Marine urbanisation: an ecological framework for designing multifunctional artificial structures

Katherine A. Dafforn[1], Tim M. Glasby[2], Laura Airoldi[3], Natalie K. Rivero[1], Mariana Mayer-Pinto[1] and Emma L. Johnston[1]

[1]Evolution and Ecology Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, NSW, Australia

[2]Port Stephens Fisheries Centre, New South Wales Department of Primary Industries, Port Stephens, NSW, Australia

[3]Dipartimento di Scienze Biologiche, Geologiche ed Ambientali, University of Bologna, Ravenna, Italy and Hopkins Marine Station, Stanford University, Pacific Grove, CA, USA

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In a nutshell

- Marine urbanisation is increasing
- Impacts of artificial structures are widely documented, but mitigation strategies are still in their infancy
- Designing marine infrastructure with many purposes could improve targeted functions, and reduce ecological impacts

Abstract

Underwater cities have long been the subject of science fiction novels, but the 'urban sprawl' of artificial structures from terrestrial to marine environments is occurring with widespread ecological consequences. The practice of combining ecological principles with the planning, design and operation of marine artificial structures is gaining in popularity, and examples of successful engineering applications are increasing. Here we use case studies to explore marine ecological engineering in practice, and introduce a conceptual framework for designing artificial structures with multiple functions. The rate of marine urbanization will almost certainly escalate and "aquatourism" is driving the development of underwater accommodations. We show that current and future marine developments could be designed to reduce ecological impacts while maximising ecosystem services.

Introduction

Urban sprawl is extending into marine environments with the construction of artificial structures. In areas of Europe, the United States, Australia and Asia more than 50% of the shoreline is now modified by artificial structures that include groynes and breakwaters for coastal defence, marinas to support boating infrastructure. The construction of offshore aquaculture facilities and platforms for oil and gas exploration is also increasing (Dugan et al. 2011) (Figure 1). Despite habitat loss associated with marine urban sprawl (Airoldi and Beck 2007), it is only recently that the ecological impacts of artificial structures have been reviewed (Bulleri and Chapman 2010) and mitigation attempted (e.g. Browne and Chapman 2011). The construction of marine artificial structures will continue and most likely escalate in the future. There will be a need for more coastal defences around ports, harbours and coastal cities for protection from sea level rise and an increasing intensity of coastal storms and flooding (Asif and Muneer 2007). In addition there are increasing demands for coastal urban development, aquaculture facilities and offshore energy infrastructures (Asif and Muneer 2007).

Human use of marine environments has modified the global seascape and ecosystem functions (Dugan et al. 2011). "Ecological engineering", which is the incorporation of ecological goals and principles into the design of marine artificial structures (Bergen et al. 2001), can help limit the decline of marine species or habitats, maintain vital ecosystem services, and ensure more efficient use of resources. Here we review selected research on ecological engineering of artificial structures in the marine environment. A systematic review was not used as much of the relevant literature crosses disciplines and is from books, conference proceedings and grey literature that would not have appeared in systematic searches. Our narrative review introduces a conceptual framework for the design of structures that both reduce ecological impacts and provide multiple ecosystem functions, with supporting case studies.

The ecological consequences of marine urban sprawl

Artificial structures have local and regional impacts on marine ecosystems (reviewed by Govaerts and Lauwaert 2009, Bulleri and Chapman 2010, Dugan et al. 2011). Here we briefly review four major types of impact including 1) direct physical disturbance, 2) addition of artificial habitat, 3) indirect physical disturbance and 4) noise and light pollution and contamination. We explore how these impacts, which occur at local and regional scales,

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relate to different engineering stages (construction, operation and decommissioning, Figure 2) in order to help identify ecological engineering options.

Local scale effects

Physical disturbances arise from the addition (during construction) or removal (during decommissioning) of artificial construction materials (Figure 2). Recipient native habitats are often damaged or destroyed, and associated assemblages lost. For example, up to 70% of coastlines have been modified globally (WebTable 1). Offshore, ca. 12.5m^2 of seabed can be lost in the footprint of a 4m diameter turbine with 10m scour protection (Wilson and Elliott 2009) and the projected loss in the United Kingdom is up to 8600km^2 of seabed by 2020 (WebTable 1). Dredging during construction can displace between 1539-2356m^3 sediment per turbine into the water column (WebTable 1) and removal of underwater scaffolding increases turbidity that can negatively affect marine plants and animals (Gill 2005). During their operation, artificial structures can alter water flow, and sediment deposition and have subsequent effects to infaunal assemblages and productivity (Coates et al. in press). Marinas surrounded by breakwaters can increase turbidity and reduce flow by up to 30% (WebTable 1). The materials added during construction change the type of resources available, for example by increasing the proportion of sheltered, shaded, vertical and floating surfaces (Figure 1, 2). The orientation of exposed defence structures seaward or landward also affects the colonisation of organisms such as barnacles (more on landward) and limpets (more on seaward) (Moschella et al. 2005), and the surface texture of construction materials can influence the settlement and recruitment of marine benthic organisms (Coombes et al. 2009). These structural factors (among others) support different assemblages to those in natural reef habitats (Moschella et al. 2005, Bulleri and Chapman 2010) and may facilitate non-indigenous species (Dafforn et al. 2012). Non-indigenous species have been found to occupy up to 80% more space on pilings or pontoons compared to natural reef (WebTable 1). The physical design of artificial structures therefore has major consequences at multiple trophic levels and across seascapes.

