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The Hard Habitats of Coastal Armoring

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The Hard Habitats of Coastal Armoring

Richard L. Hindle

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> Hard (Adj.)
> – solid, firm, and rigid
> – requiring a great deal of endurance or effort

Ecology is not always soft, vulnerable, weak, and on the verge. Many marine species are inherently resilient, tough, and tenacious, often existing in the most turbulent, deepest, and hardest of places. Similarly, coastal infrastructure such as seawalls and breakwaters that employ solid, firm, and rigid materials to armor coastlines are sometimes amenable to the habitat needs of marine species. This is the realm of "hard habitats"—a reconciliation of urban armature and marine ecosystems through the design of advanced structures that protect against rising seas and storms while providing habitat and refuge for marine species. This essay explores the scale, scope, and future outlook for the design of "hard habitats" in urbanized marine environments and points toward the productive collaboration between marine scientists, materials research, and designers. For landscape architects and urbanists concerned with the ecology of cities, hard coastal infrastructure provides an exciting frontier through which to explore the built ecologies. For marine ecologists and other scientists, the fabrication of novel urban intertidal ecosystems provides new sites for experimentation and testing. This convergence of expertise and knowledge is occurring at exactly the moment when coastal infrastructure promises to multiply exponentially around the world, making the development of resilient and environmentally sensitive armoring especially salient. Many of the advances in hard habitat creation have focused on seawalls and breakwaters. Integration of marine habitat requirements with such hard coastal infrastructure promises to incrementally improve, or reconcile, the ecology of urban marine environments. The essay begins with an overview of the problem associated with extensive coastal armoring and scope of the potential solutions, provides a survey of relevant scientific literature, summarizes design principles for ecological seawalls and breakwaters, highlights built projects, and tracks technological innovation through patents.

Hard Coastal Armoring: Extent of the Problem and Scope of the Opportunity

Precedents for "hard habitats" are abundant in the urbanized intertidal zone. We need not look any further than the spontaneous species assemblages associated with boat wrecks or the robust colonization of piers and docks by mollusks for evidence of hard surfaces and extreme conditions harboring novel ecologies in the Anthropocene. Fortunately the habitat potential of hard surfaces is more than anecdotal. Pioneering research on the ecology of urban marine structures confirms that the proliferation of species on artificial structures can be altered through design, and new technologies have, and will be developed that combine sound ecological science with advanced marine construction. The question moving forward is how, not if, we can advance the *positive* interrelations of coastal infrastructure and marine habitats.

Urbanized waterfronts present a unique design challenge at the interface of marine and terrestrial systems. Few would disagree that the urban intertidal zone and vulnerable coastlines must sometimes be armored with rigid seawalls, breakwaters, and embankments, to protect our vital cultural and economic interests. Yet, it is widely accepted that conventional construction practices alter marine environments through the introduction of foreign materials and novel three-dimensional morphologies (i.e., form) into ecosystems that have evolved distinct abiotic and biotic characteristics that are often different from the constructed infrastructure that replaces them. The scale and extent of the design challenge presented by a hardened coastal zone is enormous (Chapman, 2003). Thousands of miles of armored edges and countless artificial marine structures currently exist globally, and much more is in the process of being built or planned, as sea level rise and storm surges increase and coastal development hastens. The artificial materials and structures associated with coastal armoring impact marine environments on micro-, meso-, and macroscales, yet currently there is no coordinated strategy or framework to integrate knowledge about these diverse sites or holistically evaluate their global impact. And, as the use of "soft" engineering approaches, such as constructed sand dunes, wetlands, mangroves, and other naturalistic coastal typologies are sometimes limited by the realities of urban sites, we should consider "hard habitats" among the coastal resilience tool kit.

The extent of global coastal armoring is difficult to accurately assess, but specific urban areas provide insights about generalized conditions around the world. The marine environment of Sydney Harbor, for example, is estimated to be 96% urbanized by walls, piers, wharves, jetties, docks, and other structures, with more than 50% of the shoreline composed of seawalls (Chapman et al., 2009a,b). In California, America's most populated state, an "astonishing" 177 kilometers (km) of the entire 1,770 km coastline is armored. In highly urbanized areas, such as the four southern counties of California (Ventura, Los Angeles, Orange, and San Diego), the issue is exacerbated, with more than 33% of the 360 km coastline armored with riprap and concrete walls (Griggs, 2009) (Figure 23.1a). This urban condition is of course not unique to Sydney or southern California. Most major harbors and urban waterfronts are heavily armored with variable configurations of steel sheet piles, cut stone, riprap, concrete, and timber, leading to extensive "ocean sprawl" that negatively impacts ecological connectivity and distribution of species (Bishop et al., 2017). Urban regions, including New York, Singapore, Jakarta, Hong Kong, San Francisco, and every other major coastal city, have stabilized and armored their waterfronts, radically altering the abiotic and biotic conditions of the intertidal zone (Figure 23.1b). Although significant distances often separate major cities, the aggregative effect of the hardened anthropogenic coastline is larger than a singular site or foreshore, making the urban intertidal and coastal zone "ground zero" for the destruction, and possible reconstruction, of urban marine ecology.

The pervasiveness of artificial materials and simplified built-form of the urban intertidal zone has shifted the ecology of marine systems. This change is often cataclysmic. Imagine if you will the effect of replacing vast, gently sloping, mucky planes of seagrass, marsh plants, and fine sediment with vertical steel sheet piles or monolithic concrete seawalls, or, alternately, the replacement of naturally eroding limestone and extensive mangrove swamps with immovable vertical concrete structures that obliterate sediment and groundwater exchange, and stabilize a once dynamic intertidal condition. Vertical structures truncate the intermediated boundary between water and land, altering the edge morphology in horizontal and vertical profile and diminishing habitat areas (Figure 23.2). Armored edges also restrict the movement and exchange of groundwater, alter salinity gradients and pH levels, limit sediment transport, replace vegetated slopes and planes, and simplify the heterogeneity of microclimates, ultimately altering intertidal habitats. Integration of habitat criteria into urban marine infrastructure may never reverse this damage, but it may help to bridge the ever-expanding schism between urbanization and marine ecology.

The extent and ubiquity of anthropogenic hard structures in the marine environment is emblematic of human geologic and ecologic "agency" in the Anthropocene. In southern

