biodiversity and ecosystem services only compared to the ecological condition of the same structure without eco-engineering applications

habitats for ecological and societal benefit (Milton 2003; Hobbs et al. 2006; Macdonald and King 2018). The design of such ecosystems, which integrate human society with the natural environment for the benefit of both, has been labelled ecological engineering (or "eco-engineering"; Odum 1962; Mitsch and Jorgensen 1989; Odum and Odum 2003). Whilst the environmental context of artificial structures is likely to be fixed (e.g., tidal position, geographic position), their associated biodiversity (i.e., the variety of living organisms; Colwell 2009) and role in ecological functioning can be enhanced through eco-engineering techniques.

The field of eco-engineering is beginning to provide practitioners, developers, managers and decision makers with options for the design and management of artificial structures in the coastal and estuarine environments to support biodiversity and provide desirable ecosystem services (Fig. 1) whilst not compromising the primary function of a structure (e.g., coastal defence, safe berthing in a port). As coastal urbanisation intensifies, the pressure on coastal developers to incorporate ecologically sensitive designs will undoubtedly increase. Recently, there has been increasing impetus among stakeholders for eco-engineering of artificial structures to support ecosystem services. Evans et al. (2017) interviewed different stakeholder groups about their perceptions of artificial coastal defence structures and their potential to provide built-in secondary benefits. Respondents prioritised ecological benefits over economic, social and technical ones. At the same time, stakeholders have raised concerns relating to the impacts of eco-engineering interventions; engineers are concerned with impacts on the performance and durability of the structure whilst conservationists are concerned about invasive species (Dafforn et al. 2012; Evans et al. 2017; Naylor et al. 2017). Research has shown that the encouragement of certain colonising organisms such as barnacles, mussels, oysters and algae can have a positive "bioprotective effect" through physical strengthening of the materials and protection from temperature extremes and wave action (Risinger 2012; Coombes et al. 2013; Coombes et al. 2015). Furthermore, one of the primary functions of eco-engineering is to promote diverse native biological communities that can prevent the establishment of invasive species (Stachowicz et al. 1999; Stachowicz et al. 2002; Arenas et al. 2006b; Fig. 1).

Whilst efforts should be focused on maximising ecological benefits through eco-engineering of artificial structures, the best option is to allow natural biogenic habitats and defences to persist where possible and avoid building artificial structures unless absolutely necessary – the "do nothing" approach (Hoggart et al. 2014). Where and when human intervention is needed for reasons of public safety, infrastructure protection or energy development, the use of "soft" engineering approaches should be prioritised if possible (Dafforn et al. 2015a; Morris et al. 2018a). These interventions typically involve working with nature, such as the modification or removal of artificial structures to allow the sea to re-inundate previously reclaimed land (commonly called "managed realignment"; French 2006; Masselink et al. 2017; Mayer-Pinto et al. 2017), or using vegetation, sand-fills and sand nourishment as coastal protection (Stive et al. 2013; Hanley et al. 2014; Morris et al. 2018a). Where these soft designs are not possible, a combination of hard and soft techniques, such as "hybrid stabilisation" and "living shorelines" approaches, should be considered (Bilkovic and Mitchell 2013; Sutton-Grier et al. 2015; Polk and Eulie 2018). Quite often in urbanised areas, however, the only feasible approach is to build hard structures due to lack of space and the immediate need to protect valuable urban infrastructure (Chee et al. 2017). In this paper, we assume that the reader has already explored and rejected soft engineering options, leading to an informed decision to move forward with necessary eco-engineering of hard structures to provide secondary functional benefits.

Feedback from stakeholders and end-users has repeatedly informed us that a "photo user guide" or "manual" covering the range of eco-engineering options available would be much easier than having to sift through the rapidly expanding body of academic literature (see Dafforn et al. 2015a; Geist and Hawkins 2016; Mayer-Pinto et al. 2017 for reviews). It is increasingly accepted that one role of scientists and engineers is to inform coastal managers and government bodies of current research (Chapman and Underwood 2011; Evans et al. 2017). Thus, structured guides and frameworks (e.g., Mayer-Pinto et al. 2017; Naylor et al. 2017) tailored for decision-makers will become essential for eco-engineering to progress. Therefore, in this paper, we provide a user-friendly, illustrated review of trialled eco-engineering options and a summary of potential guidance for a range of different artificial structures for practitioners involved in the development of coastal environments. This work can thus serve as a template or model for future eco-engineering guides and frameworks that should evolve in tandem with emerging proof-of-concept evidence. Here, various types of structures are considered in turn, with guidance given on appropriate eco-engineering interventions (Supplementary Information Tables 1–4), and generic and contextual considerations on application of eco-engineering designs are discussed.

Methods

Literature search

Using literature identified by Strain et al. (2017a) as a foundation and supplemented with subsequent searches for scientific articles, conference papers and government

reports, we reviewed studies and projects on eco-engineering interventions in coastal, estuarine and tidal river systems from around the world that included measurable ecological outcomes (e.g., biodiversity, ecosystem services). We focussed only on measurable ecological effects because the vast majority of eco-engineering studies measured only these outcomes, although social, cultural and economic knock-on effects are expected (Fig. 1; Airoldi et al. 2005). Results from the literature search are displayed in Table 1 as intervention types for each category of artificial structure, including the number of studies that has tested each intervention (as a proxy for evidence base). We then selected studies from the literature search that we felt represented the range of options for the most common types of structures and presented these as separate tables for each type in a visual framework included in the Supplementary Information (see below for descriptions of structures). Information for each selected study includes design details, intended outcomes, success, photographs, habitats, key references and associated costs (if known). It is important to note that the cost of interventions was not scaled up or standardised across all studies presented. We included as much consistent information from these studies as possible, but only used information derived from the authors' original interpretations.

What structures are covered?

We considered a range of coastal and estuarine structures: (1) *Rock revetment, breakwaters and groynes* include structures perpendicular and parallel to the shore composed of armour stones or concrete units, which are typically sloping structures that function to retain land, shelter a coastal area from incident waves or dissipate wave energy. (2) *Vertical and sloping seawalls* are solid, protective structures, including harbour walls and docks, designed to retain land and reflect wave energy. (3) *Over-water structures* include bridges and piers (and their supportive

Table 1 Summary of eco-engineering intervention studies reviewed for each artificial structure type. Interventions are described below and examples are provided in Supplementary Information Tables 1–4. Studies reviewed only include projects with measurable ecological objectives published in grey and academic literature

Artificial structure type	Eco-engineering intervention	No. of studies
Rock revetment, breakwaters and groynes made of armour stones or concrete units (see SI Table 1)	Hybrid stabilisation	20
	Pits, holes, crevices, grooves, cuts, roughness, gaps	5
	Precast habitat enhancement units	3
	Rock/tidal pools	4
	Seeded, textured or complex tiles or panels	3
	Transplant target species	5
Vertical and sloping seawalls (see SI Table 2)	Addition of natural material	1
	Gabion baskets	2
	Hybrid stabilisation	1
	Modifying seawall slope or seawall removal	4
	Pits, holes, crevices, grooves, cuts, roughness, gaps	5
	Rock/tidal pools	7
	Seeded, textured or complex tiles or panels	8
	Transplant target species	2
Over-water structures (see SI Table 3)	Light-penetrating designs	7
	Seeded, textured or complex tiles or panels	2
Pier pilings (see SI Table 3)	Addition of synthetic material	1
	Precast habitat enhancement units	1
	Seeded, textured or complex tiles or panels	1
	Transplant target species	1
Tidal river walls (see SI Table 4)	Addition of natural material	1
	Floating island habitats	1
	Timber fenders & ledges	1
	Wall boxes	2
Floating pontoons	Addition of synthetic material	1
	Seeded, textured or complex tiles or panels	3

pilings). (4) *Tidal river walls* are typically vertical or sloping structures that provide flood defence and erosion mitigation where riverine freshwater meets the sea. (5) *Vulnerable, degraded and culturally valuable structures* include structures that are not permitted to be manipulated because of cultural or heritage value, or because of their state of deterioration. (6) *Floating pontoons* (or floating docks) are hollow structures used as walkways and for docking boats, most often within marinas. All the studies reviewed consisted of interventions made to existing structures or incorporated within structures during their construction. We do not describe nearshore or offshore artificial reefs as habitat for fisheries, as well as eco-engineering of the upper reaches of rivers because comprehensive reviews on these subjects exist (e.g., Nakamura 1985; Baine 2001; Palmer et al. 2005; Radspinner et al. 2010; Lokesha et al. 2013; Lima et al. 2019) and these habitats fall outside the remit of this paper.

How to use this guide

Caveat: We caution that the options outlined in this guide should be used responsibly; they should not be used to influence the consenting process for harmful coastal developments.

Whilst secondary management goals (e.g., enhance biodiversity, increase water filtration) for any eco-engineering design should be clearly defined at the outset, we appreciate that managers may not be aware of the range of potential interventions (see Evans et al. (2017) for a list of potential secondary benefits of designing multi-functional engineered structures suggested by a group of stakeholders). Consequently, we present a step-by-step approach that will direct the user to relevant information and help guide them through the range of eco-engineering options that are currently available.

Step 1. *Refer to* Fig. 2 which illustrates a series of questions that managers should consider in relation to incorporating eco-engineering into a planned development. The user should move through the questions sequentially, although some questions may not be applicable in every case.

Step 2. *Refer to the appropriate section and table.* Figure 2 directs users to the appropriate section (in-text) and table (Supplementary Information) containing information from previous studies for the particular structure type that they are working with. It is important to note that some enhancement designs may be applicable to structure types across multiple groups.

Step 3. *Refer to* Table 2 which details additional generic considerations that may be applicable.