During all engineering stages, artificial structures may be linked to a variety of pollution sources (Figure 2). This includes artificial light from offshore platforms (Depledge et al. 2010), noise and vibration during wind farm operation (Gill 2005), or contamination around vessel berths (Dafforn et al. 2009a). Night lighting and operational lights on offshore structures can result in disorientation of birds, and the death of migratory animals

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(WebTable 1). Additionally, the noise and vibrations from pile driving during construction can reach levels that increase fish eggs and embryo mortality by 25% and 85% respectively, and are associated with disorientation and eardrum rupture in marine mammals and species avoidance (WebTable 1). Estuarine infrastructures, such as marinas, are often hotspots of contamination from antifouling paints. Copper and lead sediment concentrations were 30-80% higher inside a semi-enclosed marina than outside (WebTable 1) and this has been linked to the facilitation of non-indigenous species (Piola et al. 2009).

Regional scale effects

Although marine urbanisation is a global issue, we still lack a comprehensive understanding of the regional ecological consequences of associated habitat loss and changes in connectivity (Airoldi and Beck 2007). The homogeneity of design and construction materials has been posited as a driving force behind the establishment of a suite of fouling species that dominate artificial structures in harbours and coastal areas throughout the world (Dafforn et al. 2009a, Piola et al. 2009) (Figure 2). This is analogous to terrestrial urbanisation, where uniform construction materials have been implicated in the spread of non-indigenous species and increasing global biotic homogeneity (McKinney 2006). Similarly, the popularity of pontoons has created shallow, floating stepping-stones for fouling non-indigenous species (Dafforn et al. 2009b) in almost every estuary worldwide (WebTable 1). Offshore platforms also provide opportunities for non-indigenous species with 11% of species found on oil platforms off the Brazilian coast classified as exotic (WebTable 1).

Urbanization can also result in habitat fragmentation and affect regional connectivity (Fischer and Lindenmayer 2007). On land, roads, large property developments and cities can create either barriers or corridors to dispersal (Brown et al. 2006). Similarly, the construction of coastal and offshore infrastructure and related changes to water flow can either restrict or facilitate the transportation of larvae and food (Floerl and Inglis 2003). In the North Adriatic sea, for example, >190km of coastal and offshore infrastructure in a predominantly sedimentary environment has increased rocky substrates and facilitated the regional spread of invasive species that require hard surfaces for dispersal and recruitment (WebTable 1).

Defining multifunctional targets for artificial structures

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Successful developments in terrestrial urban ecology and artificial reef design demonstrate that artificial structures can be designed as both physical infrastructure and also to provide critical services (Gaston et al. 2013). These services include habitat provision, pollution abatement, and facilities for recreation, education and food production.

Lessons from terrestrial urban design

The design of buildings and spaces in terrestrial systems has improved following the understanding that urban areas can be planned for many purposes. “Green” roofs and walls, which are plant assemblages established on the tops and sides of buildings, reduce noise and heat escape by absorbing more sound and thermal energy than a hard surface (Rowe 2011). Recent evidence shows they can reduce air pollution by up to 37% and trap 60-79% of annual stormwater (WebTable 2). “Green” roofs and walls can be seeded with target species to create habitat for native plants (Kadas 2006), including rare and endangered species (WebTable 2). While some terrestrial functions (e.g. sound absorption) may not translate well to the marine environment due to differences in the physical properties of air and water, other functions (e.g. pollution mitigation) have useful analogues particularly in estuaries.

Lessons from artificial reef design

The principles of artificial reefs have been reviewed elsewhere (Baine 2001). Here we highlight some examples of the many purposes now incorporated in artificial reef design. Artificial reefs are designed for the enhancement of target species (Baine 2001), but may also be designed to remedy habitat loss, restore degraded habitats, or mitigate the impact of tourism by providing attractive sites for recreational diving (Feary et al. 2011). Proposals for decommissioned marine infrastructure to remain as reef are becoming common and are supported by evidence that they can provide important habitat, while avoiding disturbances associated with decommissioning (Macreadie et al. 2011). This strategy will likely require careful management as structures that are just “abandoned” may become havens for non-indigenous species (Ferreira et al. 2006) or a source of contamination (Macreadie et al. 2011).