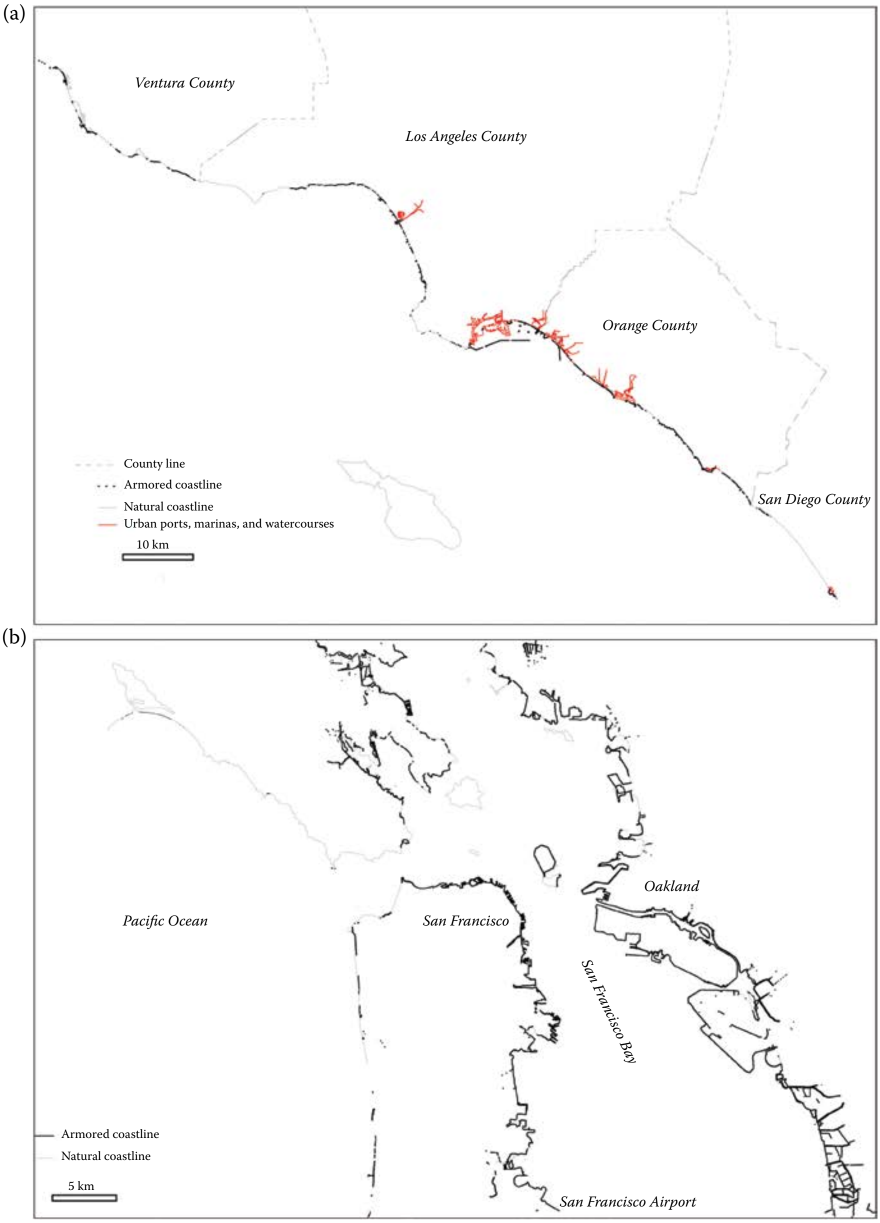

FIGURE 23.1
(a) Map of southern California armored coastline in the southern counties, showing the relationship of natural and anthropogenic structures. The image also highlights harbors and ports that contribute significantly to the urbanized intertidal zone. (Diagram by Kate Lenahan. Data source: California Coastal Commission. "Coastal Erosion Armoring." 2014. Web. 10 April 2017.) (b) Map of the San Francisco Bay area showing extent of artificial marine structures and flood control in the region. The image shows that approximately 50% of the Bay area's coastline is altered by seawalls, levee, berms, and other water control structures. (Diagram by Kate Lenahan. Data sources: San Francisco Estuary Institute (SFEI). "San Francisco Bay Shore Inventory: Mapping for Sea Level Rise Planning GIS Data." 2016. Web. 12 May 2017. California Coastal Commission. "Coastal Erosion Armoring." 2014. Web. 10 April 2017. National Oceanic and Atmospheric Administration. "NOAA Medium Resolution Shoreline." 2016. Web. 12 May 2017. Engineered levees, floodwalls, berms, shoreline protection structures, and water control structures.)

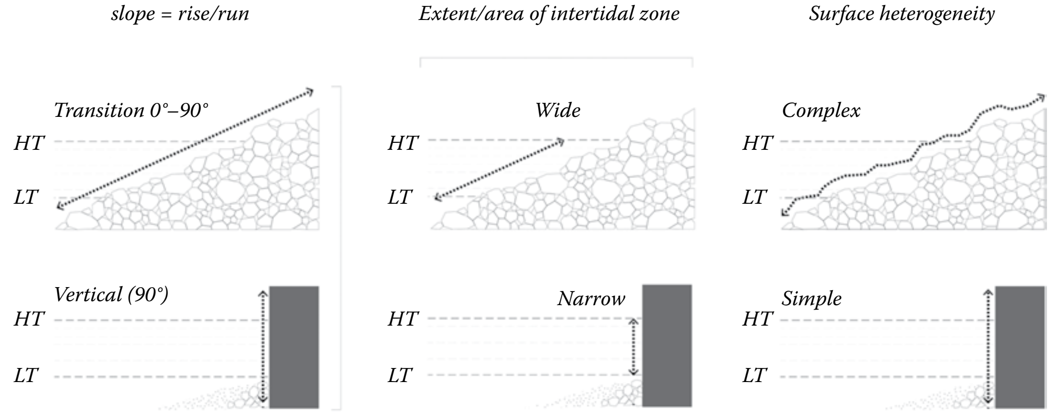

FIGURE 23.2
The shift from gradual shorelines to vertical walls shrinks and simplifies the intertidal zone. Vertical structures decrease the area of the intertidal and reduce the amount of habitat. Artificial seawall structures also simplify the form of the intertidal zone, reducing topographical heterogeneity. (Diagram by Lenahan, K. 2009. Based on similar drawings from McDonnell, M.J. Amy K. Hahs, and Jürgen H. Breuste (Eds.), *Ecology of Cities and Towns: A Comparative Approach*. Cambridge: Cambridge University Press, p. 159.)

California the extent of solid artificial armoring is commensurate with that of analogous naturally occurring geological features. Approximately 29% of southern California's coastline is classified as naturally rocky, and an estimated third is currently armored with manmade rip-rap in the form of jetties, breakwaters, and armored shorelines (Pister, 2009). Although species abundance and composition was found to be similar between riprap and naturally rocky coastlines in parts of California, the divergence in ecological structure is exacerbated in areas that were not formerly rocky. Material incongruence is therefore most commonly associated with typologies such as sandy beaches, soft bottoms, and alluvial cliffs composed of loosely consolidated sand and gravel which are often the most likely to be armored due to their structural instability. This problem is not unique to California. Studies conducted in the Mediterranean further illustrate that hard marine structures in areas with naturally soft bottoms invite invasive species and ultimately reduce biodiversity (Vaselli, Bulleri, and Benedetti-Cecchi, 2008). Likewise, in China's Yangtze river estuary, artificial hard surfaces were shown to facilitate the migration of rocky intertidal species throughout an estuary previously composed of marsh habitat—a problem that will only be exacerbated with climate change (Dong et al., 2016). Given the ability of species to migrate in association with hard coastal infrastructure, it may be concluded that the biogeography and migration of rocky intertidal species would also be radically expanded by the proliferation of coastal infrastructure in response to the threats of sea level rise and increased storm frequency. As we extrapolate to the future, the problem only appears to intensify as sea levels rise and storm surges increase.

Impacts of hard coastal infrastructure on the marine environment are truly multi-scalar as design details have the potential to impact larger scale ecological relationships. This is most succinctly illustrated in debates generated by European plans for offshore wind farms, which promise to supply sustainable energy but also require extensive marine infrastructure. As Europe plans for this massive investment, a critical dialogue has emerged around the foundation structures used to support the turbines. The reef effect (i.e., attractiveness for marine flora and fauna) of the footings are a major concern given the ubiquity of the proposed structural foundations (Petersen and Malm, 2006). Researchers concluded that at the microscale the chemical makeup and relief of the hard substratum play an important role in the composition of the epibenthic (i.e., top of the sea floor) community by impacting the formation of biofilms, anchorage of mollusks and seaweeds, and ultimately the recruitment of species that feed and forage on the structures. At the mesoscale, the size, slope, form, wave exposure, and depth relative to tidal fluctuations were identified as impacting the species associated with the footing of the turbines, and recommendations were made to use novel geometries, boulders, and artificial reefs to create habitat and reduce the negative impacts of scouring on the structure. At the macroscale, the composition of the species assemblages associated with each structure, distance between structures, size of the structures, in combination with local conditions were hypothesized to shift the ecology of the marine environment toward those commonly associated with rocky intertidal zones and reefs.

The multi-scalar and aggregative effect of artificial hard surfaces and substratum in the marine environment is hard to deny, from wind farm foundations to bulkhead walls of port lands. This results simply from the divergence of human construction practices and materials with those of unadulterated marine environments. Although the ubiquity of hard materials used in coastal armoring may be cause for alarm, effective design and technological innovations have been developed and implemented to ameliorate these effects. These hard habitats provide refuge, anchorage, and food sources for marine organisms, while helping to stabilize and protect human habitats and vital infrastructure. It is clear that armoring the intertidal zone is often essential and that the impacts are extensive and persistent. In this context, the aggregative effect of ecologically reconfiguring individual seawalls, breakwaters, and coastal infrastructure is significant on a global scale.

The Novel Ecology of Hard Materials, Vertical Surfaces, and Artificial Marine Structures

Soft engineering with plants and naturalistic landforms has its structural and conceptual limits, especially in highly urbanized areas where space is tight and waterfronts are often multifunctional. Of course, restoration of the water's edge using principles derived from local ecology is often preferable, but this is not always possible in dense urban areas. In cities, hard materials and their associated habitats play an important role in marine environments—like it or not.

Literature on the ecology of hard surfaces has advanced rapidly in the field of urban ecology. Terrestrial and marine ecologists alike have recognized the ecological potential of hard surfaces in urban systems, and many of their lessons and observations offer comparative insight. Terrestrial urban ecologists have focused on the spontaneous species diversity and ecosystems services associated with hard urban surfaces such as walls, stone surfaces, pavements, and rubble piles. In the urban landscape, vegetation commonly associated with rocky and disturbed natural habitats are found to thrive in urbanized hard habitats, including early successional genera of lichens, bryophytes, ferns, and other pioneer species for which these anthropogenic landscapes are habitat analogs (Lundholm, 2011). In this new urban ecological order, cracks in the sidewalk become habitat analogs for rock fissures, rubble piles are surrogates for natural areas of erosion, walls supplant cliff faces, and the broader anthropogenic urban landscape becomes a novel habitat with the potential to reconcile urbanization, industrialization, and ecology (Lundholm and Richardson, 2010).

