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(Article begins on next page)

Marine urbanization: an ecological framework for designing multifunctional artificial structures

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Underwater cities have long been the subject of science fiction novels and movies, but the "urban sprawl" of artificial structures being developed in marine environments has 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 accumulating. 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 as "aquatourism" drives the development of underwater accommodations. We show that current and future marine developments could be designed to reduce negative ecological impacts while promoting ecosystem services.

Urban sprawl is expanding into marine environments with the construction of artificial structures. In areas of Europe, the US, Australia, and Asia, more than 50% of the shoreline is now modified by hard engineering, including groins and breakwaters (man-made coastal defenses positioned along the shore or offshore, respectively) to protect against erosion and wave action in support of recreational boating and other activities. The construction of offshore aquaculture facilities and platforms for oil and gas exploration is also increasing (Figure 1; Dugan *et al.* 2011). Despite habitat loss associated with marine urban sprawl (Airoldi and Beck 2007), the ecological consequences of (Bulleri and Chapman 2010) and mitigation strategies for (eg Browne and Chapman 2011) such structures have only recently been reviewed and attempted. The development of marine

In a nutshell:

- Marine urbanization is increasing
- The impacts of artificial structures are widely documented, but mitigation strategies are still in development
- Designing marine infrastructure with many purposes could improve provision of ecosystem functions and reduce adverse ecological impacts

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infrastructure will continue and most likely escalate in the future, given the need for improved defenses around ports, harbors, and coastal cities as protection from both rising sea levels and increasingly severe coastal storms and flooding (Asif and Muneer 2007). In addition, there are growing demands for coastal urban development, aquaculture facilities, and offshore energy infrastructure (Asif and Muneer 2007).

Human uses of marine environments have modified the global seascape and ecosystem functions (Dugan *et al.* 2011). "Ecological engineering" – 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 and degradation of habitats, maintain vital ecosystem services, and ensure more efficient use of natural resources. Here we review selected research on ecological engineering in the marine environment. A systematic review was not possible given that much of the relevant literature crosses scholarly disciplines and is located in books, conference proceedings, and gray literature that would not have appeared in searches. Our review introduces a conceptual framework, together with supporting case studies, for the design of structures that both minimize adverse ecological impacts and provide multiple ecosystem functions.