Multifunctional targets for engineers

Marine artificial structures are primarily designed for physical protection or infrastructure. Only recently have designs begun to incorporate environmental, social and economic functions (Chapman and Underwood 2011). As research in this field progresses the efficacy

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of designs for multifunctional artificial structures could be examined with a systematic review and meta-analysis. Here we consider seven targets for the ecological engineering of marine artificial structures (Figure 2) and identify selected examples that quantify the results of practical designs to achieve these targets (Panel 1).

1) Local native biota maintenance

Biodiversity is generally thought to enhance ecosystem stability (McCann 2000). Marine artificial structures, particularly seawalls, are increasingly designed to support biodiversity (e.g. Chapman and Blockley 2009), but it is important to define what kind biodiversity to enhance and why. Increases in biodiversity may actually be a result of the recruitment of undesirable species e.g. non-indigenous species rather than a native assemblage (Glasby et al. 2007). Furthermore, if natural conditions support a diverse sediment assemblage, then designing structures to enhance rocky reef habitat rather than restoring or providing sedimentary habitat may not be appropriate. Designs that minimise changes to the environment and mimic natural habitats could go some way towards supporting the maintenance of native biota, without facilitating invasion.

Urban development has traditionally incorporated materials and designs that introduce unnatural conditions. Increasingly engineers are looking for natural solutions to increase the durability of construction materials of seawalls and breakwaters (Coombes et al. 2013, Firth et al. 2014). For example, intertidal seaweeds provide a canopy that reduces temperatures by up to 25% and creates a stable microclimate. This helps minimise weathering and reduce ecological stress for intertidal organisms (Coombes et al. 2013). Also, the features and materials used in constructions could be selected to mimic natural habitat conditions. Research has found that invertebrate abundance and species richness may increase on more complex artificial structures if they lead to the provision of refuges e.g. creation of crevices (Table 1). Similarly, different synthetic materials can influence the development of assemblages (Grozea and Walker 2009). However, caution is required when modifying designs to maintain habitats. Recent terrestrial efforts had negative effects on an endangered lizard, because attempts focused on increasing structural complexity, rather than mimicking natural conditions, and resulted in more predation (Hawlena et al. 2010). Careful measurements of the substrate type and extent of various physical crevices, and the

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presence of native propagules would be necessary to truly mimic natural conditions and ensure recruitment of native species.

2) Local biodiversity restoration

Restoration of local biodiversity could be facilitated by a shift from adding artificial defence structures to re-building natural coastal protection (WebTable 2). In addition to providing habitat for native species, natural coastal habitats dissipate wave and storm energy and capture of terrestrial runoff (Arkema et al. 2013, Ferrario et al. in press). Studies in the USA and Europe have identified the potential for freshwater wetlands to remove up to 68% of nitrates and 43% of phosphates from agricultural runoff, while saltmarsh sediments can reduce metal concentrations in run off by 50% (WebTable 2). Also, managed retreat in Seattle has removed seawalls from a foreshore development and restored pocket beaches to create sedimentary habitats that support migrating salmon (WebTable 2). This has the added advantage of providing a recreational amenity.

Where economic and social constraints make coastal retreat difficult, other opportunities for restoration of biodiversity could be considered. Structures that provide a potential analogue to a native system could support populations of threatened species. Marine artificial structures such as breakwaters and offshore platforms could therefore be “seeded” with native algae or oysters to restore or boost populations (Perkol-Finkel et al. 2012) and “gardened” to maintain specific native populations (Firth et al. 2014). Recent experimental transplants on European breakwaters had survival rates of >30% for a threatened species of algae (WebTable 2). This would be a doubly effective solution if the species selected, e.g. macroalgae, also prevented the colonisation of unwanted species e.g. non-indigenous invertebrates (Dafforn et al. 2012). Experimental seeding of surfaces with algal assemblages can reduce cover of introduced invertebrates by up to 33% (Table 2). The addition of lost natural habitat such as intertidal rock pools has also been found to increase biodiversity and density of algae and invertebrates (Browne and Chapman 2014, Firth et al. in press). Other examples of existing marine artificial structures being utilised for restoration of biodiversity include nets for protecting bathers. These could provide important habitat for seahorses where natural habitats such as kelp beds have been degraded (WebTable 2). These studies suggest that marine restoration research could provide useful insights for the design of artificial structures aiming to restore biodiversity.

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3) Regional biodiversity maintenance

The spatial distribution of artificial structures affects connectivity (WebTable 1) and therefore biodiversity at a regional scale. While increased connectivity could provide new dispersal routes to facilitate species migrations in response to climate change (Travis et al. 2013), there may be drawbacks related to the rapid expansion of "weedy" non-indigenous species which are often better able to colonise artificial structures than native species.