Importantly, many of these novel habitats and spontaneous and volunteer species offer the same ecosystems services as highly engineered and costly designed systems (Tredici, 2010).

Within this burgeoning area of ecological research, particular attention has been given to walls as ubiquitous features of the urban landscape for their ability to serve as habitat for different species and support "non-standard cosmopolitan assemblages," as well as for their capacity to be redesigned to increase their ecological function (Francis, 2011). The ecology of walls is more than just a contemporary green fad. In Europe, the "novel" ecosystems of old stone walls are studied for their ecological resilience, artifice, longevity in the landscape, and diversity of species resulting from complexity of rock types, variations in form, and age (Collier, 2013). Around the world, related studies affirm the habitat value of vertical hard surfaces. In Hong Kong, research on the ecology of walls shows that traditional construction techniques with open stone joints allow for vibrant *Ficus* communities and thriving vertical ecologies, while modern walls of monolithic concrete limit growth (Jim, 1998; Jim and Chen, 2010). What emerges from a survey of this exciting literature is a new ecological sensibility relating to hard surfaces, vertical urban structures, and their associated novel species assemblages.

Advances in the ecology of terrestrial hard surfaces are mirrored in the study of marine environments, where research indicates that hard surfaces and artificial structures, such as seawalls, may become analog or surrogate habitats for marine species. The relations between marine organisms, artificial materials, and the morphology of artificial structures has been researched at least since the early twentieth century, when scientists attempted to identity factors that contribute to the fouling, or colonization, of marine structures and vessels by sessile (i.e., fixed) organisms. Researchers at the Woods Hole Oceanographic Institute conducted studies on the attachment of sedentary marine organisms to plastics, glass, woods, metals, linoleum, and other materials with additional tests on glass surface textures ranging from flat to ribbed and factrolite (Pomerat and Weiss, 1946). In these early experiments, variable materials and textured surfaces were arrayed in a harbor or bay to determine the rate and density at which organisms attached to the artificial surfaces. The research concluded that material composition played an important role in the surface fouling (i.e., colonization) dependent on the porosity of the material. Although the study was concerned with the primary factors contributing to the unintended colonization of marine structures, it paved the way for further research that confirmed the significance of differences in artificial materials on the abundance of marine species (McGuinness, 1989).

Many of the organisms observed in the first material studies are early colonizers and play an important role in the trophic webs of functional marine environments, providing a base for further development of the community, as well as evidence of artificial materials supporting novel ecological assemblages. Field studies conducted in the 1970s furthered this research, linking successional dynamics and community structure of marine organisms to ubiquitous urban infrastructure and establishing an ecological framework for artificial surfaces and objects. The studies documented the abundance and distribution of sessile epifaunal species on marine pilings and importantly related temporal and spatial scales to habitats developed in association with manmade marine structures (Karlson, 1978). Tim M. Glasby and Sean D. Connell published the first comprehensive survey on the subject of urban structures as marine habitat in 1999, which pointed toward the habitat potential of seawalls and coastal armoring.

Even though artificial reefs have been researched throughout the twentieth century and many of the findings are echoed in the early literature on artificial marine structures, Glasby and Connell's, (1999) paper indicated an important shift in focus on urban infrastructure as a progenitor of a novel marine ecology. The paper vividly illustrates the effects of piers, pontoons, walls, and other structures on marine species assemblages. The findings of this provocative early research are clearly summarized in the following quote:

> There is the potential, therefore, for these new habitats to influence or impact upon other marine species directly and indirectly. For example, fishes are known to aggregate around structures in the water column. The different assemblages of organisms growing on urban structures could influence the types of fishes that recruit to these areas. Organisms living in sediments can be influenced by species in surrounding habitats. Seagrasses are known to be sensitive to shading, sedimentation, and regimes of water flow, all of which may be altered by the addition of urban structures.
>
> **Glasby and Connell, 1999**

Although tentative, Glasby and Connell's survey provided sound ecological context for ongoing research on artificial marine structures. A second survey, published in 2009 by M.G. Chapman, David Blockey, Julie People, and Brianna Clynick, offers a similar analysis with one significant difference—the recognition that design and engineering may facilitate the *creation* of ecologically sensitive coastal infrastructure. In the 10 years between the articles, researchers had advanced the study of artificial marine structures and concluded that species diversity increased with the availability of microhabitats such as those provided by deteriorated walls and therefore may be intentionally designed (Chapman et al., 2009a,b). The agency of design is therefore integral to the production of novel urban marine habitats, collapsing the boundaries between anthropogenic and native ecologies.

The novel marine habitats associated with urban structures are not without controversy. Researchers have identified common problems associated with the ubiquity of artificial marine habitats. Often the species associated with these structures do not exactly mirror the species of nearby natural habitats. Given the perennial comparison of artificial seawalls with unaltered marine environments, there is a tendency among scientists to "consider the impact of built structures as 'negative' if they are colonized by invasive species, but 'positive' if they attract native species (particularly fish) even if the native species would not live in the area were it not for the infrastructure" (Chapman and Underwood, 2011). In this context, the concept of reconciliation ecology, pioneered by terrestrial ecologists, is especially salient. Reconciliation ecology "discovers how to modify and diversify anthropogenic habitats so they harbor a wide variety of wild species. In essence it seeks techniques to give many species back their geographical ranges without taking away ours" (Rosenzweig, 2003). It has been used as an ecological framework through which to comprehend the ecological value of green roofs and vertical gardens in urban environments, which do not fall within strict definitions of restoration ecology (Francis and Lorimer, 2011). However imperfect from the perspective of purist ecology, the novel hard habitats associated with coastal armoring are here to stay and will multiply as sea levels rise, storms surge, and urbanization multiplies. The habitat potential of structures such as seawalls and breakwaters are at the center of this debate and are now the subject of rapid technological innovation.

Seawalls and Breakwaters as Marine Habitat

Seawalls and breakwaters are commonly used to protect urban waterfronts, harbors, and foreshores, and have radically altered the marine environment. These structures armor the shoreline against erosion, preventing inundation of low-lying areas, but they also alter the form of the coast and intertidal zone. Given their ubiquity in coastal armoring, seawalls and breakwaters also have the greatest potential to positively impact urban marine environments.

Seawalls refer to shore-parallel structures designed to stop erosion and retreat of the shoreline, limit inundation, and ameliorate wave action (Kraus, 1988) (Figure 23.3a). Seawalls are often vertical walls or steep revetments (embankments), primarily made of concrete, natural stone, riprap, steel, and even treated timbers. They are located at the intertidal zone