◾ Ecological consequences of marine urban sprawl

Artificial structures have local and regional effects on marine ecosystems (Govaerts and Lauwaert 2009; Bulleri and Chapman 2010; Dugan *et al.* 2011). Here we briefly examine four major types of impact: (1) direct physical disturbance, (2) addition of artificial habitat, (3) indirect physical disturbance, and (4) noise and light pollution.
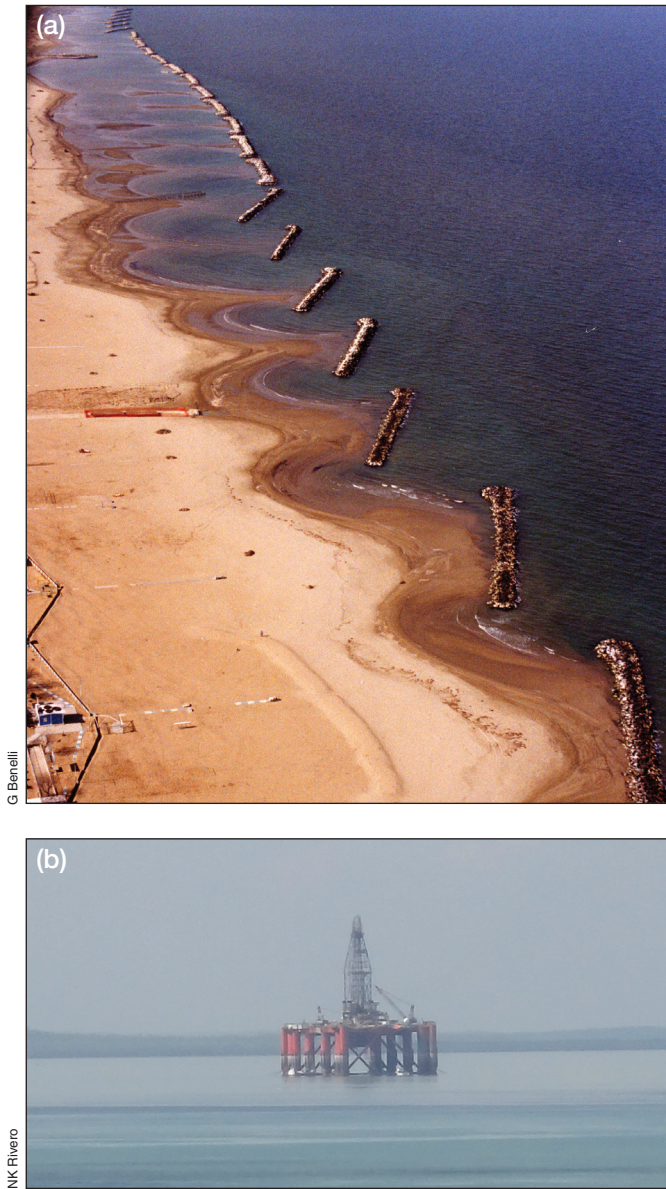
Figure 1. *(a) Coastal defense structures in the North Adriatic; (b) an offshore oil platform near Darwin, Australia; (c) a 74-berth marina with a network of pilings and pontoons; and (d) an aerial view of Wollongong Harbour, Australia, enclosed by artificial breakwaters.*
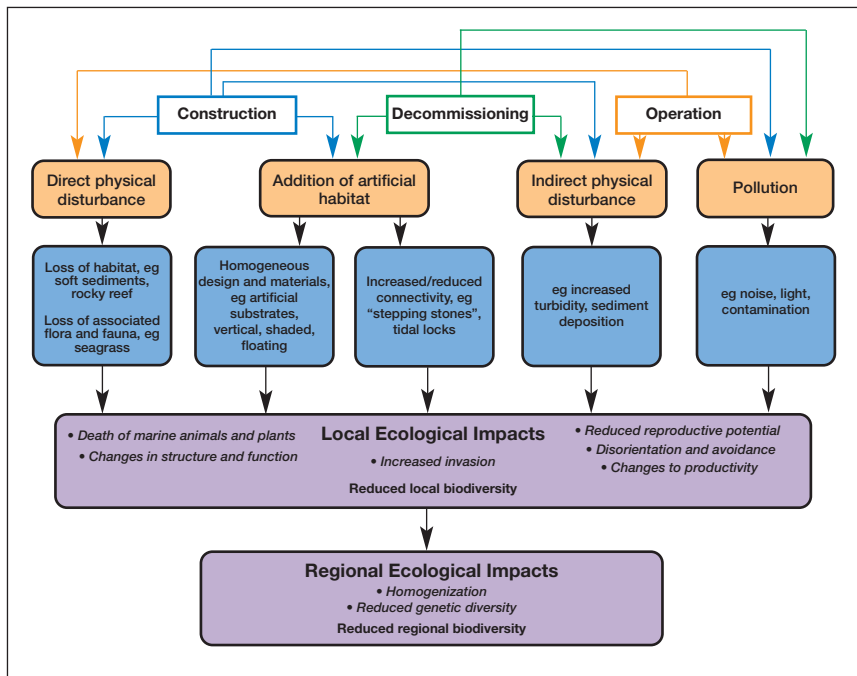
We explore how these impacts relate to different engineering stages (construction, operation, and decommissioning; Figure 2) at local and regional scales, to help identify ecological engineering options.

Local-scale effects

Physical disturbances arise from the addition or removal of artificial materials during construction and decommissioning, respectively (Figure 2). Recipient native habitats are often damaged or destroyed, and associated assemblages lost (eg up to 70% of coastlines have been modified globally; WebTable 1a). Offshore, about 12.5 m^2 of seabed can be lost in the footprint of a 4-m-diameter turbine with a 10-m base to protect it from sediment abrasion (Wilson and Elliott 2009), contributing to a projected loss in the UK of up to 8600 km^2 of seabed by 2020 from offshore wind developments (WebTable 1b). Dredging during construction can displace between 1539

and 2356 m^3 of sediment per turbine into the water column (WebTable 1b) and the removal of underwater scaffolding increases turbidity, which can negatively affect marine plants and animals (Gill 2005). During their operation, artificial structures can alter water flow and sediment deposition, with subsequent effects on benthic species assemblages and productivity (Coates *et al.* 2014). Constructing marinas surrounded by breakwaters can increase turbidity and reduce flow by up to 30% (WebTable 1c).

