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Forum

Towards an urban marine ecology: characterizing the drivers, patterns and processes of marine ecosystems in coastal cities



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Human population density within 100 km of the sea is approximately three times higher than the global average. People in this zone are concentrated in coastal cities that are hubs for transport and trade – which transform the marine environment. Here, we review the impacts of three interacting drivers of marine urbanization (resource exploitation, pollution pathways and ocean sprawl) and discuss key characteristics that are symptomatic of urban marine ecosystems. Current evidence suggests these systems comprise spatially heterogeneous mosaics with respect to artificial structures, pollutants and community composition, while also undergoing biotic homogenization over time. Urban marine ecosystem dynamics are often influenced by several commonly observed patterns and processes, including the loss of foundation species, changes in biodiversity and productivity, and the establishment of ruderal species, synanthropes and novel assemblages. We discuss potential urban acclimatization and adaptation among marine taxa, interactive effects of climate change and marine urbanization, and ecological engineering strategies for enhancing urban marine ecosystems. By assimilating research findings across disparate disciplines, we aim to build the groundwork for urban marine ecology – a nascent field; we also discuss research challenges and future directions for this new field as it advances and matures. Ultimately, all sides of coastal city design: architecture, urban planning and civil and municipal engineering, will need to prioritize the marine environment if negative effects of urbanization are to be minimized. In particular, planning strategies that account for the interactive effects of urban drivers and accommodate complex system dynamics could enhance the ecological and human functions of future urban marine ecosystems.

Keywords: climate change, ecological engineering, ocean sprawl, pollution pathways, resource exploitation

Synthesis

Urban ecology has advanced rapidly in recent decades, yet has focused primarily on terrestrial and freshwater systems. By comparison, urban marine ecology is a field in its infancy and lacks the theoretical and empirical foundations underpinning urban ecosystem science on land. This Forum-article aims to help build such a foundation, by presenting a conceptual framework of the interacting drivers of marine urbanization, identifying key characteristics of urban marine ecosystems based on research from disparate disciplines, and highlighting research priorities that can advance urban marine ecology as a discipline.



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Introduction

The world's population is urbanizing rapidly (Bloom 2011, Seto et al. 2011, UN 2017) with mass migration towards coastlines (Creel 2003, McGranahan et al. 2007) and policy reforms that favour densification (Dallimer et al. 2011, Kytta et al. 2013). Population density at the coast (≤ 100 km from the sea and ≤ 100 m above sea level) is approximately three times higher than the global average and is increasing (Small and Nicholls 2003). Most people are concentrated in coastal cities that, as hubs for trade and/or due to a fertile delta, are frequently situated where river and sea meet (Konishi 2000). Many of these conurbations have expanded into megacities of more than ten million people (Nicholls 1995, Li 2003). For ecologists, coastal cities are of particular interest and concern, not only from a terrestrial perspective, but also in terms of consequences for, and interactions with, the marine environment (Dafforn et al. 2015, Firth et al. 2016).

Understanding of the effects of urbanization on marine ecosystems and ecological processes is growing (Burt 2014, Mayer-Pinto et al. 2015, Firth et al. 2016). Human density is strongly related to resource exploitation, and one of the early effects of marine urbanization is the depletion of nearby fishery resources (Li 2003, Kirby 2004). Coastal cities create marine pollution, including the harmful chemicals, bacteria and sediments associated sewage and urban runoff (Hoffman et al. 1983, Nixon 1995, Cornelissen et al. 2008). They also lead to nearshore development, usually starting with a harbour, but also including hard coastal defences to reduce erosion of valuable land, whether it be pre-existing or reclaimed (Charlier et al. 2005, Lotze et al. 2005, Tian et al. 2016). These artificial structures have significant effects on the ecology of shorelines, especially when entire habitats are replaced with novel materials such as concrete and granite (Firth et al. 2014, Dyson and Yocom 2015, Loke et al. 2019a).

Several recent reviews have separately highlighted urban-related pollution and physical modifications of urban shorelines as critical components of urban marine ecosystem dynamics (Dafforn et al. 2015, Firth et al. 2016, Heery et al. 2018a), but exploitation of marine resources is rarely discussed in an urban context (though see Li 2003, Baum et al. 2016). The overarching characteristics of urban marine ecosystems that result from each of these factors and their potential combined effects have yet to be thoroughly considered. There is considerable need to integrate findings relating to marine urbanization across subdisciplines of ecology; this effort would be aided by conceptual frameworks that integrate multiple variables, identify potential interactions and feedbacks, incorporate historical trajectories, and facilitate the development of testable hypotheses regarding the response of urban marine ecosystems to further environmental change. Frameworks meeting this need would not only broadly support marine research in the Anthropocene, as nearly all coastal zones are now strongly impacted by anthropogenic stressors, but would also help build a foundation for urban marine ecology – a field in its nascence. Inevitably, urban