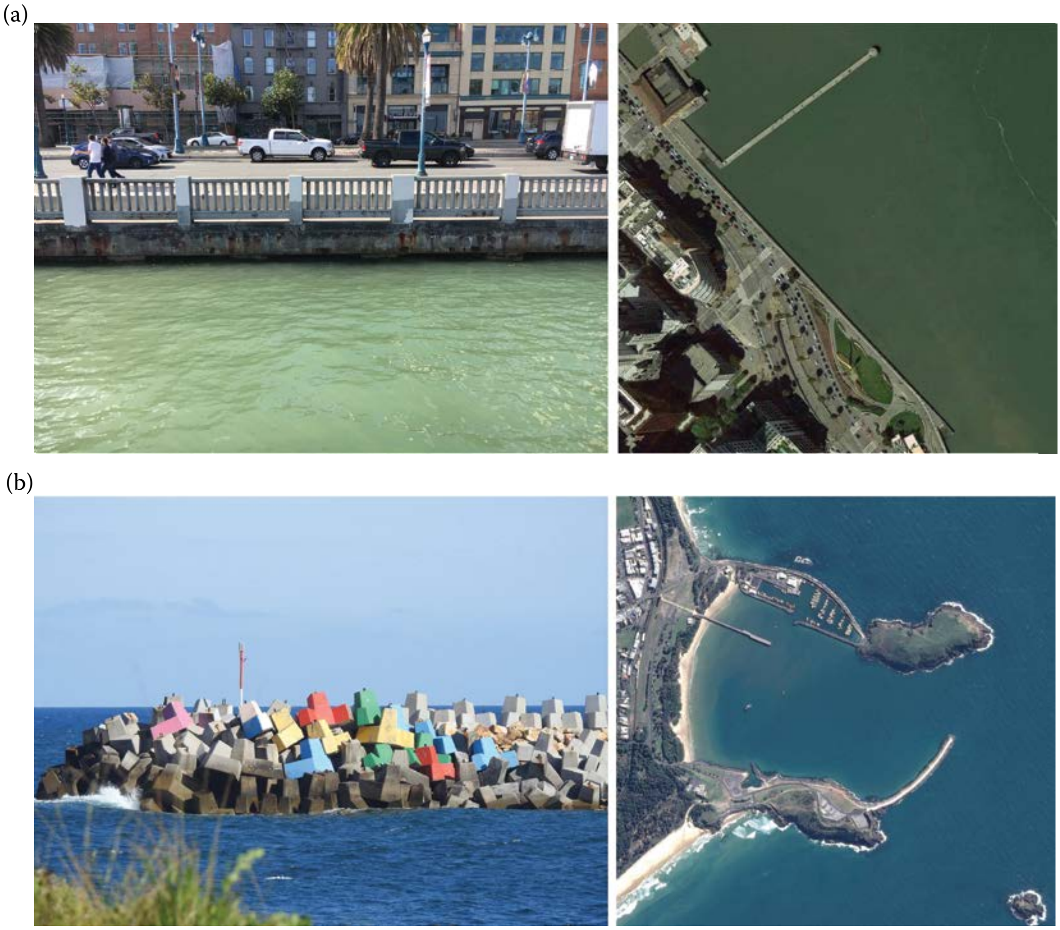

FIGURE 23.3
(a) Seawalls are artificial structures located at the interface between land and water. They often simplify the urban intertidal zone by straightening the horizontal (plan) and vertical (section) profiles of the water's edge. Alternation of the intertidal zone by conventional seawalls greatly reduces the area of marine habitat. The images shown here are of San Francisco Embarcadero seawall. (Photograph [left] by Richard Hindle, Author. Aerial [right] Source: Google Earth.) (b) Breakwaters are artificial structures located away from the shore, designed to reduce wave energy, protect vital infrastructure, and/or reduce erosion. Breakwaters are ubiquitous features of ports and harbors, often creating an entirely new intertidal zone and coastline profile. Given that they are located away from the shore, they have water on both sides of the structure. The images shown here are of a typical breakwater in Coffs Harbor, Australia. (Photograph [left] by Richard Hindle, Author. Aerial [right] Source: Google Earth.)

between marine and terrestrial environments, and many are configured to allow other functions such as boat docking (i.e., as found with bulkhead walls). Breakwaters are coastal structures that protect beaches, harbors, urban shorelines from waves and strong currents (Figure 23.3b) (Nichols and Williams, 2009). They are often linear structures constructed of stone or concrete and can be arranged perpendicular to the shore, or parallel offshore, depending on the criteria of the specific site. Two main classifications of breakwaters exist, those that are vertical in section and those that are mounded or sloped in section. They may also be low-crested (slightly subsurface, or near the surface) or intertidal with parts of the structure exposed during high and low tide. (Note: Sometimes the terms jetty and groin are used interchangeably with breakwater.) Although seawalls and breakwaters are functionally and typologically distinct, both may be similarly modified to improve habitat value utilizing similar principles.

The ecology of seawalls is significant in the design of environmentally sensitive urban waterfronts. Seawalls often differ from natural intertidal habitats in their substrates, material composition, microhabitats, and their size and slope (Chapman and Bulleri, 2003). The net effect is a shift of species composition toward those communities commonly associated with rocky habitats and the reduction of overall species diversity relative to analogous habitats. In simplest terms, seawalls often produce monocultures of species that have adapted to homogeneous material and form necessary to meet structure. As a result, they may sometimes be considered poor surrogates for natural habitat (Chapman et al., 2009a,b). Unfortunately, it is often the case that seawalls replace mangroves, salt marshes, dunes, mudflats, lowland forest, erosive cliffs, and other dynamic systems that are difficult, or impossible, to replicate. Impacts of these structures can be far-reaching, yet difficult to see. For example, studies conducted on the effects of seawalls on salt marsh plants growing adjacent to the structures show they modify groundwater exchange and sediment transport in salt marsh habitats, impacting the distribution of species and accretion of new material (Bozek and Burdick, 2005).

The seawalls of Sydney, Australia, provide an interesting case study, as the natural rocky seashore is made of similar material as the sandstone seawalls, highlighting the differences between anthropogenic and natural surfaces. Historically, the manmade seawalls are predominately vertical and lack the horizontal rock platform common with the natural rocky seashores in the harbor. The natural rocky seashore also shows varied orientation and slope, both of which are radically simplified on constructed seawalls. The reduction of slope associated with these structures shortens the intertidal zone, and within this zone their surface textures are relatively smoother. Furthermore, seawalls lack the overhangs, pools, and large crevasses commonly associated with natural habitat. As a result, conventional seawalls are sometimes considered, in terms of habitat value, as poor surrogates for the natural seawalls (Chapman and Bulleri, 2003). Australian researchers hypothesized that modification of the seawalls' physical topography to mimic the natural rocky edge would promote native biodiversity. In 2005, local government, ecologists, and construction professionals collaborated to build a seawall at McMahons Point that integrated rock pool features. Within the first year, the rock pools increased the diversity of algae, kelp, and sessile organisms such as barnacles, tubeworms, and sponges, and expanded their vertical range (Chapman and Blockley, 2009). Other experimental seawalls have been built around Sydney Harbor and the state of New South Wales. These include modifications at the base of a wall to allow space for mangroves or tidal pools, integration of artificial reef structures that vary the wall's surface texture, and the design of walls that are stepped and sloped to increase the intertidal zone area (Wiecek, 2009).

Heterogeneity, Biomineralization, and Biofilms: Key Features of Hard Habitats

Habitat complexity and heterogeneity are central to the recruitment and diversity of marine species. The habitat structure and complexity of natural oyster reefs has been shown to increase nekton (i.e., swimming organisms) diversity and abundance in comparison to mudflats, though among oyster reefs with variable complexity, abundance is reported to remain stable (Humphries et al., 2011). Niche theory posits that the number of species associated with a particular habitat increases with the number of fundamental niches. The diversity of niches allows for structural overlap and therefore an increase in species diversity. Rebuilding complexity in habitat is therefore essential in restoration and reconciliation efforts (Loke, Ladle, et al., 2015). One way to rebuild complexity is by creating heterogeneity in abiotic conditions such as surface topography, salinity, light, and sediment. Even factors such as the movement of water, and the resulting "wave-scapes" created by heterogeneous surfaces, can impact the distribution of species as well as the morphology of anthropogenic coastlines (Kozlovsky and Grobman, 2017).

Topographical heterogeneity, or the pattern in elevation over an area, is one type of spatial heterogeneity known to impact the distribution of species over a given area (Figure 23.4) (Larkin, Vivian-Smith, and Zedler, 2006). Although commonly associated with large land patterns, topographical heterogeneity can impact the distribution of organisms at smaller scales through the creation of diverse aspects, orientations, textures, rugosity, and slopes. Since this type of heterogeneity is spatial, material, and morphological, it is an area of rapid design innovation. Software has been developed to program habitat complexity and generate output files for the fabrication of heterogeneous surfaces (Loke et al., 2014). New fabrication processes are also underway to improve the topographical heterogeneity of seawall panels, or even to retrofit existing seawalls through drilling and etching (Evans, 2017). And, although there is potential for innovation in the materials and morphology of coastal structures, some of the most effective methods are deceptively simple. For example, researchers in the United Kingdom have effectively increased species diversity through the modification of coastal structures to retain water in small artificial rock pools cut into the surface (Firth et al., 2013). And, researchers in Sydney, Australia, have even used artificial turf grass, made of plastic, to improve species diversity through the richly textural surfaces and tiny spaces of refuge provided by the material (Lavender et al., 2017).