Artificial structures designed to reduce connectivity could support the maintenance of regional biodiversity by reducing the spread of invasive species. Ports and marinas need to be sheltered and are therefore low flow environments, but as a result they are heavily invaded and fouled because of the entrainment of propagules and food (Floerl and Inglis 2003, Johnston et al. 2011). Breakwalls or tidal locks often contain these populations (WebTable 2), but propagules disperse spread during storms or via vessels. Management strategies are therefore required to reduce fouling and options include biofouling regulations and regular cleaning. Furthermore, environmentally-friendly antifouling strategies, that rely on non-toxic compound, rather than toxic metal biocides, combined with better flushing would dilute the build up of metal contaminants that promote non-indigenous species over native species (Piola et al. 2009, Dafforn et al. 2011).

4) Educational and recreational opportunities

Marine artificial structures have the potential to provide educational and recreational opportunities at different stages of their lifecycle. We previously highlighted the foreshore development in Seattle's Olympic Sculpture Park where restoration of sediment habitat and biota had the additional aim of providing recreational facilities. These aims are reflected in other North American foreshore developments and described in detail in Panel 1.

The decommissioning of offshore oil and gas platforms offers opportunities to engage in educational and recreational ventures i.e. adaptive reuse (WebTable 2). During their operation, the areas around these structures are almost analogous to marine protected areas due to the restrictions on fishing and other vessel traffic (Inger et al. 2009). Adaptive reuse of these structures might therefore include recreational dive sites and large public aquaria. Decommissioned platforms are also being targeted for fisheries research with plans by to enclose an oil platform and stock it with deep-water fish, initially for

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research purposes, but ultimately for commercial aquaculture (James and Slaski 2006). Many of these structures have been in place for 30-40 years therefore reuse could prevent ecological impacts that might arise from their removal.

5) Water quality

Pollution abatement often incorporated into terrestrial urban design (Gaston et al. 2013). In marine systems, preserving or improving water quality promotes ecosystem functioning. We highlighted previously the opportunities for the restoration of wetlands and saltmarshes to trap contaminants from terrestrial run off (WebTable 2). Apart from supporting a diverse range of species and providing an opportunity to improve local water quality conditions, these habitats also provide coastal protection that requires minimal maintenance.

Engineered solutions for boating infrastructure such as marinas to reduce regional contamination include physical containment (WebTable 2). Improvements in water quality could also be achieved biologically through the seeding of structures with species that take up inorganic contaminants (e.g. seaweed) or that remove organic particles (e.g. suspension/deposit feeder) (Gifford et al. 2005). Studies have highlighted the potential for bivalves (e.g. oysters) to reduce levels of nitrogen and phosphorus in shrimp effluent by 72% and 86% respectively, although these could not then be considered for human consumption (WebTable 2). The choice of the target species may be improved by assessment of the local ecological conditions. Most artificial surfaces tend to be vertical or heavily shaded. Therefore seeding a photosynthetic organism on these structures would require additional measures e.g. reduced shading through the addition of openings or 'skylights' (see Panel 1).

6) Carbon storage

The accumulation of greenhouse gases and associated climatic change are driving research into biological solutions for carbon sequestration and storage (Perring et al. 2013). Terrestrial vegetation sequesters carbon dioxide and increases carbon storage above and below ground (Perring et al. 2013), as indeed do marine seagrasses (Lavery et al. 2013). Long-lived species of seagrass (e.g. Posidonia spp.) are likely to have the greatest capacity to store carbon (Fourqurean et al. 2012), yet these are also the most difficult species to rehabilitate. Therefore using seagrasses to enhance carbon capture may be currently unrealistic (Irving et al. 2011). Bioengineered oyster reefs have been proposed for shoreline protection and also for carbon storage (Dehon 2010). However, in some cases the carbon

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dioxide produced by oysters during shell construction exceeds the potential for sequestration so further investigation is required. Seaweeds have great capacity for carbon storage through biomass accumulation and pilot studies in Korea have estimated capture at ~10 t CO_2/ha/year (WebTable 2). Marine sediments also have the capacity to store carbon dioxide (Schrag 2009), but transport logistics prevents the practical realisation of this solution (Golomb 1993). Existing pipelines of decommissioned infrastructure may be used to transport carbon dioxide to deep-sea sediments for storage (Seevam et al. 2010). While these possible solutions may appear attractive and potentially feasible, large-scale enrichment of marine sediments requires further investigation since the ecological consequences are not fully understood.