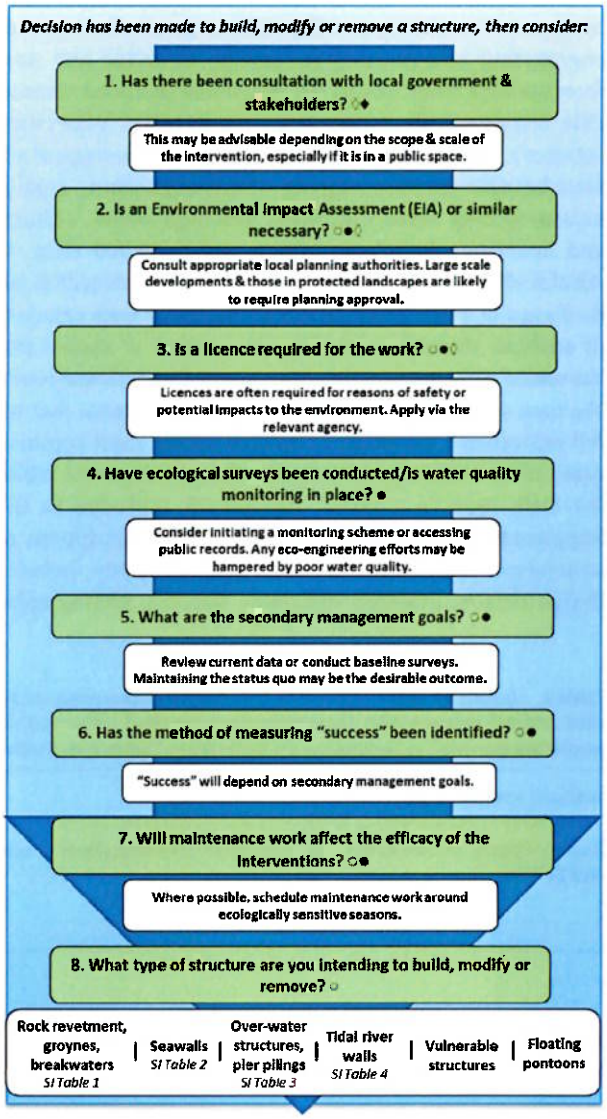

Fig. 2 Considerations for developers and managers relating to eco-engineering decisions for coastal and marine artificial structures. Question #8 prompts the user to choose the structure type of interest and refer to the associated section (in-text) and table (Supplementary Information) for design details and examples. Symbols represent different consideration types: ○ Engineering, ● Environmental, ♢ Governmental, ♦ Societal

Eco-engineering of different artificial structures

Much progress has been made in the field of eco-engineering, and a wide range of options is emerging, which are provided within this paper. We strongly caution, however, that many designs have only been trialled once, or only under certain environmental conditions or regions (i.e., temperate regions), and so it is unknown whether the same results would emerge under different environmental

Table 2 Checklist for additional generic considerations that may be applicable to the chosen eco-engineering intervention

Considerations	References
☑ **Implementation**	
Implementation of design can be during construction or retrofitted	
- During construction: Designs may be covered by the licence for the construction work, be more creative, less expensive & implemented on a larger scale than if fitted retrospectively	Firth et al. 2014b; Sella & Perkol-Finkel 2015
- Retrofitting existing structures: Cost-effective options are available, such as affixing additional material, drilling pits, grooves & pools & transplanting desirable habitats or species	Browne & Chapman 2011; Perkol-Finkel et al. 2012; Evans et al. 2016; Strain et al. 2017b
☑ **Materials**	
Geological origin of material used can affect colonising communities, therefore try to:	
- Use material local to the region	Burcharth & Lamberti 2007; Green et al. 2012
- Use eco-friendly or natural material	ECOncrete Inc.; Dennis et al. 2017
- Use cement replacements (e.g., ground granulated blast-furnace slag)	McManus et al. 2017
☑ **Placement**	
Performance of eco-engineering designs may be influenced by:	
- Immersion gradient	
Subtidal & lower intertidal: Placement of interventions here yields markedly greater biodiversity as this area is immersed on every tidal cycle & the potential pool of colonising species is greater; however the risk of sand scour is greater, which may result in loss of the intervention	Browne & Chapman 2011; Firth et al. 2016a
Middle & high intertidal: Placement of interventions here may help extend the area of suitable habitat, which is normally compressed & greatly reduced compared to the intertidal zone in natural rocky shore	Perkol-Finkel & Sella 2015
- Exposure gradient	
Sheltered sites: Design may becoming inundated with sediment	Evans et al. 2016; Firth et al. 2016a
Exposed sites: Design may be lost to currents & waves	Francis et al. 2008; Browne & Chapman 2014
- Aspect	
Directionality (north vs. south in particular) determines the magnitude of shading & thermal stress a structure receives	Chapman & Blockley 2009 Chapman & Underwood 2011
- Inclination	
Substrate slope may determine the colonising community, as survivability on horizontal vs. vertical substrate is species-specific & thus might influence success of invasive species	Francis & Hoggart 2008; Dafforn et al. 2012
☑ **Timing of installation**	
Timing of installation of eco-engineering interventions is important, as recruitment periods of marine life & subsequent community development vary throughout the year	Airoldi & Bulleri 2011; Evans 2016
☑ **Maintenance of structure**	
Maintenance can result in disturbance, often creating bare space where dense biological assemblages occurred previously, increasing the risk of colonisation by invasive species	Stachowicz et al. 1999; Airoldi & Bulleri 2011
☑ **Uncontrollable factors**	
The precise effects of eco-engineering interventions are difficult to predict because coastal & marine systems are highly variable, with many uncontrollable conditions	
- Local conditions: Consider the success of past designs in similar locations & conditions	
- Extreme weather events: Use information on weather trends in the region	
- Obtaining permissions to install a design: Many structural design features of artificial structures are non-negotiable because of their primary function & cost restrictions	

conditions. This is a major limitation in this field; we acknowledge that more evidence is needed before most eco-engineering designs can become routine practice (Evans et al. 2019). There are, however, examples showing that rigorous testing in a variety of different geographic and environmental settings can lead to large-scale implementation (see World Harbour Project 2018; ECOncrete Inc. 2019; Ecostructure 2019; Living Seawalls 2019). Thus, when choosing an eco-engineering intervention, it is vital to consider all physical (e.g., wave action, storm frequency, sediment loading, turbidity), chemical (e.g., salinity regime, nutrient supply, pollution loading) and biological factors (e.g., pool of potential colonising species, larval supply, proximity to point of introduction of invasive species). Moreover, it is crucial that developers and engineers engage with local ecologists, oceanographers and experts to discuss the feasibility of options so that valuable resources are not wasted, and the outcomes of eco-engineering installations maximised. In this light, any trials that failed to meet their ecological goals should be reported and considered when designs in new areas are being planned.

Rock revetment, breakwaters and groynes made of armour stones or concrete units (supplementary information Table 1)

There are many options for eco-engineering these structures. Small-scale physical modifications involve drilling pits and rock pools (Firth et al. 2014; Evans et al. 2016; Hall et al. 2018). Large-scale physical interventions involve placement of precast habitat-enhancement units within the existing structure or during construction (Firth et al. 2014; Perkol-Finkel and Sella 2015; Sella and Perkol-Finkel 2015). Biological modifications include transplanting target species to the structure for habitat enhancement or conservation purposes (Perkol-Finkel et al. 2012). Hybrid methods consist of combining planted vegetation (e.g., saltmarsh cordgrass, mangrove trees) or reef-forming animals (e.g., oysters, coral) with built structures to mitigate erosion and rehabilitate coastal habitat (Hashim et al. 2010; Kamali et al. 2010; Bilkovic and Mitchell 2013).

Vertical and sloping seawalls (supplementary information Table 2)

Options for eco-engineering seawalls include drilling pits into pre-existing seawalls (Martins et al. 2010; Martins et al. 2016), manipulating wet mortar to create grooves and pits in new seawalls (Firth et al. 2014; Jackson 2015) and transplanting target species or species of conservation concern directly onto seawalls (Ng et al. 2015). Structural complexity can be added by attaching concrete panels to seawalls (Cordell et al. 2017; Perkol-Finkel et al. 2017; Strain et al. 2017b; World Harbour Project 2018), and water-retaining features can be created by retro-fitting precast concrete units on seawalls or replacing blocks with cavities during seawall construction (Chapman and Blockley 2009; Browne and Chapman 2014; Morris et al. 2018b; Hall et al. 2019).

Over-water structures, such as bridges and piers, and their associated supporting pilings (supplementary information Table 3)

Over-water structures and their associated foundational support structures may alter natural physical characteristics, such as hydrodynamics, sediment movement and light penetration in the immediate area (Smith and Mezich 1999; Shafer 2002; Dugan et al. 2011; Li et al. 2014). These physical modifications result in changes to ecosystem functioning, including fish migration behaviour (Ono and Simenstad 2014; Munsch et al. 2017) and seagrass survival (Blanton et al. 2002; Shafer 2002). To alleviate some of the negative effects associated with over-water structures, ecologists have experimented with light-penetrating materials (Shafer and Lundin 1999; Alexander 2012; Cordell et al. 2017) and artificial lighting (Ono and Simenstad 2014). Ecological encasement jackets (Perkol-Finkel and Sella 2015) and synthetic free-hanging ropes (Paalvast et al. 2012) have been trialled on pier pilings, which had positive effects on biodiversity and local water quality through biofiltration, and without compromising the functional integrity of pilings.

Tidal river walls and embankments (supplementary information Table 4)

Tidal rivers and estuaries are among the most degraded and altered aquatic ecosystems in the world as many are located in urban areas (Malmqvist and Rundle 2002; Lotze et al. 2006), yet there has been a paucity of eco-engineering interventions attempted in these systems (but see Francis et al. 2008; Francis 2009; Hoggart and Francis 2014). Eco-engineering options for tidal river walls include attachment of timber fenders, wall modules and wire mesh to river walls. These can act as surface roughness elements, reducing water flow velocity and facilitating seed trapping and germination of vegetation (Steele 1999; Schanze et al. 2004; Hoggart and Francis 2014). The use of floating structures such as fish hotels is not a direct enhancement to an artificial structure, but such designs do facilitate recruitment of riparian vegetation and invertebrate species, as well as provide shelter and habitat for fish and haul-out sites for seals (Francis 2009; Yellin 2014).

Vulnerable, degraded and culturally valuable artificial structures on which manipulations are not permitted

Some artificial structures are degraded or have cultural or heritage value, which can make it challenging to obtain permissions for retrofitting eco-engineering interventions, especially interventions that involve drilling or attaching heavy materials. For example, Plymouth Breakwater, built between 1812 and 1841, is a 1.6 km long structure (Southward and Orton 1954; Hawkins et al. 1983) that is considered a historic monument (Knights et al. 2016) and that is not permitted to be manipulated. As the original structure has become undermined over the years, sacrificial concrete wave-breaker blocks (100 t) are systematically placed on the seaward side of the breakwater as an additional form of protection from wave action. These blocks may function similarly to boulders or rubble placed at the base of seawalls, in that they create additional habitat that supports species that do not live on the original structure itself (Chapman 2012, 2017; Firth et al. 2014; Liversage and Chapman 2018). Indeed, given their heritage status and aesthetic value of these kinds of structures, the best approach may be to do nothing.

To our knowledge, formal tests to enhance biodiversity on vulnerable structures have not been conducted, thus information contained within this section consists only of suggested interventions, and subsequently a guidance table on eco-

engineering approaches has not been offered. Nevertheless, designs that have been trialled for other structures have the potential to be implemented in front of vulnerable structures for protection and provision of habitat for marine life. For example, if the goal is to provide a secondary form of protection for the structure and enhance the habitat potential, artificial boulder fields (Chapman 2012, 2017) or precast armouring units (Firth et al. 2014; Sella and Perkol-Finkel 2015; Reef Ball Foundation Inc. 2017; ARC Marine 2019) could be placed in front of the structure. There are companies designing commercial products to provide hard structures for erosion prevention and scour protection, whilst simultaneously enhancing biodiversity (Reef Ball Foundation Inc. 2017; ARC Marine 2019; ECOncrete Inc. 2019; Reef Design Lab 2019). It is imperative, however, to confirm that designs from these companies are rigorously tested, analysed and results published so that there is confidence in the delivery of ecological goals (e.g., see scientific testing done by ECOncrete Inc. 2019: Perkol-Finkel and Sella 2013; Perkol-Finkel and Sella 2015; Sella and Perkol-Finkel 2015; Perkol-Finkel et al. 2017).