The materials added during construction change the type of resources available, for example by altering the proportion of sheltered, shaded, vertical, and floating surfaces (Figures 1 and 2). Both the orientation of exposed defense structures (either seaward or landward) and the surface texture of construction materials can influence the colonization and recruitment of marine organisms; for instance, barnacles and limpets favor colonization on landward- and seaward-facing structures, respectively

Figure 2. *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 boxes).*

Regional-scale effects

Although marine urbanization is a global issue, scientists lack a comprehensive understanding of the regional ecological consequences of its associated habitat loss and changes in connectivity (Airoldi and Beck 2007). The homogeneity of design and construction materials is a driving force behind the establishment of a suite of fouling species that dominate artificial structures in harbors and coastal areas throughout the world (Figure 2; Dafforn *et al.* 2009a; Piola *et al.* 2009). This is analogous to terrestrial urbanization, where use of similar construction materials between cities has 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 non-indigenous fouling species (Dafforn *et al.* 2009b) in most human-modified estuaries worldwide (WebTable 1c). Offshore platforms also facilitate the establishment of non-indigenous species, with 11% of species observed on oil platforms off the Brazilian coast classified as exotic (WebTable 1b).

Urbanization can also result in habitat fragmentation and changes to regional connectivity (Fischer and Lindenmayer 2007). On land, roads, large property developments, and cities create barriers to, or corridors for, invasive species 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 movement of marine larvae and nutrients (Floerl and Inglis 2003). In the north Adriatic Sea, for example, more than 190 km of breakwaters, groins, seawalls, and jetties has increased the prevalence of rocky substrates in a predominantly sedimentary environment, facilitating the regional spread of invasive species that require hard surfaces for dispersal and recruitment (WebTable 1a).

■ **Defining multifunctional targets for ecological engineering**

Successful developments in terrestrial urban ecology and artificial reef design demonstrate that artificial structures can be designed to provide both physical infrastructure and critical services (Gaston *et al.* 2013), including habitat provision, pollution abatement, and facilities for human recreation, education, and food production (Figure 3).

(Moschella *et al.* 2005; Coombes *et al.* 2009). These structures (among others) support assemblages that are distinct from those found in natural reef habitat (Moschella *et al.* 2005; Bulleri and Chapman 2010). They may also harbor non-indigenous species, which have been found to occupy up to 80% more space on pilings or pontoons as compared with natural reefs (WebTable 1c; Dafforn *et al.* 2012). The physical design of artificial structures therefore has major consequences at multiple trophic levels and across seascapes.

During all engineering stages, activities associated with boating and energy extraction can act as sources of various types of pollution (Figure 2). These include artificial light from offshore platforms (Depledge *et al.* 2010), noise and vibration during wind farm operation (Gill 2005), and contamination around vessel berths (Dafforn *et al.* 2009a). Night lighting and operational lights on offshore structures can disorient birds and lead to elevated mortality among migratory species (WebTable 1b). The noise and vibrations from construction-related pile driving can reach levels that increase mortality in fish eggs and embryos by 25% and 85%, respectively, and are associated with disorientation and eardrum rupture in marine mammals (WebTable 1b). Estuarine infrastructure sites such as marinas are often hotspots of contamination from antifouling paints. Copper and lead concentrations in sediments were 30–80% higher inside a semi-enclosed marina than outside (WebTable 1c); this finding has been linked to the facilitation of invasions by non-indigenous species (Piola *et al.* 2009).