Heterogeneity is a key concept across scales and throughout the physical parameters of marine environments. At the microscale, the topography, texture, and material composition of a natural or artificial structure create unique microhabitats and microclimates with varying moisture, light, sediment, and salinity gradients that regulate species diversity (Coombes et al., 2015). At the macro- (i.e., urban) scale, seawalls commonly simplify the three-dimensional morphology of the marine environment. This is especially pronounced in the horizontal profiles (i.e., planimetric) of the anthropogenic intertidal zone, where walls often straighten coastlines, decrease intertidal habitat area by increasing slopes, and replace natural substrates and vegetation with a few widely used materials. Using the concept of heterogeneity, seawalls and breakwaters could be designed to provide variability in orientation and diversity of slope wherever possible. These principles have led to a set of easily replicable design ideas, including: seawall stairs that offer horizontal surfaces, seawall texturing to create microhabitats with crevices and shallow pools, and

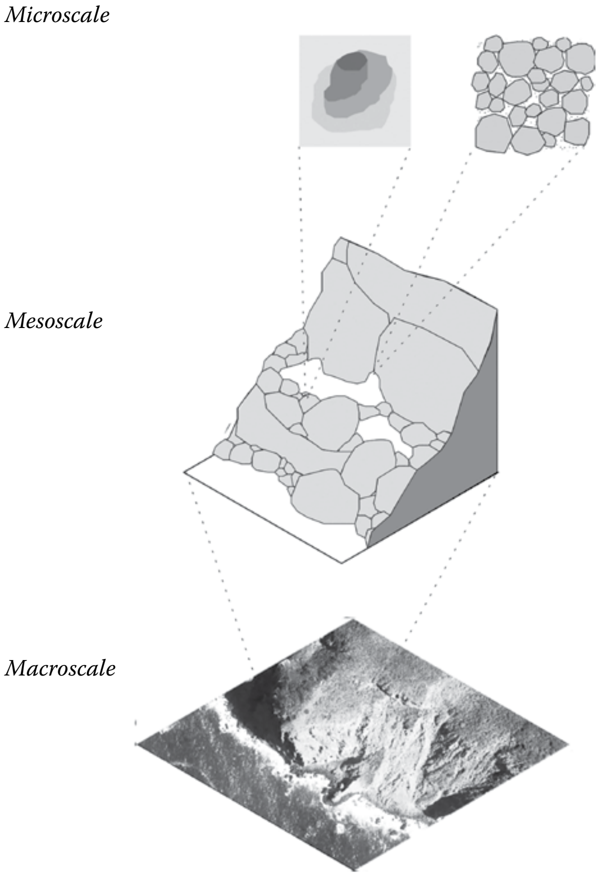

FIGURE 23.4
A diagram of topographical heterogeneity, illustrating the concept at the macroscale (entire cliff face), mesoscale (rocky tidal pool), microscale (rock pore/hole/surface texture). The design of artificial marine habitats often requires heterogeneity across scales to allow for overlapping spatial niches. Topographical heterogeneity also facilitates creation of diverse light/shade, salinity gradients, and temperature in a given area. (Diagrams by Kate Lenahan and Richard Hindle, Author.)

vegetation and substrate baskets to support emergent and aquatic vegetation (Dyson and Yocom, 2015).

The chemical composition of artificial materials is another important factor in creating artificial habitats. Modified concrete mixtures, for example, have been shown to promote colonization by marine species on infrastructure depending on pH, density, and the addition of fibrous matrices (Ido and Shimrit, 2015). Material choices for coastal armoring should consider the precedents and ongoing research generated by the U.S. National Artificial Reef Program established in 1984, which provides information on the function, compatibility, stability, and availability of materials to be used in artificial habitat creation. Diverse materials have been tested as part of the program for the development of artificial reefs including concrete, steel, wood, shell, rock, fiberglass, and waste products such as old cars, parts of gas platforms, tires, and byproducts from coal and oil combustion (Subcommittees, Lukens, and Selberg, 2004). Even though a considerable number have been tested, the effective use of artificial materials in habitat creation continues to evolve, and now includes a class of materials designed specifically to encourage the growth of marine organisms. The term, biomineralogy, is often used to help explain the interrelationship between biological systems and minerals at different hierarchical levels in an ecosystem. Studies have shown that biomineralogy plays a role in marine community development by impacting primary colonization as well as later stages of community development (Bavestrello et al., 2000). Biofilms, or accumulations of bacteria and other microorganisms, are not only essential in the early colonization of an artificial surface, but they also facilitate the settling and recruitment of macroscopic organisms. Because they are sensitive to the chemical composition of substrate materials, this chemical makeup impacts the utility of artificial materials as habitat.

Successful examples of artificial marine habitats are now abundant in scientific literature, making it possible to derive a set of generalized design principles: (1) The heterogeneity of a surface, and formal complexity of a structure increase the potential spatial niches that can be occupied by marine species; (2) Marine structures impact the environment across scales, making it important to consider the detailed rugosity and porosity in small patches in addition to the overall horizontal and vertical profile; (3) Design details that increase variations in moisture, salinity, light, texture, and temperature, are often beneficial to species diversity by creating varied abiotic conditions; (4) Materials play an important role in species establishment and colonization through the creation of biofilms, and processes of biominerology and variability in materials can positively impact species diversity; (5) Mimicking naturally and locally occurring forms, processes, and materials can improve the suitability of a structure. Although each new project will require knowledge of local ecology and coastal processes, these criteria establish a starting point for design development, and a lens through which to evaluate the ever-growing list of pilot projects and new technologies.

Hard Habitats of Coastal Armoring: Precedent Projects

Pilot projects have been constructed around the world to test the viability of ecologically engineered seawalls, breakwaters, and bulkheads. Some of the earliest, and most established prototypes are found in Sydney, Australia (Figure 23.5). The experimental walls constructed in New South Wales are summarized in a 2009 publication entitled “Environmentally Friendly Seawalls: A Guide to Improving the Environmental Value of Seawalls and Seawall-lined Foreshores in Estuaries,” which offers an introduction to the methods and results of the program (Wiecek, 2009). The success of these early prototypes and consensus in scientific literature has lead to the construction of seawalls and breakwaters with integrated habitat globally. Not only do these projects help meet sustainability goals, but they also provide researchers with real world experiments to further evaluate the impact of ecologically engineering hard coastal infrastructure. The precedent projects included here offer an introduction to the diversity of project types currently in process or recently completed. Although the project sites are geographically disparate, they are linked by the integration of marine habitat into the hard surfaces employed in coastal armoring and urbanized waterfronts. Collectively, they represent the first wave of hard habitats merged with coastal armoring.

FIGURE 23.5
Ecologically designed seawall at McMahons Point, Sydney Australia. Tide pools are integrated into the block assembly, providing habitat for intertidal marine species. (Photograph by Richard Hindle, Author.)

Habitat Panels: Seattle, Washington

Seattle's waterfront is in the process of being redesigned, with a new master plan developed by James Corner Field Operations. The need to repair large sections of dilapidated seawall, which threatened important infrastructure, served as a major catalyst for the project. The redesigned seawall will enhance habitats along the urban waterfront and improve public amenities. In preparation for the new seawall design, researchers compared three types of panel relief, including flat panel, sloped steps, and a "fin" pattern, in addition to two surface textures and an untreated wall. Early experiments confirmed that the textured and stepped panels supported more diverse communities than the existing seawall, with densities of species like mussels on the flat panels resembling those in pre-existing habitats. As a result, Seattle will incorporate habitat panels into a large expanse of seawall. The artistic team Haddad|Drugan developed a design for the seawall panels (shown in Figure 23.6) based on results from the experimental test panels and in consultation with a range of experts. The project, led by the City of Seattle Department of Transportation, involved a diverse set of consultants, including Parsons engineering as the prime consultant, and Magnusson Klemencic Associates (civil engineers) who led the overall seawall/public realm design. The University of Washington also conducted experiments and research that led to the design parameters for texture size, depth, and shelf configuration. Haddad|Drugan took the parameters and applied a conceptual and aesthetic interpretation to them that resulted in a 3-D computer model for the actual texture. The result is a visually compelling seawall

FIGURE 23.6
Example of a seawall design in Seattle, Washington, that uses texture and shelves to promote the growth of marine life through the increase of surface area and incorporation of crevices. (Photograph Courtesy of Haddad|Drugan LLC. Photo by Laura Haddad.)

that meets habitat requirements. Importantly, the city plans to monitor the seawall panels for several years after construction, generating data needed to design future ecologically beneficial seawalls in the region and around the world (Goff, 2010).

Mussel Beach: East River, New York City

Ken Smith Landscape Architects designed the Mussel Beach ecological habitat demonstration project as part of the East River Waterfront in New York City (see Figure 23.7). The project is composed of a folded terrain on Pier 35 that spans from the pier's deck level through the intertidal zone. The folded slope is composed of specially textured, precast concrete panels embedded with rocks to serve as habitat for the river's native mussel population. An upland riparian planting flanks the intertidal constructed habitat, and a footbridge crosses the area for public access and viewing. The geometry of the overall habitat increases intertidal area, and the diversity of textured surfaces provides refuge and anchorage for marine species. Significant features of the habitat are its proximity and integration of sewer outlets and the use of precast modules in construction. The precast concrete panels allowed for the development of a diversity of textures and rock patterns that increase to topographical heterogeneity of the surface as well as provide a diversity of materials for marine organisms. The Project team included the City of New York (client),

FIGURE 23.7
Mussel Beach at Manhattan's East River Waterfront Esplanade. (Photograph courtesy of Ken Smith Landscape Architects. Copyright Peter Mauss/Esto.)

Ron Aleveras (ecologist), ARUP (engineering), HDR (engineering), SHoP (architects), and Tillotson (lighting design).