Floating pontoons

Floating pontoons (also known as floating docks) are some of the most ubiquitous artificial structures in urban harbours. They are hollow structures made of materials such as concrete or fibreglass which are used as walkways and for berthing boats; they also inevitably provide substrate for biotic colonisation (Connell 2001; Toh et al. 2017). There are no natural analogues to pontoons, as they stay fixed in relation to the water level (they rise and fall with the tide so that the water depth below them varies), provide permanent shading and are typically located within enclosed environments (i.e., marinas; Hair and Bell 1992; Glasby and Connell 2001; Holloway and Connell 2002).

To date, descriptive work on pontoons has characterised the biological assemblages and has shown that these structures often support invasive species (Arenas et al. 2006a; Perkol-Finkel et al. 2008; Bishop et al. 2015; Toh et al. 2017), although few eco-engineering studies have been carried out on pontoons (but see Hair and Bell 1992; Stachowicz et al. 2002; Paalvast et al. 2012). This knowledge gap is reflected in the absence of a guidance table on eco-engineering approaches to pontoons in this paper. It is important to note that eco-engineering pontoons may be undesirable for marina operators because additional material on pontoons may affect buoyancy of pontoons and impede mooring of boats, and the associated organisms typically cover boat hulls and marina equipment (Connell 2001). In particular, invasive species (e.g., the carpet sea squirt, *Didemnum vexillum*) have been responsible for smothering pontoons, marina equipment and boat hulls and engines, costing marina managers and boat owners extra expenses in anti-fouling remedies (Coutts and Forrest 2007; Piola et al. 2009). Thus, trials are urgently needed to test eco-engineering interventions that will support native biodiversity, thereby offsetting the success of invasive species.

Concluding remarks

As urbanisation along coastlines continues to increase, the pressure on coastal developers and local governments to invest in the design and management of defence structures to protect valuable infrastructure and preserve human lives will also increase. Stress from urbanisation will be exacerbated by rising sea level and more frequent and intense storms. Fortunately, there is impetus among stakeholders to work with natural processes where possible to preserve biodiversity and maintain valuable ecosystem services (Evans et al. 2017). Effective siting, planning and management of coastal developments to provide desirable ecological benefits to society and nature require a wide range of proof-of-concept options in a variety of environmental contexts. This paper has shown the range of eco-engineering options currently available, as well as provided a template upon which to build a practitioner-friendly user guide for environmentally sensitive development along urbanised coastlines.

The future of eco-engineering will necessarily include a wider ecosystem perspective; this will include combining "hard" and "soft" engineering (Bilkovic and Mitchell 2013; Temmerman et al. 2013; Hanley et al. 2014; Chee et al. 2017), and will involve a multifunctional approach to design structures that can synergistically support aquaculture, energy production, diverse biological communities and healthy ecosystems (Ten Voorde et al. 2009; Zanuttigh et al. 2015; Evans et al. 2017). Ecologists and engineers have developed a wide range of eco-engineering options and are beginning to develop frameworks and guidelines for end-users (Dafforn et al. 2015b; Dyson and Yocom 2015; Mayer-Pinto et al. 2017); but we caution that significant knowledge gaps remain regarding the applicability of these techniques outside the environmental scenarios in which they were trialled, and all designs carry with them an associated risk. As Bulleri and Chapman (2010) warned, it is not yet possible to provide a full "recipe book" of interventions from which engineers and developers may select the best approach with absolute confidence to possible outcomes (see also Evans et al. 2017). Thus, to inform sound eco-engineering practice, there is a need for wider testing of existing designs in different environmental settings, and to develop the predictive capability to forecast ecological outcomes (Airoldi et al. 2005; Hulme 2014; Evans 2016). Meticulous planning, informed decision-making and setting and measuring secondary management goals are vital in maximising the ecological and societal benefits of eco-engineering (Russell et al. 1983; Hawkins et al. 1992). Collaboration between developers, government bodies, ecologists and engineers is an essential prerequisite for

maximising biodiversity gains and minimising ecological impacts of coastal development (Department for Communities and Local Government 2012).

The field of eco-engineering is still in its infancy; public and practitioner knowledge of eco-engineering may be limited due to lack of awareness (Strain et al. 2019). Ecologists should, therefore, communicate eco-engineering information to managers, decision-makers and the general public in a variety of different formats that will reach a diverse audience, such as integrating environmental education into school curricula (Strain et al. 2019) and children's media (e.g., Firth et al. 2016c), gaining corporate sponsorship (e.g., Living Seawalls 2019) and presenting at Soapbox Science events (Soapbox Science 2019). Eco-engineering information should be communicated without exaggeration or promise of desired results, with a foundational message that the best option for managing biodiversity and ecosystem functioning is to minimise interventions and work with nature whenever possible (e.g., sand banks, saltmarshes, mangroves; Airoldi et al. 2005; Hanley et al. 2014; Morris et al. 2018a).

Arguably more is learnt from failure than from success (see Firth et al. 2016b), and we advocate that reporting of failure is imperative. Reflecting the restricted distribution of eco-engineering trials grouped in a few geographical hotspots (i.e., Australia, Italy, Singapore, UK, USA; Firth et al. 2016a; Strain et al. 2017a) and limited types of structures studied (i.e., limited research on pontoons, offshore structures), we caution against unconsidered implementation of these recommendations without full consideration of the environmental context (see Table 2), overall management goals and desired target effects. With careful planning and consultation with the appropriate team of experts – local ecologists, engineers and societal stakeholders – even heavily stressed coastal urban ecosystems can support greater biodiversity, enhancing functioning, thereby providing valuable ecosystem services for both nature and society.

Acknowledgements The authors would like to acknowledge all those who have contributed information and photographs to this work. The individual stages of research were supported by the European Commission DELOS project ("Environmental Design of Low Crested Coastal Defence Structures"); and the THESEUS project ("Innovative technologies for safer European coasts in a changing climate"). Supplementary funding was provided by the Esmée Fairbairn Foundation (URBANE; "Urban Research on Biodiversity on Artificial and Natural coastal Environments: enhancing biodiversity by sensitive design"); Marine Ecological Solutions Ltd.; KESS ("Knowledge Economy Skills Scholarships"; part-funded by the European Social Fund [ESF] through the European Union's Convergence Programme [West Wales and the Valleys] administered by the Welsh Government); the Ecostructure project (part-funded by the European Regional Development Fund [ERDF] through the Ireland Wales Cooperation Programme 2014-2020); the British Ecological Society [small grant: 5546-6590]; and the Royal Society [International Exchanges Grant: IE150435].

References

Airoldi L, Beck MW (2007) Loss, status and trends for coastal marine habitats of Europe. Oceanogr Mar Biol Annu Rev 45:345–405

Airoldi L, Abbiati M, Beck MW, Hawkins SJ, Jonsson PR, Martin D, Moschella PS, Sundelöf A, Thompson RC, Åberg P (2005) An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. Coast Eng 52: 1073–1087. https://doi.org/10.1016/j.coastaleng.2005.09.007

Alexander, C. (2012). Field Assessment and Simulation of Shading from Alternative Dock Construction Materials. Technical report to the Office of Ocean and Coastal Resource Management, National Oceanic and Atmospheric Administration. Final Report, 18

ARC Marine (2019). http://www.arcmarine.co.uk/. Accessed 10 Nov 2017

Arenas F, Bishop JDD, Carlton JT, Dyrynda PJ, Farnham WF, Gonzalez DJ, Jacobs MW, Lambert C, Lambert G, Nielsen SE, Pederson JA, Porter JS, Ward S, Wood CA (2006a) Alien species and other notable records from a rapid assessment survey of marinas on the south coast of England. J Mar Biol Assoc UK 86:1329–1337. https://doi.org/10.1017/S0025315406014354

Arenas F, Sánchez I, Hawkins SJ, Jenkins SR (2006b) The invasibility of marine algal assemblages: role of functional diversity and identity. Ecology. 87:2851–2861. https://doi.org/10.1890/0012-9658(2006)87[2851:TIOMAA]2.0.CO;2

Arnold CL Jr, Gibbons CJ (1996) Impervious surface coverage: the emergence of a key environmental indicator. J Am Plan Assoc 62:243–258. https://doi.org/10.1080/01944369608975688

Baine M (2001) Artificial reefs: a review of their design, application, management and performance. Ocean Coast Manag 44:241–259. https://doi.org/10.1016/S0964-5691(01)00048-5

Barnes KB, Morgan J, Roberge M (2001) Impervious surfaces and the quality of natural and built environments. Department of Geography and Environmental Planning, Towson University, Baltimore

Bilkovic DM, Mitchell MM (2013) Ecological tradeoffs of stabilized salt marshes as a shoreline protection strategy: effects of artificial structures on macrobenthic assemblages. Ecol Eng 61:469–481. https://doi.org/10.1016/j.ecoleng.2013.10.011

Bishop JD, Wood CA, Lévêque L, Yunnie AL, Viard F (2015) Repeated rapid assessment surveys reveal contrasting trends in occupancy of marinas by non-indigenous species on opposite sides of the western English Channel. Mar Pollut Bull 95:699–706. https://doi.org/10.1016/j.marpolbul.2014.11.043

Bishop MJ, Mayer-Pinto M, Airoldi L, Firth LB, Morris RL, Loke LH, Hawkins SJ, Naylor LA, Coleman RA, Chee SY, Dafforn KA (2017) Effects of ocean sprawl on ecological connectivity: impacts and solutions. J Exp Mar Biol Ecol 492:7–30. https://doi.org/10.1016/j.jembe.2017.01.021

Blanton S, Thom R, Borde A, Diefenderfer H, Southard J (2002) Evaluation of methods to increase light under ferry terminals. Report prepared for Washington State Department of Transportation https://doi.org/10.2172/15001597

Browne MA, Chapman MG (2014) Mitigating against the loss of species by adding artificial intertidal pools to existing seawalls. Mar Ecol Prog Ser 497:119–129. https://doi.org/10.3354/meps10596

Bulleri F, Chapman M (2004) Intertidal assemblages on artificial and natural habitats in marinas on the north-west coast of Italy. Mar Biol 145:381–391

Bulleri F, Chapman MG (2010) The introduction of coastal infrastructure as a driver of change in marine environments. J Appl Ecol 47:26–35. https://doi.org/10.1111/j.1365-2664.2009.01751.x

Chapman MG (2012) Restoring intertidal boulder-fields as habitat for "specialist" and "generalist" animals. Restor Ecol 20:277–285. https://doi.org/10.1111/j.1526-100X.2011.00789.x

Chapman MG (2017) Intertidal boulder-fields: a much neglected, but ecologically important, intertidal habitat. In: Hawkins SJ, Evans AJ, Dale AC, Firth LB, Hughes DJ, Smith IP (eds) Oceanography and Marine Biology: an Annual Review

Chapman MG, Blockley DJ (2009) Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. Oecologia. 161: 625–635. https://doi.org/10.1007/s00442-009-1393-y

Chapman MG, Underwood AJ (2011) Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. J Exp Mar Biol Ecol 400:302–313. https://doi.org/10.1016/j.jembe.2011.02.025

Chee SY, Othman AG, Sim YK, Adam ANM, Firth LB (2017) Land reclamation and artificial islands: walking the tightrope between development and conservation. Glob Ecol Conserv 12:80–95. https://doi.org/10.1016.j.gecco.2017.08.005

Colwell RK (2009) Biodiversity: concepts, patterns, and measurement. In: Levin SA (ed) The Princeton guide to ecology. Princeton University Press, Princeton, pp 257–263