7) Aquaculture and food production

The potential for artificial reefs to support fish populations and food production has been reviewed elsewhere (Feary et al. 2011). Therefore we focus here on the opportunities to design offshore platforms (e.g. wind farms) and coastal infrastructure (e.g. breakwaters) that support aquaculture such as seaweed and shellfish.

Aquaculture has incorporated offshore farming for several decades since many species are unsuited for land-based ponds or tanks. Moving aquaculture offshore means that habitats and organisms suffer less from anoxia and disease because off shore areas have greater movements of water that rapidly disperse waste and oxygenate the water (Buck et al. 2004). These ventures are costly and there are already moves to target multiple species including mussels, oysters and seaweed. Since energy-harnessing structures such as wind turbines and oil platforms are effectively built on foundations similar to artificial reefs, these may create cost-effective opportunities for offshore aquaculture by providing anchor points in high-energy environments (Buck et al. 2004). While operational, these structures can incorporate the needs of different stakeholders and also spread the costs (Buck et al. 2004).

Coastal environments are replete with defence structures such as breakwaters and these may be another good option for aquaculture development. Seeding of structures with the commercially important Pacific Oyster *Crassostrea gigas* has the potential to improve water quality through filtration, and also provide an economical return (Forrest et al. 2009). Projects involving seeding of artificial structures require careful analysis to target

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appropriate native species and avoid ecological issues that might negate any benefits (e.g. the unintentional transfer of non-indigenous species).

Conclusions

The urbanisation of our oceans is set to increase (Panel 2), and while the design of artificial structures remains focused on engineering goals, their multifunctional potential may not be fulfilled. We have highlighted opportunities to incorporate multiple targets into designs and this conceptual framework could underpin future policy documents. Legal frameworks now exist in Europe to support biodiversity enhancements on artificial structures e.g. European Convention on Biological Diversity integrates biodiversity into all planning processes (Naylor et al. 2012). However, key coastal policies in other countries lack the same specificity e.g. the Australian Coastal Protection Act 1979 requires ecologically sustainable development, but does not specifically identify artificial structures. Similarly, the U.S. Coastal Zone Management Act 1972 requires that coastal and estuarine areas be managed to restore or enhance ecological function, but the management of artificial structures is not specifically addressed. We suggest that biodiversity enhancement and other multifunctional targets e.g. pollution mitigation could be incorporated into policy. Marine structures need not be designed solely for protection or infrastructure, but can incorporate essential ecological, social and provisioning services while reducing environmental impacts. Policy requiring multifunctional targets to be identified during planning stages could drive this important change in future marine urbanisation.

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Panel 1

Early ecological engineering of seawall designs that aimed to increase biodiversity by increasing the slope and complexity or by adding habitat met with varying degrees of success (Table 1). Adding blocks and boulders to increase the slope of seawalls resulted in no increases in biodiversity on the seawalls and assemblages remained different to those on natural reef (Table 1). However, increasing the surface complexity of seawalls and breakwaters with the addition of pits, grooves and crevices resulted in increased colonisation by mobile invertebrates that were not found normally on the exposed smooth surfaces of the structures (Table 1). Creating cavities in or on these structures added to this complexity and in some designs the additional habitat created conditions that facilitated colonisation by rockpool species. Subsequent designs that incorporated a range of strategies such as the Bioblock (Table 1) and mimicked more closely the complexity of natural reefs (Browne and Chapman 2011) were successful at encouraging native species colonisation (Table 1). Recent foreshore developments in North America have progressed

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these principles further using the main objective of local biodiversity maintenance, but targeting a wider suite of native species (Leonard and Kullmann 2010). Construction engineers on the Vancouver Convention Centre development implemented solutions to reduce local impacts of seawalls to natural sedimentary habitats by building stepped structures ("habitat skirts") that incorporate horizontal surfaces with pits for sediment accumulation. This stepped design also adds intertidal and subtidal zones with the aim of restoring conditions suitable for colonisation by invertebrates and seaweed that would normally inhabit the natural substrata present locally and to attract fish. The ecological engineered sections of the Vancouver foreshore are accompanied by an educational trail along the boardwalk that identifies and explains particular features of the design that aim to enhance native biodiversity. Future foreshore developments in North America are also introducing novel designs to reduce the ecological impacts of shading from marine infrastructure. Innovations have included the creation of boardwalk windows and "skylights" designed to maximize light penetration beneath the structure e.g. designs for the Elliot Bay Seawall in Seattle. These developments are very new and their capacity to maintain or restore natural assemblages is yet to be rigorously assessed (but see Goff 2010). Carefully designed survey and experimental work similar to the progressive development of seawall ecological engineering will be required to test the effectiveness of foreshore developments at maintaining and restoring native biodiversity (Chapman and Underwood 2011).