Lessons from terrestrial urban design

The design of buildings and spaces in terrestrial systems has improved with increased understanding of the multiple purposes that urban areas can serve. "Green" roofs and walls – plant assemblages established on the tops and sides of buildings – reduce noise and heat loss by absorbing more sound and thermal energy than would a hard surface (Rowe 2011). Green infrastructure may reduce air pollution by up to 37% and trap 60–79% of annual stormwater (see WebTable 2a for references). These structures can be intentionally seeded with target organisms to create habitat for native plants (Kadas 2006), including rare and endangered species (WebTable 2a). While some terrestrial functions (eg sound absorption) may not translate well to the marine environment due to differences in the physical properties of air and water, other functions (eg pollution mitigation) have useful analogs, particularly in estuaries.

Lessons from artificial reef design

The principles of artificial reef creation have been reviewed elsewhere (eg Baine 2001); below, we highlight some examples of the many purposes now incorporated into their design. Artificial reefs are designed for the benefit of target species (Baine 2001) but may also offset habitat loss by restoring degraded ecosystems or mitigate the impacts of tourism on natural reefs by providing attractive alternative sites for recreational diving (Feary *et al.* 2011). Proposals for decommissioned marine infrastructure to remain in place as reefs are becoming common, and are supported by evidence indicating that such structures can provide important habitat while avoiding the disturbances associated with decommissioning (Macreadie *et al.* 2011). This strategy will likely require careful management because structures that are simply "abandoned" may become havens for non-indigenous species (Ferreira *et al.* 2006) or act as a source of contamination (Macreadie *et al.* 2011).

Multifunctional targets for engineers

Marine artificial structures are primarily designed for physical protection of 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 of designs for multifunctional structures could be examined with a systematic review and meta-analysis. Here we consider seven goals for marine ecological engineering (Figure 2)
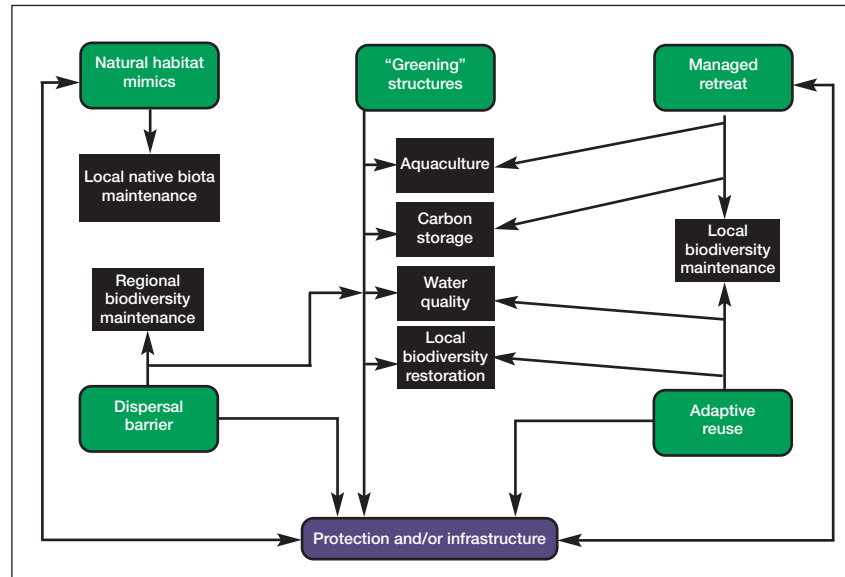
Figure 3. Conceptual framework identifying examples of practical design solutions (green boxes) that will provide key multifunctional targets for the ecological engineering of marine artificial structures (black boxes) while still fulfilling the structures' primary hard engineering objective (purple box).

and identify selected examples of practical designs that can help to achieve these goals (WebPanel 1).

Maintaining local native biota

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

Urban development has traditionally incorporated materials and designs that create novel conditions. Engineers are now investigating the use of features and materials not only to improve the durability of seawalls and breakwaters but also to more closely resemble historical conditions (Coombes *et al.* 2013; Firth *et al.* 2014b). For instance, intertidal seaweeds provide a canopy that reduces temperatures by up to 25% and creates a stable microclimate, which minimizes weathering and reduces ecological stress for intertidal organisms (Coombes *et al.* 2013). Observed increases in invertebrate abundance and species richness have been associated with more complex artificial structures that provide refugia (eg crevices; see Table 1 for examples and corresponding references). Similarly, different synthetic materials can influence the

development of species assemblages (Grozea and Walker 2009). However, caution is required when modifying designs to maintain habitats. In a misguided effort to restore the habitat of an imperiled terrestrial lizard population, increasing structural complexity, rather than mimicking natural conditions, resulted in increased lizard mortality through predation (Hawlena *et al.* 2010). Careful measurements of substrate types and extent of various physical crevices, as well as the presence of native propagules, would be necessary to truly mimic natural conditions and ensure recruitment of native species.