Connell SD (2001) Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoons and rocky reefs. Mar Environ Res 52:115–125

Coombes MA, Naylor LA, Viles HA, Thompson RC (2013) Bioprotection and disturbance: seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. Geomorphology. 202:4–14. https://doi.org/10.1016/j.geomorph.2012.09.014

Coombes MA, La Marca EC, Naylor LA, Thompson RC (2015) Getting into the groove: opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures. Ecol Eng 77:314–323. https://doi.org/10.1016/j.ecoleng.2015.01.032

Cordell JR, Toft JD, Munsch S, Goff M (2017) Benches, beaches, and bumps: how habitat monitoring and experimental science can inform urban seawall design. Living shorelines: the science and management of nature-based coastal protection. CRC press, Boca Raton, Florida

Coutts AD, Forrest BM (2007) Development and application of tools for incursion response: lessons learned from the management of the fouling pest *Didemnum vexillum*. J Exp Mar Biol Ecol 342:154–162. https://doi.org/10.1016/j.jembe.2006.10.042

Daffom KA, Johnston EL, Glasby TM (2009) Shallow moving structures promote marine invader dominance. Biofouling. 25:277–287. https://doi.org/10.1080 08927010802710618

Daffom KA, Glasby TM, Johnston EL (2012) Comparing the invasibility of experimental "reefs" with field observations of natural reefs and artificial structures. PLoS One 7:e38124. https://doi.org/10.1371/journal.pone.0038124

Daffom KA, Mayer-Pinto M, Morris RL, Waltham NJ (2015a) Application of management tools to integrate ecological principles with the design of marine infrastructure. J Environ Manag 158:61–73. https://doi.org/10.1016/j.jenvman.2015.05.001

Daffom KA, Glasby TM, Airoldi L, Rivero NK, Mayer-Pinto M, Johnston EL (2015b) Marine urbanization: an ecological framework for designing multifunctional artificial structures. Front Ecol Environ 13:82–90. https://doi.org/10.1890/140050

Del Río L, Gracia FJ, Benavente J (2013) Shoreline change patterns in sandy coasts. A case study in SW Spain. Geomorphology 196:252–266. https://doi.org/10.1016/j.geomorph.2012.07.027

Department for Communities and Local Government (2012) National Planning Policy Framework, London

Duarte CM, Pitt KA, Lucas CH, Purcell JE, Uye S, Robinson K, Brotz L, Decker MB, Sutherland KR, Malej A, Madin L, Mianzan H, Gili J-M, Fuentes V, Atienza D, Pagés F, Breitburg D, Malek J, Graham WM, Condon RH (2012) Is global ocean sprawl a cause of jellyfish blooms? Front Ecol Environ 11:91–97. https://doi.org/10.1890/110246

Dugan JE, Hubbard DM, Rodil IF, Revell DL, Schroeter S (2008) Ecological effects of coastal armoring on sandy beaches. Mar Ecol 29:160–170. https://doi.org/10.1111/j.1439-0485.2008.00231.x

Dugan J, Airoldi L, Chapman M, Walker S, Schlacher T (2011) Estuarine and coastal structures: environmental effects, a focus on shore and nearshore structures. Treatise Estuar Coast Sci 8:17–41. https://doi.org/10.1016/B978-0-12-374711-2.00802-0

Dyson K, Yocom K (2015) Ecological design for urban waterfronts. Urban Ecosyst 18:189–208. https://doi.org/10.1007/s11252-014-0385-9

ECOncrete Inc. (2019). http://www.econcretetech.com/. Accessed 15 June 2019

Ecostructure (2019). http://www.ecostructureproject.eu/. Accessed 10 May 2019

Evans AJ (2016) Artificial coastal defence structures as surrogate habitats for natural rocky shores: giving nature a helping hand. Aberystwyth University, Aberystwyth

Evans AJ, Firth LB, Hawkins SJ, Morris ES, Goudge H, Moore PJ (2016) Drill-cored rock pools: an effective method of ecological enhancement on artificial structures. Mar Freshw Res 67:123–130. https://doi.org/10.1071/MF14244

Evans AJ, Garrod B, Firth LB, Hawkins SJ, Morris-Webb ES, Goudge H, Moore PJ (2017) Stakeholder priorities for multi-functional coastal defence developments and steps to effective implementation. Mar Policy 75:143–155. https://doi.org/10.1016/j.marpol.2016.10.006

Evans AJ, Firth LB, Hawkins SJ, Hall AE, Ironside JE, Thompson RC, Moore PJ (2019) From ocean sprawl to blue-green infrastructure–a UK perspective on an issue of global significance. Environ Sci Pol 91:60–69

Everard, M (2017) Ecosystem Services: Key Issues, London and New York, Taylor & Francis.

Firth LB, Thompson RC, Bohn K, Abbiati M, Airoldi L, Bouma TJ, Bozzeda F, Ceccherelli VU, Colangelo MA, Evans A, Ferrario F, Hanley ME, Hinz H, Hoggart SPG, Jackson JE, Moore PJ, Morgan EH, Perkol-Finkel S, Skov MW, Strain EM, Belzen JV, Hawkins SJ (2014) Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. Coast Eng 87:122–135. https://doi.org/10.1016/j.coastaleng.2013.10.015

Firth LB, Knights AM, Bridger D, Evans AJ, Mieszkowska N, Hawkins SJ, Moore PJ, O'Connor NE, Sheehan EV, Thompson RC (2016a) Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. Oceanogr Mar Biol Annu Rev 54: 189–262. https://doi.org/10.1201/9781315368597

Firth LB, Browne KA, Knights AM, Hawkins SJ, Nash R (2016b) Eco-engineered rock pools: a concrete solution to biodiversity loss and urban sprawl in the marine environment. Environ Res Lett 11: 094015. https://doi.org/10.1088/1748-9326/11/9/094015

Firth LB, Evans A, Knights A, Nash R, Browne K, Moore P, Morris-Webb E, Goudge H, Hawkins S (2016c) Could this be a concrete solution to biodiversity loss? Environmental Science Journal for Teens. www.ScienceJournalForKids.org

Francis RA (2009) Perspectives on the potential for reconciliation ecology in urban riverscapes. CAB Rev: Perspect Agric Vet Sci Nutr Nat Resour 4:1–20. https://doi.org/10.1079/PAVSNNR20094073

Francis RA, Hoggart SP, Gurnell AM, Coode C (2008) Meeting the challenges of urban river habitat restoration: developing a methodology for the river Thames through Central London. Area. 40:435–445

French PW (2006) Managed realignment–the developing story of a comparatively new approach to soft engineering. Estuar Coast Shelf Sci 67:409–423. https://doi.org/10.1016/j.ecss.2005.11.035

Geist J, Hawkins SJ (2016) Habitat recovery and restoration in aquatic ecosystems: current progress and future challenges. Aquat Conserv Mar Freshwat Ecosyst 26:942–962. https://doi.org/10.1002/aqc.2702

Glasby TM, Connell SD (2001) Orientation and position of substrata have large effects on epibiotic assemblages. Mar Ecol Prog Ser 214:127–135

Glasby TM, Connell SD, Holloway MG, Hewitt CL (2007) Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? Mar Biol 151:887–895. https://doi.org/10.1007/s00227-006-0552-5

Govarets A, Lauwaert B (2009) Assessment of the impact of coastal defence structures. Biodiversity series: OSPAR Commission

Hair C, Bell J (1992) Effects of enhancing pontoons on abundance of fish: initial experiments in estuaries. Bull Mar Sci 51:30–36

Hall A, Herbert RH, Britton JR, Hull S (2018) Ecological enhancement techniques to improve habitat heterogeneity on coastal defence structures. Estuar Coast Shelf Sci. https://doi.org/10.1016/j.ecss.2018.05.025

Hall AE, Herbert RJH, Britton RJ, Boyd I, George N (2019) Shelving the coast with Vertipools: retrofitting artificial rock pools on coastal structures as mitigation for coastal squeeze. Front Mar Sci 6:456. https://doi.org/10.3389/fmars.2019.00456

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R, Watson R (2008) A global map of human impact on marine ecosystems. Science. 319:948–952. https://doi.org/10.1126/science.1149345

Hanley ME, Hoggart SPG, Simmonds DJ, Bichot A, Colangelo MA, Bozzeda F, Heurtefeux H, Ondiviela B, Ostrowski R, Recio M, Trude R, Zawadzka-Kahlau E, Thompson RC (2014) Shifting sands? Coastal protection by sand banks, beaches and dunes. Coast Eng 87:136–146. https://doi.org/10.1016/j.coastaleng.2013.10.020

Hashim R, Kamali B, Tamin NM, Zakaria R (2010) An integrated approach to coastal rehabilitation: mangrove restoration in Sungai haji Dorani. Malaysia Estuar Coast Shelf Sci 86:118–124. https://doi.org/10.1016/j.ecss.2009.10.021

Hawkins SJ, Southward AJ, Barrett RL (1983) Population structure of *Patella vulgata* L. during succession on rocky shores in southwest England. Oceanologica Acta, Special Issue

Hawkins SJ, Allen JR, Russell G, White KN, Conlan K, Hendry K, Jones HD (1992) Restoring and managing disused docks in inner city areas. In: Thayer G (ed) Restoring the Nation's Marine Environment. . pp 473–542

Heery EC, Bishop MJ, Critchley LP, Bugnot AB, Airoldi L, Mayer-Pinto M, Sheehan EV, Coleman RA, Loke LH, Johnston EL (2017) Identifying the consequences of ocean sprawl for sedimentary habitats. J Ex Mar Biol Ecol 492:31–48

Hobbs RJ, Arico S, Aronson J, Baron JS, Bridgewater P, Cramer VA, Epstein PR, Ewel JJ, Klink CA, Lugo AE, Norton D, Ojima D, Richardson DM, Sanderson EW, Valladares F, Vilà M, Zamora R, Zobel M (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. Glob Ecol Biogeogr 15:1–7. https://doi.org/10.1111/j.1466-822x.2006.00212.x

Hoggart SPG, Francis RA (2014) Use of coir rolls for habitat enhancement of urban river walls. Fundam Appl Limnol 185:19–30. https://doi.org/10.1127/fal/2014/0571

Hoggart SPG, Hanley ME, Parker DJ, Simmonds DJ, Bilton DT, Filipova-Marinova M, Franklin EL, Kotsev I, Penning-Rowsell EC, Rundle SD (2014) The consequences of doing nothing: the effects of seawater flooding on coastal zones. Coast Eng 87:169–182. https://doi.org/10.1016/j.coastaleng.2013.12.001

Holloway M, Connell S (2002) Why do floating structures create novel habitats for subtidal epibiota? Mar Ecol Prog Ser 235:43–52

Hulme PE (2014) EDITORIAL: bridging the knowing–doing gap: know-who, know-what, know-why, know-how and know-when. J Appl Ecol 51:1131–1136. https://doi.org/10.1111/1365-2664.12321

Jackson JE (2015) The influence of engineering design considerations on species recruitment and succession on coastal defence structures. Plymouth University, Plymouth

Kamali B, Hashim R, Akib S (2010) Efficiency of an integrated habitat stabilisation approach to coastal erosion management. Int J Phys Sci 5:1401–1405

