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

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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

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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

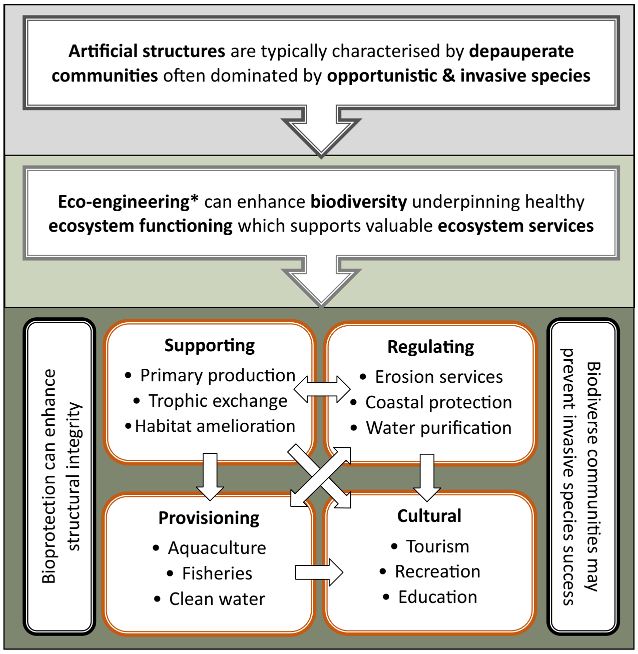

Fig. 1 Typical characteristics of artificial structures and how eco-engineering optimises the potential ecosystem services as outlined by the Millennium Ecosystem Assessment (red boxes) (Millennium Ecosystem Assessment 2005; Everard 2017). The arrows show the potential linkages and feedbacks between 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.

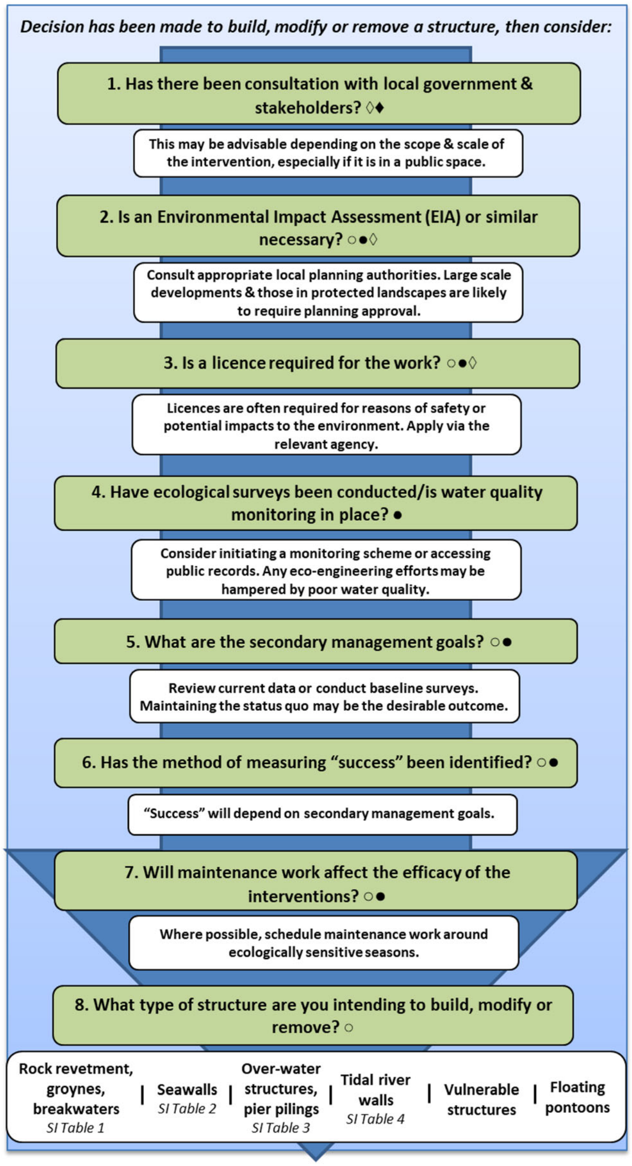

Fig. 2 Considerations for developers and managers relating to eco-engineering decisions for coastal and marine artificial structures. Question #8 prompts the user to choose the structure type of interest and refer to the associated section (in-text) and table (Supplementary Information) for design details 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.

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