Panel 2

Global interest in diving tourism has driven the design of floating and submarine accommodation and restaurant structures (Bitterman 2013). "Aquatourism" now refers to submerged tourism and is a developing industry (Bitterman 2013). Between the 1960s and1970s few of these designs were realised due to technical issues and constraints (Kaji-o'grady and Raisbeck 2005). More recently, operational examples of underwater accommodation include the Jules' Undersea Lodge in Florida and Utter Inn in Sweden designed for less than 10 guests. These represent relatively small structures compared to the proposed Poseidon Undersea Resort in Fiji (20 suites) and the Hydropolis Undersea Resort in Dubai (220 suites) (Bitterman 2013). The architects of these designs have

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highlighted the potential for the structures to provide both recreational (tourism) and educational (marine research) services (Bitterman 2013).

On a larger scale, there is increasing interest in developing larger floating and submerged cities and underwater solutions to overcrowding (Kaji-o'grady and Raisbeck 2005)(Figure 4). These designs may not be realised in the near future, but the potential ecological impacts from the addition of these hard substrates to the marine environment could still be considered at this conceptual stage (Naylor et al. 2012)(Figure 2), together with other opportunities for the provision of ecosystem services, particularly the maintenance or restoration of biodiversity (Figure 3).

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Table 1 - Case study of ecological engineering of coastal infrastructure to increase hard substrate diversity

Location	Engineering	Results	Refs.
Increase sloping intertidal habitat			
White Bay, Australia	Added a sloping wall of small blocks to a seawall	No increase in biodiversity: sessile invertebrate cover lower and fewer mobile species on horizontal than vertical	(Chapman and Underwood 2011)
Quakers Hat Bay, Australia	Added a sloping wall of boulders to seawall	No increase in biodiversity	(Chapman and Underwood 2011)
Increase complexity			
Azores Is, Portugal	Drilled pits of various sizes and densities on seawall	Up to 10 times more mobile limpets in quadrats with pits due to immigration and recruitment	(Martins et al. 2010)
Farm Cove, Australia	Added holes and grooves to seawall	Increased densities of limpets in grooves compared to holes and background; smaller densities of chitons in large holes than grooves	(Chapman and Underwood 2011)
Kirribilli, Australia	Surveyed crevices between blocks on seawall	Increased densities of chitons in crevices (77-100%) than on exposed surfaces of seawalls (0-23%)	(Moreira et al. 2007)
Kirribilli, Australia	Added crevices between blocks on seawall	Increased taxonomic richness of algae and sessile invertebrates in crevices than on exposed surfaces of seawalls	(Dugan et al. 2011)
W Sussex, UK	Added pits (large/small) and mixed to seawall	Increased abundances of barnacles in small crevices and rough compared to smooth surfaces; increased diversity with increasing complexity	(Moschella et al. 2005)
Plymouth, UK	Added pits (large/small) and mixed to seawall	60% of functional groups unique to drilled pits; increased species richness in pits	(Firth et al. 2014)
Shaldon, UK	Added grooves, pits and recessed crevices	Barnacles unique to recesses	(Firth et al. 2014)
Add additional habitat			
Rose Bay, Australia	Added cavity	Rapid colonisation by mobile rockpool species	(Chapman and Underwood 2011)
McMahons Pt, Australia	Added cavity and lip to form pool	Increased diversity of foliose algae and sessile and mobile animals; more species in constructed pools than in nearby natural pools	(Chapman and Blockley 2009)
Tywyn, UK	Added artificial rock pools with two depths to breakwater	30% more species in shallow pools than emergent substrata	(Firth et al. 2014)
Colwyn Bay, UK	Added Bioblock unit (rockpools, crevices, pits) to breakwater	60% more species on Bioblock than adjacent adjacent rocks	(Firth et al. 2014)

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Figure Legends

Figure 1 - Clockwise from top left a) Coastal defence structures in the North Adriatic; b) an Offshore Oil Platform, Darwin, Australia; c) a 74-berth marina with a network of pilings and pontoons; and d) an aerial view of Wollongong Harbour, Australia enclosed by artificial breakwaters. Courtesy of © Benelli (1), © Rivero (2), © Dafforn (3) and © Glasby (4).

Figure 2 – Diagram illustrating the three engineering phases (construction, operation and decommissioning) that result in habitat modification (orange boxes). Examples of the physical/chemical changes are described (blue boxes) and potential ecological impacts identified at the local and regional scale (purple).

Figure 3 - Conceptual framework identifying 1) examples of practical design solutions (blue boxes) that will provide 2) key multifunctional targets for the ecological engineering of marine artificial structures (unboxed) and 3) still fulfil the primary hard engineering objective.