Restoring local biodiversity

Restoration of local biodiversity could be facilitated by a shift from adding artificial defense structures to rebuilding natural coastal protection (WebTable 2b). In addition to providing habitat for native species, these natural habitats dissipate wave and storm energy and capture terrestrial runoff (Arkema *et al.* 2013; Ferrario *et al.* 2014). Studies in the US and Europe have demonstrated the potential for freshwater wetlands to remove up to 68% of nitrates and 43% of phosphates from agricultural runoff, and salt marsh sediments can reduce metal concentrations in runoff by 50% (WebTable 2b). Also, managed retreat, where hard engineering structures are replaced by natural habitats that provide physical protection, is a feature of the recently developed Seattle Olympic Sculpture Park. Here, seawalls have been removed from a foreshore development and sediments restored to create a small beach that supports migrating salmon (WebTable 2b). This strategy has the added advantage of providing a recreational amenity.

Where economic and social constraints make coastal retreat difficult, other opportunities for restoration of biodiversity can be considered. Structures that provide a potential analog of a native system could support populations of threatened species. Breakwaters and offshore platforms could therefore be intentionally "seeded" with native algae or oysters to restore or boost existing populations (Perkol-Finkel *et al.* 2012) and "cultivated" to maintain specific native populations (Firth *et al.* 2014b). Survival rates for a threatened species of algae were improved by more than 30% through recent experimental transplants on European breakwaters (WebTable 2d). This outcome would be doubly effective if the transplanted species also helped to inhibit colonization by unwanted species (eg use of macroalgae to prevent colonization by non-indigenous invertebrates; Dafforn *et al.* 2012). Experimental seeding of surfaces with algal assemblages can reduce populations of introduced invertebrates by up to 33% (WebTable 2d). Supplementing formerly "lost" natural habitat such as intertidal rock pools increases biodiversity and density of algae and invertebrates (Browne and Chapman 2014; Firth *et al.* 2014a). Purposefully installed to protect recreational swimmers at coastal locations in Australia, artificial nets also serve as important habitat for seahorses, the populations of which have suffered from degradation of natural habitat such as kelp beds (WebTable 2e). These studies suggest that marine restoration research could offer useful insights for marine urban design aiming to restore underwater biodiversity.

Maintaining regional biodiversity

The spatial distribution of coastal defense structures, boating facilities, and offshore aquaculture facilities and platforms affects connectivity (WebTable 1a) 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 colonize artificial structures than are native species.

Marine urban developments designed to reduce connectivity could maintain regional biodiversity by restricting the spread of invasive species. Given that they are sited in sheltered, low-flow environments, ports and marinas are often heavily invaded and fouled due to the inflow of propagules (invertebrate larvae and algal spores) and nutrients (Floerl and Inglis 2003; Johnston *et al.* 2011). Breakwaters or tidal locks often contain these populations (WebTable 2f), but propagules can also spread via stormwater or ships. Management strategies such as regular cleaning and regulations to reduce biofouling are therefore required in such areas. However, antifouling strategies sometimes rely on toxic metal biocides, which promote non-indigenous species over native ones; this could be prevented through improved flushing and the use of non-toxic compounds (Piola *et al.* 2009; Dafforn *et al.* 2011).

Providing educational and recreational opportunities

Marine artificial structures – including decommissioned offshore oil and gas platforms – may provide educational and recreational opportunities (eg adaptive reuse; WebTable 2c) at different stages of their lifecycle. We previously highlighted the foreshore development in Seattle's Olympic Sculpture Park, where habitat restoration facilitated the provision of recreational services (see WebPanel 1 for related examples). During their operation, oil rigs and their environs are similar in part to marine protected areas due to restrictions on fishing and vessel traffic (Inger *et al.* 2009). Adaptive reuse of the foundations of these structures after decommissioning might therefore include recreational dive sites. Plans have already been developed to enclose a decommissioned oil platform and stock the surrounding vicinity with deep-water fish, initially for fisheries research purposes but ultimately for commercial aquaculture (James and Slaski 2006). Because many of these structures have been in place for 30–40 years, their re-purposing could avoid the adverse ecological impacts associated with their removal.