Knights AM, Piet GJ, Jongbloed RH, Tamis JE, White L, Akoglu E, Boicenco L, Churilova T, Kryvenko O, Fleming-Lehtinen V, Leppanen JM, Galil BS, Goodsir F, Goren M, Margonski P, Moncheva S, Oguz T, Papadopoulou KN, Setala O, Smith CJ, Stefanova K, Timofte F, Robinson LA (2015) An exposure-effect approach for evaluating ecosystem-wide risks from human activities. ICES J Mar Sci 72:1105–1115. https://doi.org/10.1093/icesjms/fsu245

Knights AM, Firth LB, Thompson RC, Yunnie AL, Hiscock K, Hawkins SJ (2016) Plymouth—a world harbour through the ages. Reg Stud Mar Sci 8:297–307. https://doi.org/10.1016/j.rsma.2016.02.002

Knott NA, Underwood AJ, Chapman MG, Glasby TM (2004) Epibiota on vertical and on horizontal surfaces on natural reefs and on artificial structures. J Mar Biol Assoc UK 84:1117–1130. https://doi.org/10.1017/S0025315404010550h

Krauss J, Bommarco R, Guardiola M, Heikkinen RK, Helm A, Kuussaari M, Lindborg R, Öckinger E, Pärtel M, Pino J (2010) Habitat fragmentation causes immediate and time-delayed biodiversity loss at different trophic levels. Ecol Lett 13:597–605

Lai S, Loke LH, Bouma TJ, Todd PA (2018) Biodiversity surveys and stable isotope analyses reveal key differences in intertidal assemblages between tropical seawalls and rocky shores. Mar Ecol Prog Ser 587:41–53. https://doi.org/10.3354/meps12409

Li P, Li G, Qiao L, Chen X, Shi J, Gao F, Wang N, Yue S (2014) Modeling the tidal dynamic changes induced by the bridge in Jiaozhou Bay, Qingdao. China Cont Shelf Res 84:43–53. https://doi.org/10.1016/j.csr.2014.05.006

Lima JS, Zalmon IR, Love M (2019) Overview and trends of ecological and socioeconomic research on artificial reefs. Mar Environ Res. https://doi.org/10.1016/j.marenvres.2019.01.010

Liversage K, Chapman M (2018) Coastal ecological engineering and habitat restoration: incorporating biologically diverse boulder habitat. Mar Ecol Prog Ser 593:173–185. https://doi.org/10.3354/meps12541

Living Seawalls (2019). https://www.volvocars.com/au/why-volvo/discover/living-seawall. Accessed 09 May 2019

Lokesha N, Sundar V, Sannasiraj S (2013) Artificial reefs: a review. Int J Ocean Clim Syst 4:117–124

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH, Jackson JB (2006) Depletion, degradation, and recovery potential of estuaries and coastal seas. Science. 312:1806–1809. https://doi.org/10.1126/science.1128035

Ma Z, Melville DS, Liu J, Chen Y, Yang H, Ren W, Zhang Z, Piersma T, Li B (2014) Rethinking China's new great wall. Science. 346:912–914. https://doi.org/10.1126/science.1257258

Macdonald E, King EG (2018) Novel ecosystems: a bridging concept for the consilience of cultural landscape conservation and ecological restoration. Landsc Urban Plan 177:148–159

Malmqvist B, Rundle S (2002) Threats to the running water ecosystems of the world. Environ Conserv 29:134–153. https://doi.org/10.1017/S0376892902000097

Martins GM, Thompson RC, Neto AI, Hawkins SJ, Jenkins SR (2010) Enhancing stocks of the exploited limpet *Patella candei* d'Orbigny via modifications in coastal engineering. Biol Conserv 143:203–211. https://doi.org/10.1016/j.biocon.2009.10.004

Martins GM, Jenkins SR, Neto AI, Hawkins SJ, Thompson RC (2016) Long-term modifications of coastal defences enhance marine biodiversity. Environ Conserv 43:109–116. https://doi.org/10.1017/S0376892915000284

Masselink G, Hanley ME, Halwyn AC, Blake W, Kingston K, Newton T, Williams M (2017) Evaluation of salt marsh restoration by means of self-regulating tidal gate - Avon estuary, South Devon. UK Ecol Eng 106:174–190. https://doi.org/10.1016/j.ecoleng.2017.05.038

Mayer-Pinto M, Johnston EL, Bugnot AB, Glasby TM, Airoldi L, Mitchell A, Dafforn KA (2017) Building 'blue': an eco-engineering framework for foreshore developments. J Environ Manag 189:109–114. https://doi.org/10.1016/j.jenvman.2016.12.039

Mayer-Pinto M, Cole V, Johnston EL, Bugnot A, Hurst H, Airoldi L, Glasby T, Dafforn K (2018a) Functional and structural responses to marine urbanisation. Environ Res Lett 13(1):014009. https://doi.org/10.1088/1748-9326/aa98a5

Mayer-Pinto M, Dafforn K, Bugnot A, Glasby T, Johnston E (2018b) Artificial structures alter kelp functioning across an urbanised estuary. Mar Environ Res

McGranahan G, Balk D, Anderson B (2007) The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban 19:17–37. https://doi.org/10.1177/0956247807076960

Millennium Ecosystem Assessment (2005) Ecosystems and Human Well-being: Synthesis, Washington, DC, Island Press.

Milton SJ (2003) 'Emerging ecosystems' - a washing-stone for ecologists, economists and sociologists? S Afr J Sci 99:404–406

Mitsch WJ, Jorgensen SE (1989) Ecotechnology - an introduction to ecological engineering. Wiley, New York

Morris RL, Konlechner TM, Ghisalberti M, Swearer SE (2018a) From grey to green: efficacy of eco-engineering solutions for nature-based coastal defence. Glob Chang Biol. https://doi.org/10.1111/gcb.14063

Morris RL, Martinez AS, Firth LB, Coleman RA (2018b) Can transplanting enhance mobile marine invertebrates in ecologically engineered rock pools? Mar Environ Res 141:119–127

Morse NB, Pellissier PA, Cianciola EN, Brereton RL, Sullivan MM, Shonka NK, Wheeler TB, McDowell WH (2014) Novel ecosystems in the Anthropocene: a revision of the novel ecosystem concept for pragmatic applications. Ecol Soc 19. https://doi.org/10.5751/ES-06192-190212

Moschella PS, Abbiati M, Åberg P, Airoldi L, Anderson JM, Bacchiocchi F, Bulleri F, Dinesen GE, Frost M, Gacia E (2005) Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. Coast Eng 52:1053–1071. https://doi.org/10.1016/j.coastaleng.2005.09.014

Munsch SH, Cordell JR, Toft JD (2017) Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement. J Appl Ecol 54:1373–1384. https://doi.org/10.1111/1365-2664.12906

Nakamura M (1985) Evolution of artificial fishing reef concepts in Japan. Bull Mar Sci 37:271–278

Naylor LA, Kippen H, Coombes MA, Horton B, MacArthur M, Jackson N (2017) Greening the Grey: a framework for integrated green grey infrastructure (IGGI). University of Glasgow, Glasgow

Ng CSL, Lim SC, Ong JY, Teo LMS, Chou LM, Chua KE, Tan KS (2015) Enhancing the biodiversity of coastal defence structures: transplantation of nursery-reared reef biota onto intertidal seawalls. Ecol Eng 82:480–486. https://doi.org/10.1016/j.ecoleng.2015.05.016

Nordstrom KF (2014) Living with shore protection structures: a review. Estuar Coast Shelf Sci 150:11–23

Odum HT (1962) Man in the ecosystem. Conn Storrs Agric Exp Stat Bull 652:75–75

Odum HT, Odum B (2003) Concepts and methods of ecological engineering. Ecol Eng 20:339–361. https://doi.org/10.1016/j.ecoleng.2003.08.008

Ono K, Simenstad CA (2014) Reducing the effect of overwater structures on migrating juvenile salmon: an experiment with light. Ecol Eng 71:180–189. https://doi.org/10.1016/j.ecoleng.2014.07.010

Paalvast P, van Wesenbeeck BK, van der Velde G, de Vries MB (2012) Pole and pontoon hulas: an effective way of ecological engineering to increase productivity and biodiversity in the hard-substrate environment of the port of Rotterdam. Ecol Eng 44:199–209. https://doi.org/10.1016/j.ecoleng.2012.04.002

Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN, Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM, Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E (2005) Standards for ecologically successful river restoration. J Appl Ecol 42:208–217. https://doi.org/10.1111/j.1365-2664.2005.01004.x

Perkol-Finkel S, Sella I (2013) Ecologically active concrete for coastal and marine infrastructure: innovative matrices and designs. ICE Publishing, Edinburgh

Perkol-Finkel S, Sella I (2015) Harnessing urban coastal infrastructure for ecological enhancement vol 168. Thomas Telford Ltd https://doi.org/10.1680/jmaen.15.00017

Perkol-Finkel S, Zilman G, Sella I, Miloh T, Benayahu Y (2008) Floating and fixed artificial habitats: spatial and temporal patterns of benthic communities in a coral reef environment. Estuar Coast Shelf Sci 77:491–500. https://doi.org/10.1016/j.ecss.2007.10.005

Perkol-Finkel S, Ferrario F, Nicotera V, Airoldi L (2012) Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. J Appl Ecol 49:1457–1466. https://doi.org/10.1111/j.1365-2664.2012.02204.x

Perkol-Finkel S, Hadary T, Rella A, Shirazi R, Sella I (2017) Seascape architecture–incorporating ecological considerations in design of coastal and marine infrastructure. Ecol Eng 120:645–654. https://doi.org/10.1016/j.ecoleng.2017.06.051

Piola RF, Dafforn KA, Johnston EL (2009) The influence of antifouling practices on marine invasions. Biofouling. 25:633–644. https://doi.org/10.1080/08927010903063065

Polk MA, Eulie DO (2018) Effectiveness of living shorelines as an Erosion control method in North Carolina. Estuaries Coast 41:2212–2222. https://doi.org/10.1007/s12237-018-0439-y

Popkin G, (2015) Fourteen percent of U.S. coastline is covered in concrete. Science [Online]. Available: https://www.sciencemag.org/news/2015/08/fourteen-percent-us-coastline-covered-concrete. Accessed 19 December 2019

Radspinner RR, Diplas P, Lightbody AF, Sotiropoulos F (2010) River training and ecological enhancement potential using in-stream structures. J Hydraul Eng 136:967–980. https://doi.org/10.1061/(ASCE)HY.1943-7900.0000260

Reef Ball Foundation Inc (2017). http://www.reefball.org. Accessed 05 October 2019

Reef Design Lab (2019). www.reefdesignlab.com. Accessed 9 May 2017

Risinger JD (2012) Biologically dominated engineered coastal breakwaters. Louisiana State University, Baton Rouge

Russell G, Hawkins SJ, Evans LC, Jones HD, Holmes GD (1983) Restoration of a disused dock basin as a habitat for marine benthos and fish. J Appl Ecol 20:43–58

Schanze J, Olfert A, Tourbier JT, Gersdorf I, Schwager T (2004) Existing Urban River rehabilitation schemes. Final report of WP2 from urban river basin enhancement methods, funded by the European Commission

Sella I, Perkol-Finkel S (2015) Blue is the new green - ecological enhancement of concrete based coastal and marine infrastructure. Ecol Eng 84:260–272. https://doi.org/10.1016/j.ecoleng.2015.09.016