Figure 4 - Clockwise from top left a) Amsterdam's plans to utilise subterranean car parking under the city's canal network; b) the Sub Biosphere is a self-sustainable city for 100 inhabitants that presents recreational and educational opportunities; and c) and d) Views from above and below the Gyre "seascraper" whichs plan to provide accommodation and berthing for passenger vessels (Part of Panel 2). Courtesy of © Zwarts & Jansma (1), © Pauley.co.uk (2), © Zigloo.ca (3 & 4).

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WebTable 1 – The magnitude of effects of marine urban sprawl and ecological consequences

Process	Magnitude of effect	Refs.
Coastal protection and infrastructure		
	Europe: 22,000 km^2 of coastal zone armoured	(Airoldi and Beck 2007)
	North Adriatic: >190 km artificial structures protect 60 % of coastline	(Dugan et al. 2011)
	United States: > 50 % of some estuaries and bays modified and ca. 5 – 30% coastlines armoured	(Dugan et al. 2011)
	Chesapeake Bay and San Diego Bay: > 50 % estuaries and bays armoured	(LSC 2006)
	New Jersey: ca. 17% of coastline	(Lathrop Jr and Love 2007)
	Florida: ca. 21 % of 759 km coastline	(DEP 1990)
	California: ca. 12 % of 1763 km coastline	(Griggs 1998)
	S. California: ca. 30 % of 371km coastline	(Griggs 1998)
	Oregon: 6 % of 582 km coastline	(Foundation 2010)
	Washington: 30 % of 3788 km coastline	(Dugan et al. 2011)
	Japan: ca. 27 % of 34 500 km coastline hardened with coastal defence structures	(Koike 1996)
	Australia: 32 – 49% of foreshore modified in some Sydney estuaries	(Creese et al. 2009)
	Loss of native sedimentary habitats, spread of NIS and opportunistic species, ca. 7% loss of genetic diversity	(Airoldi and Beck 2007, Glasby et al. 2007, Fauvelot et al. 2009)
Offshore energy platform installation and operation		
	1200 km^2 - 8600 km^2 seabed proposed for offshore wind-farm development in the UK by 2020	(Byrne and Houlsby 2003, Wilson et al. 2010)
	Minimum of 12.5 m^2 seabed lost to the footprint of a 4 m^2 turbine with 10 m^2 scour protection	(Wilson and Elliott 2009)
	Dredging increases turbidity by adding between 1539 m^3 – 2356 m^3 sediment per turbine to water column	(Lozano-Minguez et al. 2011)
	2-4 y recovery for benthic assemblage after dredging	(van Dalfsen et al. 2000)
	Noise pollution up to 260dB re: 1uPa (foundation construction), 178 dB re: 1uPA (cable laying), 80-110 dB re: 1uPa (turbine operation), 132 dB re: 1uPa (associated boats), up to 180 dB re: 1uPa (seismic surveys)	(Fristedt et al. 2001, McCauley et al. 2003, Nedwell et al. 2004, Codarin et al. 2009)
	Fish startle and alarm response above 150 dB re: 1uPa	(Blaxter et al. 1981)
	Eardrum rupture in marine mammals above 163 udB re: 1uPa	(Yelverton et al. 1973)
	Increased mortality in fish eggs (20-25 %) and embryos (85 %) >15 dB re: 1uPA above ambient	(Banner and Hyatt 1973)
	Light pollution from artificial lights on platforms and vessels	(Wiese et al. 2001)
	480 birds killed or injured from light-induced bird strikes in 42 incidents over 3 winters	(Merkel and Johansen 2011)
	Construction with homogeneous design and materials	(Sheehy and Vik 2010)
	11% of species found on oil platforms off Brazilian coast were non-indigenous	(Ferreira et al. 2006)
Marina construction and operation		
	> 97,000 m^2 intertidal and subtidal boulder habitat disrupted, ca. 50 % less substrate available for algal colonisation	(Iannuzzi et al. 1996)

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	Estimated 17 % reduction in algal production	(Iannuzzi et al. 1996)
	Turbidity ca. 30 % greater inside a marina with a breakwall than outside	(Rivero et al. 2013)
	Increased copper (80%) and lead (30%) concentrations inside a marina with a breakwall cf. outside	(Rivero et al. 2013)
	Barnacles and ascidians absent; bryozoans, spirorbid polychaetes and sponges 1-10% greater cover inside the marina	(Rivero et al. 2013)
	Light pollution from pontoon illuminated at night by 400-W floodlight	(Becker et al. 2013)
	Increased abundance of large-bodied predatory fish and small shoaling fish associated with lit structure	(Becker et al. 2013)
	Construction with homogeneous design and materials	(Dafforn et al. 2012)
	Non-indigenous species occupy up to 80 % more space on pilings or pontoons compared to reef	(Dafforn et al. 2012)
Breakwater design		
	Flow decreased ca. 30 % inside marina	(Rivero et al. 2013)
	Flow reduced 50 % on rocky intertidal adjacent to breakwater	(Martins et al. 2009)
	Barnacles, limpets and frondose algae replaced by ephemeral algae	(Martins et al. 2009)
	Infaunal species richness increased by up to 70% on landward side of coastal defence structures	(Martin et al. 2005)