"Green" Breakwater Habitat: Cleveland, Ohio

The Green Breakwater at Cleveland Harbor is a pilot project to test the viability of ecological breakwater blocks to function as marine and intertidal habitat. The project was developed as part of the United States Army Corps of Engineers "Engineering with Nature" program, which aims to develop environmentally sensitive solutions to engineering problems. The Cleveland Breakwater is 7.5 km long, providing for safe navigation and protection of the harbor. The "green" breakwater project modifies the design of standard concrete toe blocks to create habitat opportunities. The redesigned concrete blocks feature grooved surface textures, dimpled surface textures, and indented surfaces for refuge and spawning. Sample blocks were installed in 2012 and 2014, and results from monitoring suggest they stimulated an increase in algae species (*Cladophora* spp.) as well as a variety of aquatic invertebrates (Dreissenid mussels, oligochaetes, amphipods, etc.). The blocks are currently being maintained and evaluated for use in other breakwaters around the Great Lakes (Figure 23.8) (Fredette et al., 2014).

FIGURE 23.8
Precast concrete blocks for use in seawall construction. (Photograph courtesy of the United States Army Corps of Engineers Buffalo District.)

Living Breakwaters: Staten Island, New York

SCAPE Landscape Architecture DPC developed the Living Breakwaters project and program as part of their winning entry for HUD's Rebuild by Design Competition. The Living Breakwaters proposal envisions a series of breakwaters flanking the Staten Island shoreline. Community outreach and education are integrated with the design through programs that educate and cultivate the coastal defense structures. The breakwaters are configured to provide habitat at the macro- and microscale through a series of "reef streets" that offer habitat complexity and heterogeneity to host finfish, shellfish, and other marine species. The SCAPE team developed the Living Breakwaters concept for the U.S. Department of Housing and Urban Development's Rebuild by Design (RBD) initiative. SCAPE's approach is unique for its integration of resilient coastal infrastructure with habitat enhancement techniques and environmental stewardship. A pilot project is being developed for the South Shore of Staten Island using special ECOncrete habitat blocks. The concrete mixture for the blocks is specially formulated to encourage marine organisms, and the surface of the block is textured to enhance surface heterogeneity. The blocks are arranged to provide spatial complexity and variability (Figure 23.9).

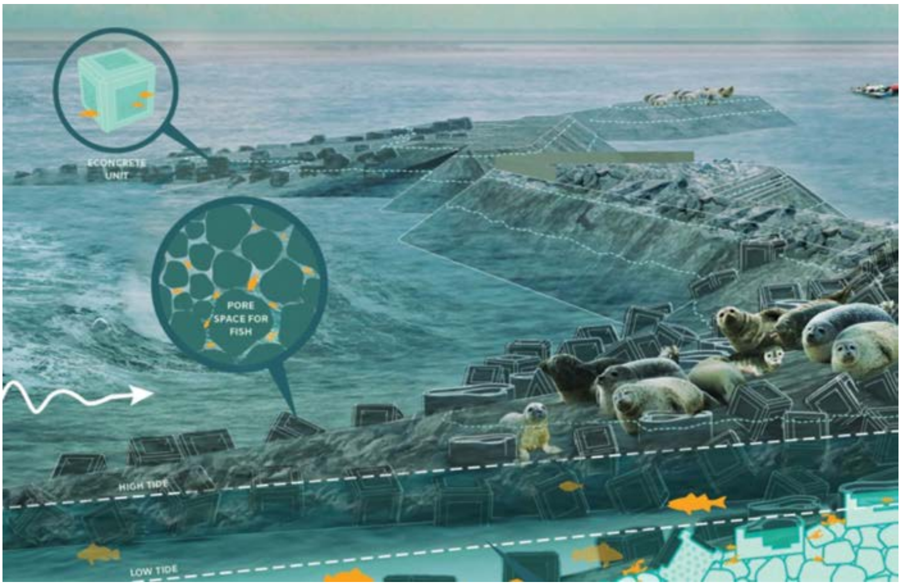

FIGURE 23.9
Building ecological resiliency. (Photograph Courtesy of SCAPE Landscape Architecture DPC.)

Fish Habitat Enhancement Devices (FishHEDs): Rhinebeck, New York

The Hudson River Sustainable Shorelines program has developed a series of demonstration projects to make science-based information available about best shoreline management techniques. As steel sheet piles were identified as exhibiting almost no habitat value, prototypes for Fish Habitat Enhancement Devices (fishHEDs) were installed at Rhinecliff Landing in Rhinebeck, New York. The pilot project aims to improve fish and invertebrate habitat within the corrugations of the steel bulkhead wall while maintaining human use and function of the dock. The team designed, built, and installed the fishHEDs in 2015 to increase habitat complexity and diversity on the site (Figure 23.10) (https://www.hrnerr.org/fishheds.html).

Artificial Tide Pools: Brooklyn, New York

Brooklyn Bridge Park, designed by Michael Van Valkenburgh Associates, integrates precast tide pools into the riprap slopes at Pier 4. The ECOncrete tide pools are intended to increase intertidal biodiversity by improving habitats for species that that are not typically associated with riprap, specifically by providing refuge during low tide. The patented concrete mixture composite closely resembles the texture and makeup of rock and coral. It facilitates the growth of algae, seaweed, oysters, and other marine life, which offers habitat, breeding grounds, and food sources for fish, crabs, and other organisms. Since the precast tide pools are specifically designed for use with riprap slopes, they can be easily integrated with existing construction practices (see Figure 23.11).

FIGURE 23.10
FishHEDs mounted on bulkhead. (Photograph courtesy of Hudson River Estuary Program and New York State Department of Environmental Conservation.)

Patent Innovation and the Development of New Habitats

Technology plays an important role in the development of artificial habitats, as it does in all ecologically designed and engineered systems. In this sector of "ecotechnology," patents are an effective method of tracking innovation while offering insights about what the manmade habitats of the future may look like. Since hard habitats are entirely fabricated, they are liable to undergo many phases of design iteration, research, and development before new best practices and preferred systems are adopted. Irrespective of this sector's infancy, patent innovation parallels, outpaces, and even predicts scientific discoveries. Artificial reefs, for example, have been the subject of scientific inquiry and patent documentation since at least the 1960s. Many of the advances made in artificial reef technology, such as techniques to enrich surface textures, provide three-dimensional refuge, and attract fish, may now be utilized for the creation of habitats on seawalls and breakwaters. Technological innovation can sometimes outpace scientific discovery. For example, marine ecologists first altered seawalls to integrate habitats such as rock-pools in 2005, yet a similar system for integrating habitat in seawalls was patented in 1992, leaving a 13-year lag between invention and materialization of the idea in the built environment.

FIGURE 23.11
ECOncrete tide pool. (Photograph Courtesy of ECOncrete.)

Technology and ecology continue to converge; yet debates persist about the role and viability of innovative materials and construction systems in marine ecosystems. For instance, a survey of "alternative" shoreline devices published in 2012 questioned the environmental impact and efficacy of non-conventional technologies such as artificial seaweeds or net groins (Pilkey and Cooper, 2012). Yet, similar systems are now being studied for their capacities to create habitat for species like seahorses, which introduce filamentous textures to the marine environment that facilitate anchorage of marine species (Hellyer, Harasti, and Poore, 2011). Notwithstanding scientific opinion, this sector of technology and industry continues to grow. Companies such as ECOncrete are developing new concrete compositions and marine habitat modules, with pilot projects around the world (http://www.econcretetech.com). To date, there are hundreds of patented artificial habitat and shore protection systems that address complex environmental problems, from the dissipation of wave energy, to the construction of large ports in open water. The question moving forward is how to best implement, test, and evaluate novel construction systems and new materials.

Patent innovation in hard habitats can be reduced to two main categories: (1) systems and complex assemblages that create novel three-dimensional form to serve as habitat and/or stabilize coastal infrastructure by mitigating wave energy or reducing scouring, and (2) material compositions or production processes that modify the chemistry or physical properties of substrates to catalyze growth of marine organisms. The patents listed below provide a sampling of the techniques and technologies related to the creation of hard habitats (see Figure 23.12a–g).