Shafer DJ (2002) Recommendations to minimize potential impacts to seagrasses from single-family residential dock structures in the Pacific northwest. US Army Corps of Engineers, Seattle

Shafer DJ, Lundin J (1999) Design and construction of docks to minimize Seagrass impacts. DTIC Document,

Small C, Nicholls RJ (2003) A global analysis of human settlement in coastal zones. J Coast Res:584–599

Smith K, Mezich R (1999) Comprehensive assessment of the effects of single family docks on seagrass in Palm Beach County, Florida. Office of Environmental Services, Tallahassee

SoapBox Science (2019). http://soapboxscience.org/. Accessed 16 Aug 2019

Southward AJ, Orton JH (1954) The effects of wave-action on the distribution and numbers of the commoner plants and animals living on the Plymouth breakwater. J Mar Biol Assoc UK 33:1–19

Stachowicz JJ, Whitlatch RB, Osman RW (1999) Species diversity and invasion resistance in a marine ecosystem. Science. 286:1577–1579. https://doi.org/10.1126/science.286.5444.1577

Stachowicz JJ, Fried H, Osman RW, Whitlatch RB (2002) Biodiversity, invasion resistance, and marine ecosystem function: reconciling pattern and process. Ecology. 83:2575–2590. https://doi.org/10.1890/0012-9658(2002)083[2575:BIRAME]2.0.CO;2

Steele J (1999) Deptford Creek surviving regeneration. Deptford Forum Pub., Deptford Forum Publishing, London

Stive MJF, de Schipper MA, Luijendijk AP, Aarninkhof SGJ, van Gelder-Maas C, van Thiel de Vries JSM, de Vries S, Henriquez M, Marx S, Ranasinghe R (2013) A new alternative to saving our beaches from sea-level rise: the sand engine. J Coast Res 29:1001–1008. https://doi.org/10.2112/JCOASTRES-D-13-00070.1

Strain EM, Olabarria C, Mayer-Pinto M, Cumbo V, Morris RL, Bugnot AB, Dafforn KA, Heery E, Firth LB, Brooks P, Bishop MJ (2017a) Eco-engineering urban infrastructure for marine and coastal biodiversity: which interventions have the greatest ecological benefit? J Appl Ecol 55:426–441. https://doi.org/10.1111/1365-2664.12961

Strain EMA, Morris RL, Coleman RA, Figueira WF, Steinberg PD, Johnston EL, Bishop MJ (2017b) Increasing microhabitat complexity on seawalls can reduce fish predation on native oysters. Ecol Eng 120:637–644. https://doi.org/10.1016/j.ecoleng.2017.05.030

Strain E, Alexander K, Kienker S, Morris R, Jarvis R, Coleman R, Bollard B, Firth L, Knights A, Grabowski J (2019) Urban blue: a global analysis of the factors shaping people's perceptions of the marine environment and ecological engineering in harbours. Sci Total Environ 658:1293–1305. https://doi.org/10.1016/j.scitotenv.2018.12.285

Sutton-Grier AE, Wowk K, Bamford H (2015) Future of our coasts: the potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. Environ Sci Pol 51:137–148. https://doi.org/10.1016/j.envsci.2015.04.006

Temmerman S, Meire P, Bouma TJ, Herman PMJ, Ysebaert T, De Vriend HJ (2013) Ecosystem-based coastal defence in the face of global change. Nature. 504:79–83. https://doi.org/10.1038/nature12859

Ten Voorde M, do Carmo JA, Neves M (2009) Designing a preliminary multifunctional artificial reef to protect the Portuguese coast. J Coast Res:69–79. https://doi.org/10.2112/07-0827

Tessler Z, Vörösmarty CJ, Grossberg M, Gladkova I, Aizenman H, Syvitski J, Foufoula-Georgiou E (2015) Profiling risk and sustainability in coastal deltas of the world. Science. 349:638–643. https://doi.org/10.1126/science.aab3574

Todd PA, Heery EC, Loke LH, Thurstan RH, Kotze DJ, Swan C (2019) Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities. Oikos. https://doi.org/10.1111/oik.05946

Toh KB, Ng CSL, Wu B, Toh TC, Cheo PR, Tun K, Chou LM (2017) Spatial variability of epibiotic assemblages on marina pontoons in Singapore. Urban Ecosyst 20:183–197. https://doi.org/10.1007/s11252-016-0589-2

Vitousek PM, Mooney HA, Lubchenco J, Melillo JM (1997) Human domination of Earth's ecosystems. Science. 277:494–499. https://doi.org/10.1126/science.277.5325.494

Waltham NJ, Sheaves M (2015) Expanding coastal urban and industrial seascape in the great barrier reef world heritage area: critical need for coordinated planning and policy. Mar Policy 57:78–84

Wicke D, Cochrane TA, O'Sullivan AD (2012) Atmospheric deposition and storm induced runoff of heavy metals from different impermeable urban surfaces. J Environ Manag 14:209–216. https://doi.org/10.1039/C1EM10643K

World Harbour Project (2018). http://www.worldharbourproject.org. Accessed 25 May 2017

Yellin, J.M. (2014). Evaluating the efficacy of an artificial floating island as fish habitat in the Chicago River: A pilot study. Thesis. University of Illinois at Urbana-Champaign. 42pp

Zanuttigh B, Angelelli E, Bellotti G, Romano A, Krontira Y, Troianos D, Suffredini R, Franceschi G, Cantù M, Airoldi L, Zagonari F, Taramelli A, Filipponi F, Jimenez C, Evriviadou M, Broszeit S (2015) Boosting blue growth in a mild sea: analysis of the synergies produced by a multi-purpose offshore installation in the northern Adriatic, Italy. Sustainability 7:6804–6853. https://doi.org/10.3390/su7066804

NPWS

Rockabill to Dalkey Island SAC (site code: 3000)

Conservation objectives supporting document - Marine Habitats and Species

Version 1

April 2013

Introduction

Rockabill to Dalkey Island SAC is designated for the marine Annex I qualifying interest Reefs (Figure 1) and the Annex II species *Phocoena phocoena* (harbour porpoise).

Intertidal and subtidal surveys were undertaken in 2010 and 2011 (MERC, 2010, MERC 2012a and MERC, 2012b). These data were used to determine the physical and biological nature of the Annex I habitat.

A considerable number of records of harbour porpoise have been gathered within the site and adjacent waters of the western Irish Sea, particularly over the last two decades (e.g. Pollock et al., 1997; Reid et al., 2003; Ó Cadhla et al., 2004; SCANS-II, 2008; Berrow et al., 2010; Berrow et al., 2011; Baines & Evans, 2012; Wall et al., 2012). In addition, targeted surveys of the harbour porpoise community were conducted in 2008 (Berrow et al., 2008) in order to investigate species occurrence, abundance, distribution and community composition in Irish coastal waters including those situated off the east coast.

Aspects of the biology and ecology of the Annex I habitat and Annex II species are provided in Section 1. The corresponding site-specific conservation objectives will facilitate Ireland delivering on its surveillance and reporting obligations under the EU Habitats Directive (92/43/EC).

Ireland also has an obligation to ensure that consent decisions concerning operations/activities planned for Natura 2000 sites are informed by an appropriate assessment where the likelihood of such operations or activities having a significant effect on the site cannot be excluded. Further ancillary information concerning the practical application of the site-specific objectives and targets in the completion of such assessments is provided in Section 2.

Section 1

Principal Benthic Communities

Within the Rockabill to Dalkey Island SAC two community types are recorded within the Annex I habitat, namely Intertidal reef community complex and Subtidal reef community complex, as summarised in table 1. A description of each community type is given below.

	Reefs (1170)
Intertidal reef community complex	✓
Subtidal reef community complex	✓

Table 1 The community types recorded in Rockabill to Dalkey Island SAC

Estimated areas of each community type within the Annex I habitat, based on interpolation, are given in the objective targets in Section 2.

The development of a community complex target arises when an area possesses similar abiotic features but records a number of biological communities that are not regarded as being sufficiently stable and/or distinct temporally or spatially to become the focus of conservation efforts. In this case, examination of the available data from Rockabill to Dalkey Island SAC identified a number of biological communities whose species composition overlapped significantly. Such biological communities are grouped together into what experts consider are sufficiently stable units (i.e. a complex) for conservation targets.

INTERTIDAL REEF COMMUNITY COMPLEX

This reef community complex is recorded on the islands within this site and on the south coast of Howth. The exposure regime of the complex ranges from exposed to moderately exposed reef (Figure 2). Exposed reef is recorded on the east side of Dalkey Island, on the east and southern shores of Ireland's Eye and on all shores of Rockabill and the Muglins. Moderately exposed reef occurs on the western shores of Dalkey and at Howth and Ireland's Eye.

The substrate here is that of flat and sloping bedrock; around Rockabill cobbles and boulders occur on bedrock. Vertical cliff faces are found on the north and northeast shores of Ireland's Eye; steep shorelines are a feature of Rockabill, Muglins and the eastern shore of Dalkey Island.

The species associated with this community complex include the fucoids *Fucus serratus*, *F. vesiculosus*, *F. spiralis*, *Ascophyllum nodosum* and *Pelvetia canaliculata*, the barnacle *Semibalanus balanoides* and the bivalve *Mytilus edulis* (Table 2). In the more exposed areas *Semibalanus balanoides* and *Mytilus edulis* dominate while in the more moderately exposed

areas it is the fucoid species that are more abundant. The gastropods *Patella vulgata* and *Littorina* sp. are also recorded here. In all area the kelp species *Laminaria digitata* is recorded at the low water mark.

Species associated with the Intertidal reef community complex	
Fucus serratus	*Fucus spiralis*
Fucus vesiculosus	*Semibalanus balanoides*
Ascophyllum nodosum	*Mytilus edulis*
Pelvetia canaliculata	*Patella vulgata*
Laminaria digitata	*Littorina* sp.

Table 2 Species associated with the Intertidal reef community complex.

SUBTIDAL REEF COMMUNITY COMPLEX

This community complex is recorded off the islands within the site and also off the coast between Lambay Island and Rush Village (Figure 2). The exposure regime here ranges from moderately exposed reef at the Muglins to exposed reef over the remainder of the site.

The substrate ranges from that of flat and sloping bedrock, to bedrock with boulders and also a mosaic of cobbles and boulders. Vertical rock walls occur on the north and east of Ireland's Eye and to the east of Lambay Island where they give way to sloping bedrock at c.20m. In the northern reaches of the site, at Rockabill and Ireland's Eye, areas of both sediment scouring and a thin veneer of silt were observed on the reefs; the veneer of silt was also recorded at Lambay Island. In the south of the site, strong currents were experienced in the channel between Dalkey Island and the Muglins.

In the shallow reaches of this community complex (<10m) a sparse covering of the kelp species *Laminaria hyperborea* occurs with an undercover of red algal species including *Hypoglossum hypoglossoides*, *Brongniartella byssoides, Membranoptera alata, Phycodrys rubens* and *Delesseria sanguinea*. In deeper water (>10m) the anemone *Alcyonium digitatum* occurs in moderate abundances and *Metridium senile* also being recorded here (Table 3). Faunal crusts of bryozoans such as *Flustra foliacea* and *Chartella papyracea* and hydroids including *Nemertesia antennina* are recorded in deeper water (>20m) along with the ascidian *Aplidium punctum*. The asteroid *Asterias rubens* is recorded throughout the site while the barnacle *Balanus crenatus*, the echinoderms *Echinus esculentus* and *Antedon bifida* also occur here.