Bold = ecological consequences of urban sprawl

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WebTable 2 – Examples of solutions to address multifunctional objectives for terrestrial and marine artificial structures

Solution	Objective	Examples	Refs.
Green roof	Air quality		
		Detroit, USA: 20% increase in commercial/industrial green roofs could remove 0.5% NO_2 emissions	(Clark et al. 2005)
		Singapore: 37% decrease in SO_2 and 21% decrease in NO	(Tan and Sia 2005)
	Water quality		
		Washington DC, USA: 20% increase in green roofs could store 958 million l/yr rainwater	(Deutsch et al. 2005)
		Berlin, Germany: 60-79% annual stormwater runoff retained	(Kohler et al. 2002)
		Berlin, Germany: retention of Pb (95%), Cd (88%), NO_3 (80%) and PO_4 (68%)	(Kohler et al. 2002)
	Local biodiversity maintenance		
		Berlin, Germany: Plant species richness increased more than 10 fold over 20 years	(Kohler 2006)
		Zurich, Switzerland: 175 species recorded from 100 yo green roofs including 3 endangered species	(Brenneisen 2006)
		London, UK: Invertebrate species richness included 10% of nationally rare species	(Kadas 2006)
	Educational and recreational opportunities		
		Vancouver, Canada: Designs incorporate views of green roofs to integrate user experience indoors with outdoors	(Sutton 2014)
Managed retreat	Local biodiversity restoration		
		Seattle, USA: Seawalls removed from foreshore development and pocket beaches restored to support prey species of migratory salmon	(Nordstrom in press)
	Water quality		
		Maryland, Illinois and Iowa, USA: wetlands can remove up to 68% N and 43% P	(Woltemade 2000)
		Wadden Sea, The Netherlands: Experimental saltmarsh sediments retained ca. 50% of macro nutrients and heavy metals	(Leendertse et al. 1996)
		Aarhus, Denmark: average attenuation of 19% of emerging contaminants	(Matamoros et al. 2012)
		Maryland, USA: restored wetlands removed 25% NH_3, 52% N (nitrate) and 34% C	(Jordan et al. 2003)
	Carbon storage		
		North Sea: 1 million metric tons of CO_2 injected into sandstone reservoir beneath ocean sediments	(Schrag 2009)
		New Jersey, USA: sandstones have capacity to store several hundred billion tons of CO_2	(Schrag 2009)
Adaptive reuse	Educational and recreational opportunities		

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		London, UK: Modern Tate built on former industrial site	(Hein and Houck 2008)
		Arabian Gulf: Decommissioned offshore structures and breakwaters might mitigate impact of tourism by providing attractive sites for recreational diving or public aquaria	(Feary et al. 2011)
	Aquaculture and food production		
		Offshore, UK: Enhancement of target species e.g. fish, lobsters, seaweed, shellfish	(James and Slaski 2006)
Native seeding	Local biodiversity maintenance		
		Adriatic Sea, Italy: >30% survival of threatened species transplanted to landward artificial habitats	(Perkol-Finkel et al. 2012)
	Regional biodiversity maintenance		
		Sydney, Australia: 33% reduction in non-indigenous species cover when plates seeded with native algae	(Dafforn et al. 2012)
	Water quality		
		Port Stephens, Australia: each ton of pearl oysters harvested removed ca. 703g metals, 7452g N and 545g P from the waters	(Gifford et al. 2005)
		Brisbane, Queensland: Oysters reduced levels of N and P in shrimp effluent by 72% and 86% respectively	(Jones et al. 2001)
	Carbon storage		
		Southern Coast, Korea: pilot studies with seaweeds estimate capture at ~10 t CO_2/ha/yr	(Chung et al. 2013)
		USA, Australia: Saltmarshes, mangroves and seagrass can capture carbon at 60-210 t C/km^2/yr	(Irving et al. 2011)
Bather protection nets	Local biodiversity restoration		
		Sydney, Australia: 86% of the population of a threatened seahorse was maintained by translocating individuals during the cleaning of a net	(Harasti et al. 2010)
Breakwalls and tidal locks	Regional biodiversity maintenance		
		Darwin, Australia: 3 separate marina locks closed and treated with chemicals to contain and eradicate dense populations (23,650 individuals/m^2) of invasive mussel *Mytilopsis sallei*	(Willan et al. 2000)
	Water quality		
		Batemans Bay, Australia: 30-80% reduction in metal contamination from physical containment with breakwalls	(Rivero et al. 2013)

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