Maintaining water quality

Pollution abatement is often incorporated into terrestrial urban design (Gaston *et al.* 2013). In marine systems, preserving or improving water quality promotes ecosystem

functioning. Apart from supporting a wide range of species and providing an opportunity to improve local water-quality conditions, habitats such as wetlands and salt marshes also provide low-maintenance coastal protection.

Engineering-based solutions such as physical containment (WebTable 2f) may be required to reduce pollutant contamination at boating infrastructure sites (eg marinas). However, improvements in water quality could also be achieved through biological means, by seeding structures with organisms that absorb inorganic contaminants (eg seaweed) or remove organic particles (eg suspension/deposit feeders; Gifford *et al.* 2005). Studies have highlighted the potential for bivalves (eg oysters) to

reduce levels of nitrogen and phosphorus in effluent from shrimp aquaculture by 72% and 86%, respectively, although the oysters could not then be harvested for human consumption (WebTable 2d). 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; thus, seeding these structures with a photosynthetic organism would require further measures, such as adding openings or "skylights" to reduce shading (see WebPanel 1).

Facilitating carbon storage

Increased atmospheric concentrations of greenhouse gases and associated climate change are driving research

Table 1. Examples of ecological engineering of coastal infrastructure to increase hard substrate diversity
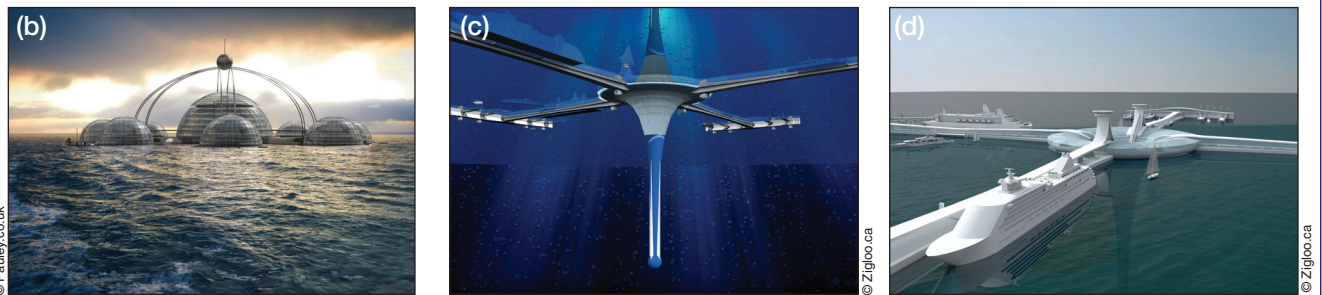
Location	Engineering	Results	References
Increase sloping intertidal habitat			
White Bay, Australia	Added a sloping wall of small blocks to seawall	No increase in biodiversity: reduced sessile invertebrate cover, and fewer mobile species on horizontal than vertical surfaces	Chapman and Underwood (2011)
Quakers Hat Bay, Australia	Added a sloping wall of boulders to seawall	No increase in biodiversity	Chapman and Underwood (2011)
Increase complexity of seawall			
Azores Is, Portugal	Drilled pits of various sizes and densities	Up to 10 times as many 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; lower densities of chitons in large holes than in grooves	Chapman and Underwood (2011)
Kirribilli, Australia	Surveyed crevices between blocks	Increased densities of chitons in crevices (77–100%) than on exposed surfaces (0–23%)	Moreira *et al.* (2007)
Kirribilli, Australia	Added crevices between blocks	Increased taxonomic richness of algae and sessile invertebrates in crevices than on exposed surfaces	Dugan *et al.* (2011)
West Sussex, UK	Added pits (large and/or small) to seawall	Increased abundances of barnacles in small crevices and rough compared to smooth surfaces; increased diversity with greater complexity	Moschella *et al.* (2005)
Plymouth, UK	Added pits (large/small) to seawall	60% of functional groups unique to drilled pits; improved species richness in pits	Firth *et al.* (2014b)
Shaldon, UK	Added grooves, pits, and recessed crevices	Barnacles unique to recesses	Firth *et al.* (2014b)
Add additional habitat			
Rose Bay, Australia	Added cavity	Rapid colonization by mobile tide pool 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 tide pools with two depths to breakwater	30% more species in shallow pools than on projections	Firth *et al.* (2014b)
Colwyn Bay, UK	Added Bioblock unit (tide pools, crevices, pits) to breakwater	60% more species on Bioblock than on adjacent rocks	Firth *et al.* (2014b)