In general, it was noted that where the reef was subjected to the effects of sediment, either through scouring or settlement of silt, low numbers of species and individuals occurred.

Species associated with the Subtidal reef community complex	
Alcyonium digitatum	*Echinus esculentus*
Asterias rubens	*Brongniartella byssoides*
Metridium senile	*Pomatoceros triqueter*
Necora puber	*Chartella papyracea*
Laminaria hyperborea	*Antedon bifida*
Nemertesia antennina	*Flustra foliacea*
Balanus crenatus	*Membranoptera alata*
Aplidium punctum	*Phycodrys rubens*
Hypoglossum hypoglossoides	*Delesseria sanguinea*
Sagartia elegans	

Table 3 Species associated with the Subtidal reef community complex.

Annex II Marine mammals

***PHOCOENA PHOCOENA* (HARBOUR PORPOISE)**

This small toothed cetacean species (from the mammal Order Cetacea - whales, dolphins and porpoises) occurs in estuarine, coastal and offshore waters in which it carries out breeding, foraging, resting, social activity and other life history functions. Its distribution extends predominantly throughout continental shelf waters and the species may range over many hundreds or thousands of kilometres. As air-breathing mammals, harbour porpoises must return to the water surface to breathe but they are otherwise wholly aquatic. Individual porpoises of all ages use sound as their primary sensory tool in order to navigate, communicate, avoid predators, or locate and facilitate the capture of prey under water. Group sizes tend to be small (i.e. in single figures, more commonly 2 to 3 individuals) although larger aggregations may occasionally be recorded, particularly in the summer months.

Harbour porpoise breed annually in Ireland, predominantly during the months of May to September. The principal calving period in Irish waters is thought to occur in the months of May and June, although it may extend throughout the summer months and into early autumn. Newborn calves are weaned before they are one year old. Mating commonly occurs several weeks after the calving season.

The occurrence of harbour porpoises within a prescribed marine area can be estimated using visual observation and passive acoustic methods in order to deliver an assessment of community or population size (i.e. relative abundance or absolute abundance), density and distribution. The size, community structure and distribution or habitat use of harbour porpoise inhabiting Rockabill to Dalkey Island SAC are not fully understood. In acknowledging limitations in the understanding of aquatic habitat use by the species within the site, it should be noted that all suitable aquatic habitat (Figure 3) is considered relevant to the species range and ecological requirements at the site and is therefore of potential use by harbour porpoises.

Survey effort targeting the 2008 summer-autumn season delivered initial estimates of 0.54-6.93 animals per km^2 within the northern half of the site (overall estimate across four surveys: 2.03 individuals per km^2, N=211±47 individuals, 95% Confidence Intervals: 137-327, Coefficient of Variation=0.23) and 0.48-2.05 animals per km^2 within the southern half of the site, including outer Dublin Bay (overall estimate across four surveys: 1.19 individuals per km^2, N=138±33 individuals, 95% Confidence Intervals: 86-221, Coefficient of Variation=0.24). While the numbers of harbour porpoise encountered during any survey within the site are variable, additional acoustic data plus casual and effort-related sighting rates from coastal observation stations are significant for the east coast of Ireland and, comparatively high group sizes (>5 individuals) have been recorded from this area. The species is present at the site in all seasons, while important cohorts within the harbour porpoise community such as adults,

juveniles and newborn calves have also been recorded within the site, including during the calving/breeding season.

Harbour porpoise is a successful aquatic predator that feeds on a wide variety of fish, cephalopod and crustacean species occurring in the water column or close to the seabed. Dive depths in excess of 200m have been recorded for the species. Foraging areas for harbour porpoise are often associated with areas of strong tidal current and associated eddies; therefore the occurrence of porpoises close to shore or adjacent to islands and prominent headlands is commonly reported. However gaps remain in the knowledge of the species foraging ecology within Rockabill to Dalkey Island SAC and the available data may be biased toward particular locations due to the nature of survey effort and opportunistic reports from a range of sources. No detailed information is currently available on individual or group movements by harbour porpoise within or into and out of the site, nor is it known whether individuals or groups of the species demonstrate any faithfulness to the site (i.e. site fidelity or residency). Nevertheless, the consistent annual and seasonal occurrence of the species at the site, its occurrence during the calving/breeding period and density/population estimates available to date all indicate the importance of this coastal site for the species.

Section 2

Appropriate Assessment Notes

Many operations/activities of a particular nature and/or size require the preparation of an environmental impact statement of the likely effects of their planned development. While smaller operations/activities (i.e. sub threshold developments) are not required to prepare such statements, an appropriate assessment and Natura Impact Statement is required to inform the decision-making process in or adjacent to Natura 2000 sites. The purpose of such an assessment is to record in a transparent and reasoned manner the likely effects on a Natura 2000 site of a proposed development. General guidance on the completion of such assessments has been prepared and is available at www.npws.ie.

Annex I Habitats

It is worth considering at the outset that in relation to Annex I habitat structure and function, the extent and quality of all habitats varies considerably in space and time and marine habitats are particularly prone to such variation. Habitats which are varying naturally, i.e. biotic and/or abiotic variables are changing within an envelope of natural variation, must be considered to have favourable conservation condition. Anthropogenic disturbance may be considered significant when it causes a change in biotic and/or abiotic variables in excess of what could reasonably be envisaged under natural processes. The capacity of the habitat to recover from this change is obviously an important consideration (i.e. habitat resilience) thereafter.

This Department has adopted a prioritized approach to conservation of structure and function in marine Annex I habitats.

1. Those communities that are key contributors to overall biodiversity at a site by virtue of their structure and/or function (keystone communities) and their low resilience should be afforded the highest degree of protection and any significant anthropogenic disturbance should be avoided.
2. In relation to the remaining constituent communities that are structurally important (e.g. broad sedimentary communities) within an Annex I marine habitat, there are two considerations.
    2.1. Significant anthropogenic disturbance may occur with such intensity and/or frequency as to effectively represent a continuous or ongoing source of disturbance over time and space (e.g. effluent discharge within a given area). Drawing from the principle outlined in the European Commission's Article 17 reporting framework that disturbance of greater than 25% of the area of an Annex I habitat represents unfavourable conservation status, this Department takes the view that licensing of activities likely to cause continuous disturbance of each community type should not exceed an approximate area of 15%. Thereafter, an increasingly cautious approach

is advocated. Prior to any further licensing of this category of activities, an inter-Departmental management review (considering *inter alia* robustness of available scientific knowledge, future site requirements, etc) of the site is recommended.

2.2. Some activities may cause significant disturbance but may not necessarily represent a continuous or ongoing source of disturbance over time and space. This may arise for intermittent or episodic activities for which the receiving environment would have some resilience and may be expected to recover within a reasonable timeframe relative to the six-year reporting cycle (as required under Article 17 of the Directive). This Department is satisfied that such activities could be assessed in a context-specific manner giving due consideration to the proposed nature and scale of activities during the reporting cycle and the particular resilience of the receiving habitat in combination with other activities within the designated site.

The following technical clarification is provided in relation to specific conservation objectives and targets for Annex I habitats to facilitate the appropriate assessment process:

Objective **To maintain the favourable conservation condition of Reefs in Rockabill to Dalkey Island SAC, which is defined by the following list of attributes and targets**

Target 1	The permanent area is stable or increasing, subject to natural processes.

- The area of this habitat represents the minimum estimated area of reef at this site and underestimates the actual area due to the presence of vertical rock wall and steeply sloping rock within the reef habitat.
- This target refers to activities or operations that propose to permanently remove habitat from the site, thereby reducing the permanent amount of habitat area. It does not refer to long or short term disturbance of the biology of a site.
- Early consultation or scoping with the Department in advance of formal application is advisable for such proposals.

Target 2	The distribution of reefs is stable or increasing, subject to natural processes.

- The likely distribution of reef habitat in this SAC is indicated in figure 1.
- This target refers to activities or operations that propose to permanently remove reef habitat, thus reducing the range over which this habitat occurs within the site. It does not refer to long or short term disturbance of the biology of reef habitats.
- Early consultation or scoping with the Department in advance of formal application is advisable for such proposals.

Target 3	Conserve the following community types in a natural condition: Intertidal reef community complex and Subtidal reef community complex

- A semi-quantitative description of the communities has been provided in Section 1.
- An interpolation of their likely distribution is provided in figure 2.
- The estimated areas of the communities within the Reefs habitat given below are based on spatial interpolation and therefore should be considered indicative. In addition, as this habitat contains areas of vertical rock wall and steeply sloping rock, the mapped community extents will be underestimated:
  - Intertidal reef community complex - 10ha
  - Subtidal reef community complex - 172ha

- This target relates to the structure and function of the reef and therefore it is of relevance to those activities that may cause disturbance to the ecology of the habitat.
- Significant continuous or ongoing disturbance of communities should not exceed an approximate area of 15% of the interpolated area of each community type, at which point an inter-Departmental management review is recommended prior to further licensing of such activities.
- Proposed activities or operations that cause significant disturbance to communities but may not necessarily represent a continuous or ongoing source of disturbance over time and space may be assessed in a context-specific manner giving due consideration to the proposed nature and scale of activities during the reporting cycle and the particular resilience of the receiving habitat in combination with other activities within the designated site.

Annex II species

The following technical clarification is provided in relation to specific conservation objectives and targets for Annex II species to facilitate the appropriate assessment process:

Objective **To maintain the favourable conservation condition of harbour porpoise in Rockabill to Dalkey Island SAC, which is defined by the following list of attributes and targets**

Target 1	Species range within the site should not be restricted by artificial barriers to site use.

- This target may be considered relevant to proposed activities or operations that will result in the permanent exclusion of harbour porpoise from part of its range within the site, or will permanently prevent access for the species to suitable habitat therein.
- It does not refer to short-term or temporary restriction of access or range.
- Early consultation or scoping with the Department in advance of formal application is advisable for proposals that are likely to result in permanent exclusion.

Target 2	Human activities should occur at levels that do not adversely affect the harbour porpoise community at the site.

- Proposed activities or operations should not introduce man-made energy (e.g. aerial or underwater noise, light or thermal energy) at levels that could result in a significant negative impact on individuals and/or the community of harbour porpoise within the site. This refers to the aquatic habitats used by the species in addition to important natural behaviours during the species annual cycle.
- This target also relates to proposed activities or operations that may result in the deterioration of key resources (e.g. water quality, feeding, etc) upon which harbour porpoises depend. In the absence of complete knowledge on the species ecological requirements in this site, such considerations should be assessed where appropriate on a case-by-case basis.
- Proposed activities or operations should not cause death or injury to individuals to an extent that may ultimately affect the harbour porpoise community at the site.

Bibliography:

Baines, M.E. & Evans, P.G.H. (2012). Atlas of the marine mammals of Wales. CCW Marine Monitoring Report No. 68, 2nd edition. Countryside Council for Wales. 143pp.

Berrow, S.D., Whooley, P., O'Connell, M. & Wall, D. (2010). Irish Cetacean Review (2000-2009). Irish Whale and Dolphin Group, Kilrush, Co. Clare. 60pp.