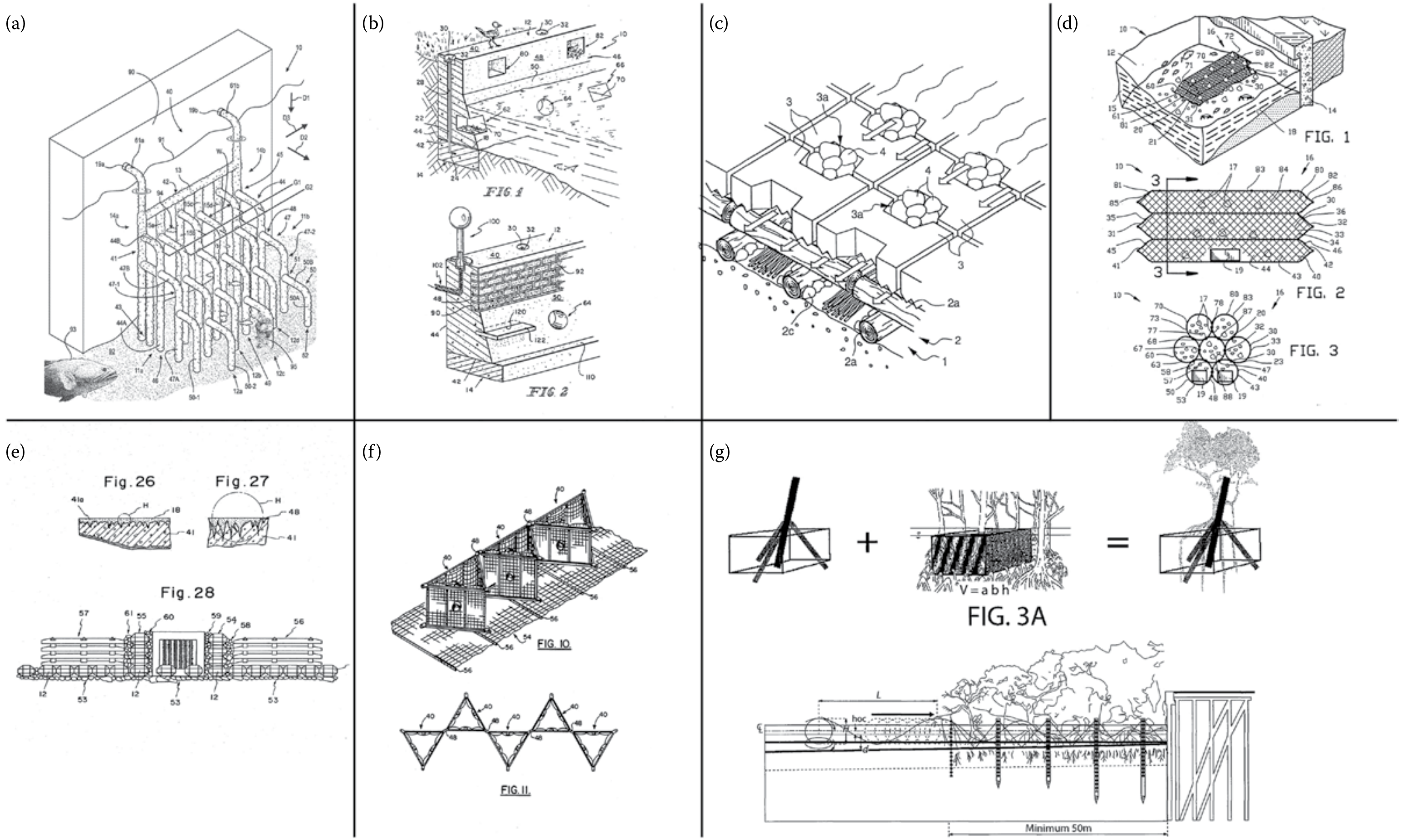

FIGURE 23.12
(a–g) Patent images for coastal armoring integrated with marine habitats. (http://patft.uspto.gov.)

Three-Dimensional Structures and Complex Assemblages

U.S. 8,635,973: Artificial Mangrove Assembly (2014)

The artificial mangrove assembly provides habitat and refuge that replicates the three-dimensional structure of mangrove roots. The system provides habitat complexity throughout the water column directly in front of a seawall and can be affixed to the surface of existing walls to improve intertidal habitat. Each artificial root element is secured to the mounting assembly, extending downward though the water column, and eventually contacting the bottom through a respective distal end. In nature, the roots of the mangrove provide habitat for marine flora and fauna such as fish, crustaceans, and birds. Moreover, they trap aquatic nutrients for marine life and act as a substrate for colonization. Naturally occurring mangroves are rapidly disappearing for a number of reasons, including climate change, barnacle infestation, weeds, pollution, logging, oil exploration and extraction, shrimp aquaculture, tourism, and urban development. The artificial mangrove assembly proposes a formal substitute that can foster habitat complexity comparable to that of this threatened system.

U.S. 5,125,765: Seawall Construction (1992)

The patent for "Seawall Construction" is an early design concept for a rigid wall with integrated habitat for marine species. The seawall is formed to have a plurality of recesses in the lower front panel, providing nesting places and refuge for marine life and other associated wildlife. A diverse array of recessed geometries, shelves, and textures enhance habitat complexity for marine species. The design also permits the movement of organisms through the wall so they may build habitat in the soil and stone behind it. This type of connectivity would simultaneously permit the exchange of groundwater with the water body. It is important to note that this seawall patent was developed more than 10 years before its first prototypes were tested in Sydney.

U.S. 6,746,177: Block and a Riparian Improvement Structure Inhabitable for Aquatic Life (2004)

The riparian improvement structure is designed to stabilize shores, allow for the exchange of water and oxygen between soils and water, and provide habitat for marine organisms. It consists of a series of blocks and wooden materials that accommodate the exchange of oxygen and water through the system, facilitate the movement and anchorage of marine organisms, and stabilize the shore. The structure creates an environment suitable for aquatic life such as fish and crustaceans by incorporating void spaces, diverse textures, and organic materials into the assembly. The blocks are each provided with a water passage through a series of grooves. This configuration admits flow through the riparian improvement structure to accelerate the exchange of water containing a sufficient amount of dissolved oxygen for aquatic life, thereby creating an environment suitable for its growth.

U.S. 5,007,377: Apparatus and Method for Marine Habitat Development (1991)

This patent discloses a method for the development of a marine habitat through the growth of mollusks adjacent to urban waterfronts. The system and strategy comprise a plurality of retaining members made of a mesh wall that may be filled and colonized by mollusks and other marine organisms. This early design for "oystertecture" aggregates permeable bags of adult mollusks to seed a reef in a desired location. The permeability of the bags permits the growth of mollusks inside, through, and outside the retaining structure. The patent also anticipated that other marine organisms might pass through and occupy the reef bags, cultivating a functional reef habitat. Importantly, the reef modules can be arranged as necessary along an urban shoreline and may be incorporated into seawalls.

U.S. 4,508,057: Algal Culturing Reef Unit, Artificial Reef Unit, and Artificial Culturing and Fishing Field Unit (1985)

The artificial algal culturing reef unit aims to raise fish or culture algae, fishes, and shellfishes and is typically submerged in a shallow sea zone. Because these units must resist high waves and fast oceanic currents usually encountered in this environment, they are made of concrete. Although concrete materials are suitable because of their strength and cost, an alkali is necessarily emitted from their surfaces that is extremely harmful to diatoms and algae, as well as fishes and shellfishes. The algal culturing reef unit uses a layer of iron sulfate or acid and iron oxide powders to penetrate the surface of the concrete blocks, whereby the alkali from the concrete is oxidized to create a surface chemistry preferred by algae and shellfish and thereby facilitates rapid colonization.

U.S. 5,269,254: Method and Apparatus for a Growing Oyster Reef (1993)

The patent proposes a method for oyster reef formation by setting seed oysters on cultch material, such as recycled oyster shells. The placement of seeded cultch material in permeable panels forms a vertical wall through which water may flow. The modules are made of welded wire metal frames and mesh material and arranged in a stable triangular form that may be arrayed along the shoreline. The structures can be configured in a manner that effectively accretes sediment, and in conditions favorable for oyster growth, become living walls that grow oyster reef. The thin panels of cultch material and metal allow water passage, but also accumulate sediment.

U.S. 8,511,936: Method and Apparatus for Coastline Remediation, Energy Generation, and Vegetation Support (2013)

The reinforced mangrove infrastructure integrates living mangrove plants into a biomechanical structure for coastline remediation. A structural framework supports mangrove plants such that they may take root, forming a biomechanical skeleton that may catalyze the development of a mangrove forest and habitat for oysters and other marine organisms. The system may be incorporated into the existing coastline morphology for restoration of degraded mangrove habitat within the native range of the species. It can also be adapted for use in combination with existing coastal infrastructure, such as seawalls, to dissipate wave energy from storm surges and sea level rise.

Chemical Modification of Materials

U.S. 8,312,843: Artificial Material Conducive to Attract and Grow Oysters, Mollusks, or Other Productive and/or Stabilizing Organisms (2012)

The artificial construction material facilitates the setting and growth of oysters, other mollusks, and other organisms for the purposes of food production and creation of marine infrastructure such as artificial reefs/breakwaters. The material is a composite concrete that acts as both an attractant and nutrient source for mollusks and other aquatic organisms. The binder for the composite consists of both cement and an organic material with several admixtures that modify the physical and chemical properties of the cement. The organic component is selected to attract and feed aquatic organisms, and may include cottonseed, peanuts in the shell, animal byproducts, slow release fertilizers, and other materials containing the desired levels of nitrogen, fat, and sugar. Because the material releases nutrients in a form usable by microorganisms in its vicinity, quality grades of organic material that may not otherwise be suitable for consumption or normal animal feed may be used in the artificial material. Previously useless material, such as cottonseed high in free fatty acid and peanuts below acceptable grade, can be incorporated into the composite material to manage waste products, as well as beneficially grow mollusks and other organisms.