toward biological solutions for carbon (C) sequestration and storage (Perring *et al.* 2013). Terrestrial vegetation sequesters carbon dioxide (CO_2) and increases C storage above- and belowground (Perring *et al.* 2013), as do marine seagrasses (Lavery *et al.* 2013). Long-lived species of seagrass (eg *Posidonia* spp) are likely to have the greatest capacity to store C (Fourqurean *et al.* 2012), yet are also the most difficult species to rehabilitate. Therefore, using seagrasses to enhance C capture may currently be unrealistic (Irving *et al.* 2011). Bioengineered oyster reefs have been proposed for both shoreline protection and C storage (Dehon 2010); however, this option requires further investigation because in some cases the CO_2 produced by oysters during shell construction exceeds the potential for sequestration. Seaweeds have the capacity for major C storage through biomass accumulation, which pilot studies in South Korea have estimated at around 10 t CO_2 ha^{-1} yr^{-1} (WebTable 2d). Marine sediments also have the ability to store CO_2 (Schrag 2009), but transport logistics prevent the practical realization of this solution (Golomb 1993). Existing pipelines associated with decommissioned infrastructure may be used to transport CO_2 to deep-sea sediments for storage (Seevam *et al.* 2010). Although potentially feasible, large-scale enrichment of marine sediments requires further scrutiny, given that the ecological consequences are not yet fully understood.

Supporting 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 (eg wind farms) and coastal infrastructure (eg breakwaters) that support aquaculture such as seaweed and shellfish.

For several decades, aquaculture has included offshore operations because many farmed species are unsuitable for land-based ponds or tanks. Relocating aquaculture to offshore sites reduces the risk of anoxia and disease because the offshore movement of water rapidly disperses nutrient-rich animal waste and promotes oxygenation (Buck *et al.* 2004). These ventures are costly and there are already plans to culture 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, which will help to spread the financial costs (Buck *et al.* 2004).

Coastal environments are replete with defense structures such as breakwaters, which may be another option

for aquaculture development. Seeding of structures with the commercially important Pacific oyster (*Crassostrea gigas*) has the potential to improve water quality through filtration while providing an economic return (Forrest *et al.* 2009). Such projects require careful analysis to target appropriate native species and avoid negative ecological outcomes (eg the unintentional transfer of non-indigenous species) that might negate any benefits.

■ Conclusions

The urbanization of the oceans is likely to increase (Panel 1), and while the design of artificial structures remains linked solely to engineering goals, their multifunctional potential may not be fulfilled. We have highlighted opportunities to incorporate multiple targets into designs: a conceptual framework that could underpin future policy. In Europe, there are legal frameworks to support biodiversity enhancements on marine developments; for instance, the 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; for example, the Australian Coastal Protection Act 1979 requires ecologically sustainable development but does not specifically require habitat enhancements or the application of ecological engineering. Similarly, the US Coastal Zone Management Act of 1972 requires that coastal and estuarine areas be managed to restore or enhance ecological function, but fails to address the management of artificial structures. We suggest that biodiversity enhancement and other multifunctional goals (eg pollution mitigation) could be incorporated into policy. Marine structures need not be designed solely for purposes such as coastal protection but can incorporate essential ecological, social, and provisioning services while minimizing adverse environmental impacts. Developing policies that require multifunctional targets to be identified during planning stages could drive this important change in future marine urbanization.

■ Acknowledgements

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