Berrow, S. D., Hickey, R., O'Brien, J., O'Connor, I. and McGrath, D. (2008). Harbour porpoise survey 2008. Unpublished report to the National Parks and Wildlife Service, Department of the Environment, Heritage and Local Government, Dublin. Irish Whale and Dolphin Group. 33pp.

Berrow, S.D., O'Brien, J., Ryan, C., McKeogh, E. & O'Connor, I. (2011). Inshore boat-based surveys for cetaceans: Irish Sea. Report to the National Parks and Wildlife Service. Irish Whale and Dolphin Group. 24pp.

MERC (2010). Irish Sea Reef Survey Project Report. Carried out by MERC on behalf of National Parks and Wildlife Service, Department of Environment, Heritage and Local Government.

MERC (2012a). Intertidal Reef Survey of Lambay Island SAC and SPA, Rockabill Island SPA, Ireland's Eye SAC, Dalkey Islands SPA and Muglins. Carried out by MERC on behalf of the Marine Institute in partnership with National Parks and Wildlife Service, Department of Environment, Heritage and Local Government.

MERC (2012b). Subtidal Reef Survey of Lambay Island SAC and SPA, Rockabill Island SPA, Ireland's Eye SAC, Dalkey Islands SPA and Muglins. Carried out by MERC on behalf of the Marine Institute in partnership with National Parks and Wildlife Service, Department of Environment, Heritage and Local Government.

Ó Cadhla, O., Mackey, M., Aguilar de Soto, N., Rogan, E. & Connolly, N. (2004). Cetaceans and Seabirds of Ireland's Atlantic Margin. Volume II - Cetacean distribution and abundance. Report on research carried out under the Irish Petroleum Infrastructure Programme (PIP): Rockall Studies Group (RSG) projects 98/6 and 00/13, Porcupine Studies Group project P00/15 and Offshore Support Group (OSG) project 99/38. 82pp.

Pollock, C.M., Reid, J.B., Webb, A. & Tasker, M.L. (1997). The distribution of seabirds and cetaceans in the waters around Ireland. JNCC Report No. 267. Joint Nature Conservation Committee, Peterborough. 167pp.

Reid, J.B., Evans, P.G.H. & Northridge, S.P. (2003). Atlas of Cetacean Distribution in North-west European Waters. Joint Nature Conservation Committee, Peterborough, 76pp.

SCANS-II (2008). Small Cetaceans in the European Atlantic and North Sea. Final Report to the European Commission under project LIFE04NAT/GB/000245. Sea Mammal Research Unit, Gatty Marine Laboratory, University of St Andrews, St Andrews, Fife, KY16 8LB.

Wall, D., O'Brien, J., Kavanagh, L., Ryan, C., Hunt, L. & Fennelly, S. (2012). Monitoring of spatial and temporal habitat use and abundance of cetaceans. In S.D. Berrow, J.O'Brien, I. O'Connor, D. McGrath & D. Wall. Marine Mammals and Megafauna in Irish Waters - behaviour, distribution and habitat use. Final project report for Grant-Aid Agreement No. PBA/ME/07/005(02) under the Sea Change Strategy with the support of the Marine Institute, the Marine Research Sub-Programme of the National Development Plan 2007-2013 and the Department of Arts, Heritage and the Gaeltacht. Galway-Mayo Institute of Technology, Galway. p.1-187.

Figure 1. Extent of Reefs in Rockabill to Dalkey Island SAC

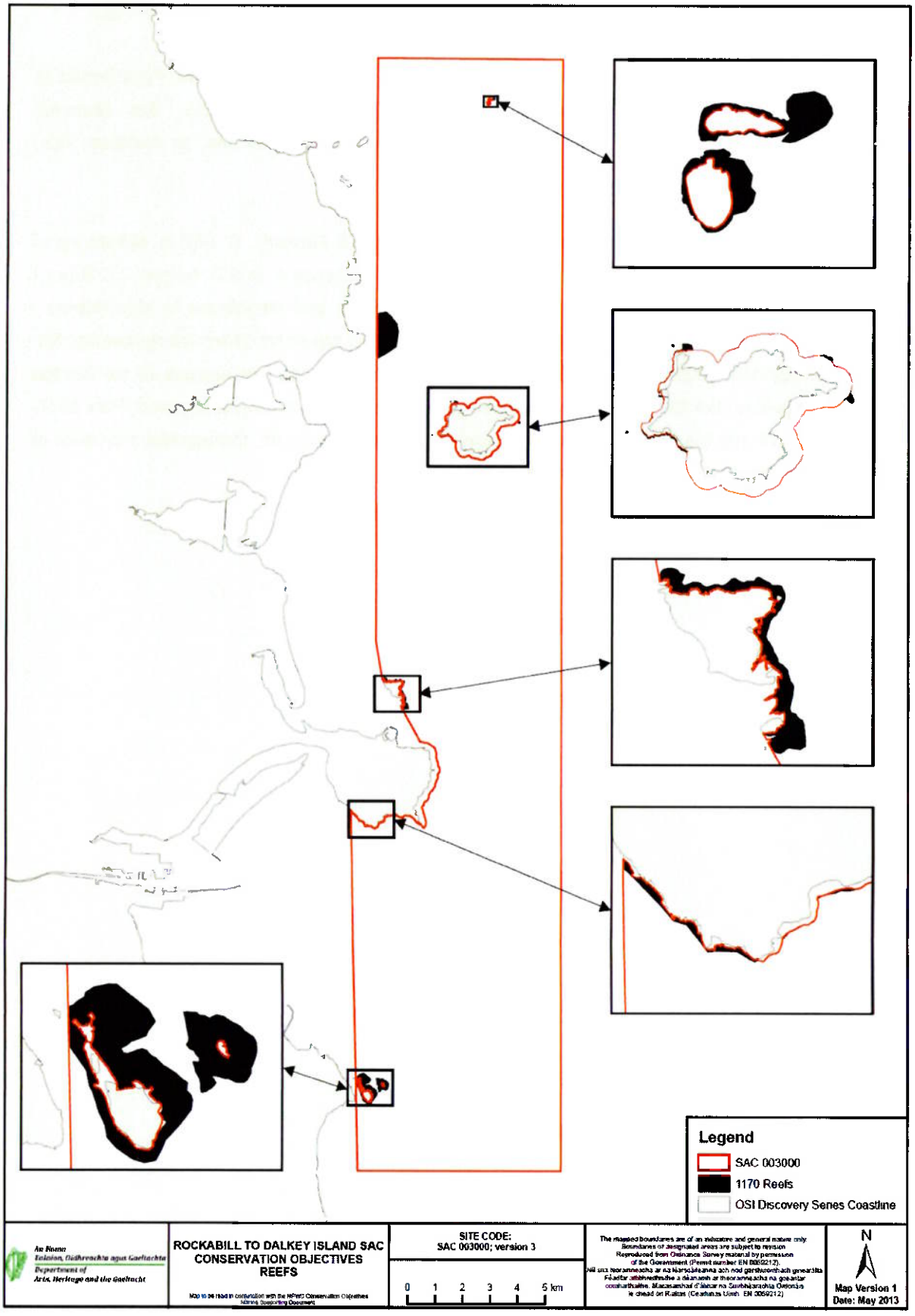

Figure 2. Distribution of community types in Rockabill to Dalkey Island SAC

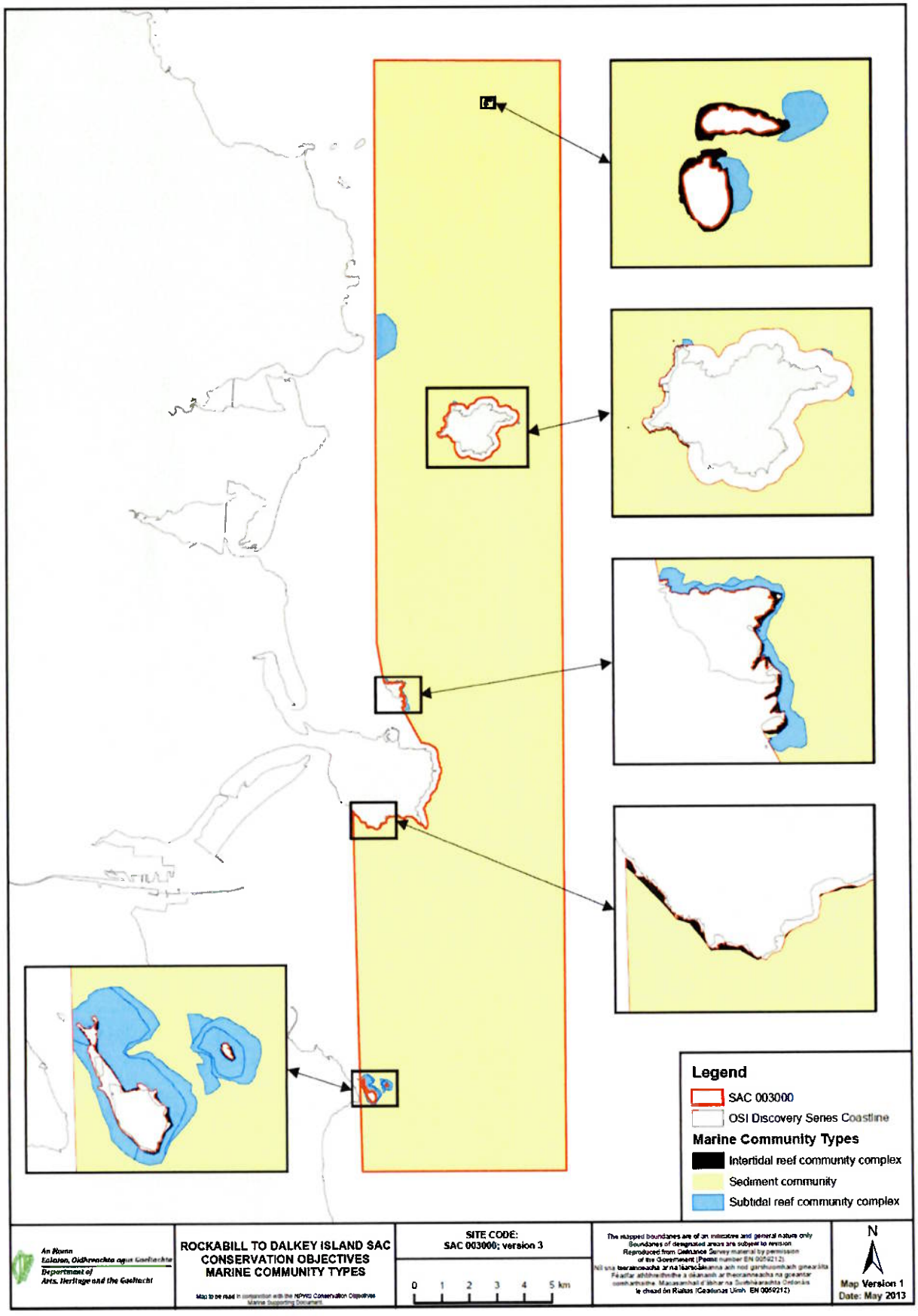

Figure 3. Suitable habitat of *Phocoena phocoena* within Rockabill to Dalkey Island SAC