CA 2,901,149: Methods and Matrices for Promoting Fauna and Flora Growth (2014)

The invention proposes a marine infrastructure comprising a concrete matrix having a pH of less than 12, which is beneficial to the generation of biofilms, and supplemental admixtures that promote the growth of fauna and flora in the aquatic environment. This is reported to include endolitic and epilitic, anaerobic and aerobic flora and fauna (lichens, fungi, mosses, and blue-green algae). In addition to its pH requirement, the concrete matrix is modified to have a roughness grade beneficial to the anchorage of marine organisms and a compressive strength that meets construction standards.

DE 69806616: Stone Material for Submerging into Water, Method of Production Thereof, and Method of Forming Submarine Forest (2003)

This patent discloses a method of producing stone material for submerged conditions to cultivate a submarine forest of seaweeds and algae. The procedure to prepare the stone mixture integrates a granular slag generated in the steel production process, applies carbonized treatment, and uses the resulting carbonates as a binder. In prior processes calcium contained in slag is eluted (washed out) in the sea, raising the pH of seawater in the periphery. Compared with concrete products, the agglomerated slag obtained in iron- and steel-making processes is more suitable as a block for a seaweed bed or the like due to its surface properties. However, it has the same degree of function (adhesion and viability of marine algae) as natural stone, and it does not by design promote the growth of marine algae.

U.S. 20150230434: Application of Green Technology Techniques to Construct a Biodegradable Artificial Reef (2015)

This invention provides a cellulose-based surface that is coated in nutrients to promote the rapid growth of marine microbes at the base of the marine food chain. The reef material intends to catalyze rapid growth by providing mineral based substrate attached to the cellulose-based material which is denser than water to allow the entire structure to sink; both the cellulose- and mineral-based materials will degrade rapidly, leaving behind nucleation sites for microbes, corals, invertebrate collections, and more. The reef is constructed entirely from biodegradable materials, and production costs are economical. To achieve the goals, a cellulose-based material is soaked in nutrients, combined with a mineral-based biodegradable substrate, sunk in an aquatic or marine environment, and used to function as a nucleation and nutrition site for a variety of organisms. As opposed to other approaches for constructing artificial reefs, this method utilizes green technologies' principles to stimulate the rapid colonization of the structure by the microbial community, the bottom of the food chain, shortly after being submerged. Tests have been conducted in Florida as part of a pilot project.

(Note: *Additional information on each patent, or expanded searches, are available on the United States Patent and Trademark Office website* www.uspto.gov, *or the European Patent Office website* https://worldwide.espacenet.com/.)

Conclusion

The integration of habitat within the armored intertidal zone attempts to reconcile the schism between marine ecosystems and the need for urban infrastructure, creating fertile ground for research, experimentation, and technological innovation. The triple threats of sea level rise, increased storm surges, and ongoing development pressure will hasten the demand for coastal armoring and expand the hardened anthropogenic intertidal zone, ultimately shifting the ecology of urban marine environments. Although fraught with risk, proliferation of coastal armoring also provides opportunities to create novel habitats in highly altered environments and offers alternatives to soft engineering in areas where space is limited or structural requirements are stringent. It is also worth noting that these new habitat types occur at the convergence of capitol investment, infrastructure, and environment cost typically associated with urban waterfronts. Given these economic and environmental factors, it is a safe assumption that innovation will continue in this relatively new sector of technology.

Coastal infrastructure integrated with habitat necessitates collaborative research, design experimentation, and creates business opportunities. Patent submissions indicate that new materials and structural systems are being invented as scientific observations continue to verify the novel habitat benefits of coastal infrastructure. Simultaneously, creative precedent projects are being developed that provide real world experiments for urban marine scientists to verify. The intersection of expertise, capitol, and technology, evident at the urban intertidal zone, reveals a unique "innovation model" for physical urban infrastructure in which new technologies beget novel ecologies that improve the city and incentivize investment. This convergence of factors has recently been coined as a "blue" framework for the eco-engineering of urban marine environment in which technological progress, investment, primary research, and ultimately new forms of multifunctional infrastructure are coordinated to improve urban intertidal ecology (Mayer-Pinto et al., 2017).

Of course, hard habitats are not merely a scientific or technical proposition, they are in fact cultural in nature, requiring a shift in consciousness and socio-technical and socio-ecological evolution. Culturally, our recent consideration of the ecologies of hard surfaces and coastal armoring represents a significant change in attitude from a strict division between marine and urban environments toward a kind of mutualism. Whether or not this technological form of reconciliation ecology can drastically improve the ecology of cities is yet to be determined at a significant scale, but in this early phase of innovation it is best to dream big as the next phase of coastal infrastructure will undoubtedly be mightier, harder, and more extensive than the last. And, as awareness about the threats to urbanized marine environments is foregrounded by shifts in our changing climate, *hard habitats* will provide a valuable framework for sustainability and potentially a robust catalyst for future innovation. We can already observe positive trends in patent submissions, built precedent projects, and experimental fabrication and scientific research projects that are pushing the boundaries of ecology and technology in global cities. And, the next generation promises to be even move exciting and foreword looking. For example, experiments in 3-D printing of artificial reefs conducted by Fabien Cousteau, grandson of Jacques Cousteau, suggest that synthetic reefs composed of calcium carbonate may be created to augment natural reefs using additive manufacturing. And, in the San Francisco Bay Area, students at UC Berkeley have developed fabrication processes for complex seawall modules using dissolving and biodegradable formwork which allows for the creation of heterogeneous habitat surfaces and voids not currently achievable using conventional construction practices. These projects are only the beginning of a concerted effort by researchers, designers, and city makers, to rebuild the ecology of a rapidly urbanizing planet and materialize the “hard habitats” of the future.

References

Bavestrello, G. et al. 2000. “Bio-mineralogy as a structuring factor for marine epibenthic communities.” *Marine Ecology Progress Series* 193:241–249.

Bishop, M.J. et al. 2017. “Effects of ocean sprawl on ecological connectivity: Impacts and solutions.” *Journal of Experimental Marine Biology and Ecology* 492:7–30. http://dx.doi.org/10.1016/j.jembe.2017.01.021 (accessed June 12, 2017).

Bozek, C.M., and D.M. Burdick. 2005. “Impacts of Seawalls on Saltmarsh Plant Communities in the Great Bay Estuary, New Hampshire USA.” *Wetlands Ecology and Management* 13(5):553–568.

Chapman, M.G. 2003. “Paucity of mobile species on constructed seawalls: Effects of urbanization on biodiversity.” *Marine Ecology Progress Series* 264:21–29.

Chapman, M.G., and A.J. Underwood. 2011. “Evaluation of ecological engineering of “armoured” shorelines to improve their value as habitat.” *Journal of Experimental Marine Biology and Ecology* 400(1–2):302–313.

Chapman, M.G., and D.J. Blockley. 2009. “Engineering novel habitats on urban infrastructure to increase intertidal biodiversity.” *Oecologia* 161(3):625–635.

Chapman, M.G., and F. Bulleri. 2003. “Intertidal seawalls—New features of landscape in intertidal environments.” *Landscape and Urban Planning* 62(3):159–172.

Chapman, M.G. et al. 2009a. “Comparative effects of urbanisation in marine and terrestrial habitats.” *Ecology of cities and towns: A comparative approach*, pp. 51–70.

Chapman, M.G. et al. 2009b. “Effect of urban structures on diversity of marine species.” *Ecology of Cities and Towns: A Comparative Approach. Cambridge University Press, Cambridge*, pp. 156–176.

Collier, M.J. 2013. “Field boundary stone walls as exemplars of “novel” ecosystems.” *Landscape Research* 38(1):141–150.

Coombes, M.A. et al. 2015. “Getting into the groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures.” *Ecological Engineering* 77:314–323.

Dong, Y.-W. et al. 2016. “The marine “great Wall” of China: Local- and broad-scale ecological impacts of coastal infrastructure on intertidal macrobenthic communities.” *Diversity and Distributions* 22(7):731–744.

Dyson, K., and K. Yocom. 2015. “Ecological design for urban waterfronts.” *Urban Ecosystems* 18(1):189–208.

Evans, A.J. et al. 2017. “Stakeholder priorities for multi-functional coastal defence developments and steps to effective implementation.” *Marine Policy* 75:143–155. January 2017.