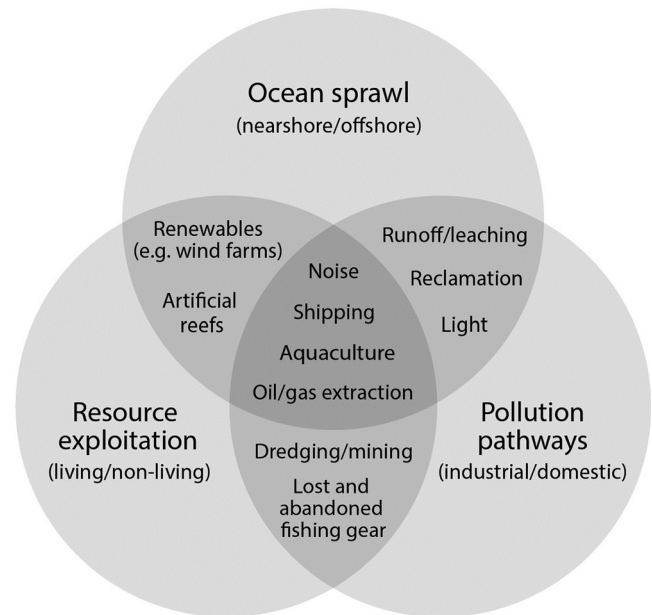


Figure 1. Activities, installations, processes and issues that represent instances of overlap and interaction among the three major drivers of marine urbanization: resources exploitation, ocean sprawl and pollution pathways.

marine ecosystems are coupled social–ecological systems and are heavily influenced by what is happening ‘upstream’ in the urban fabric, by physical modifications nearshore and offshore, and by current and future consequences of climate change, such as sea-level rise and punctuated extreme weather events. As such, the dynamics and prevailing ecological paradigms for these systems have yet to be tested experimentally, and it is only through expanded field manipulations that it will be possible to understand the core properties of urban marine ecosystems: how they are structured, how they function and the key parameters that drive the ecosystem services they provide.

In this paper, we outline the primary drivers of marine urbanization and identify the known patterns exhibited by marine ecosystems in urban areas. Empirical testing of the underlying processes that create these patterns and further research in areas we highlight in this paper can help build a framework for understanding multifaceted impacts of marine urbanization, and future trajectories of urban marine ecosystems in the face of climate change.

Three main drivers of marine urbanization

The process of marine urbanization comprises three primary drivers (Fig. 1). The first is exploitation of both living and non-living resources (see ‘Resource exploitation (both living and non-living)’) and includes recreational, subsistence and commercial fishing, as well as dredging and mining for minerals (Table 1). In post-industrialized nations, this may largely be historical, but with long lasting effects that are still

Table 1. Types of marine exploitation and their scope, scale and potential effects.

Exploitation type	Scope and scale	Potential effects on marine life and habitats
Recreational fishing	Estuarine, inshore, offshore; scale can range from hundreds to tens of thousands of participants in a region.	Removal of target fish and shellfish, potentially leading to population- and/or ecosystem-wide impacts. Delayed mortality from catch and release practices; mortality of bycatch species; mortality or injury from boat collisions. Damage or degradation of sensitive habitats from contact fishing gear or the launching/recovery of boats. Lost and abandoned fishing gear issues (Table 2).
Subsistence fishing and gleaning	Estuarine, intertidal, inshore; numbers unknown but likely to vary greatly by region.	Removal of target fish and shellfish, potentially leading to population- and/or ecosystem-wide impacts; mortality of bycatch species; mortality or injury from boat collisions. Damage or degradation of sensitive habitats from contact fishing gear and the launching/recovery of boats. Impacts from practices such as cyanide or dynamite fishing. Lost and abandoned fishing gear issues (Table 2).
Commercial fisheries	Estuarine, inshore, offshore; scale variable by fishery and region but can range from tens to thousands of participants.	Removal of large numbers of target species, potentially leading to major population- and/or ecosystem-wide impacts; mortality of bycatch species; mortality or injury from boat collisions; damage or degradation of sensitive habitats from contact fishing gear and the launching/recovery of boats. Lost and abandoned fishing gear issues (Table 2).
Mariculture	Estuarine, inshore (offshore in the future); scale varies widely and depends upon the species being farmed.	Transmission of disease and parasites between farmed and native species; eutrophication due to addition of nutrients (although shellfish farms may remove nutrients from water column); smothering of benthic fauna due to build-up of organic material (also leading to changes to sediment type/chemistry).
Dredging for minerals/ aggregates	Inshore and offshore; scale variable but can range from tens to hundreds of km ² .	Physical disturbance and removal of the substrate and associated benthic biota; changes to the composition of the sediment/substrate; changing bathymetry and sediment transport patterns; smothering of biota; reduced light and enhanced turbidity due to sediment suspension, toxicant release (Table 2).
Beach mining	Inshore; usually conducted at the local scale but with possible regional-scale effects.	Direct removal of species and substrate; loss of soft-sediment habitat; lowering/loss of beach leading to erosion, changing sediment transport patterns, increased turbidity, changing conditions for fauna/flora and/or saline water intrusion.
Oil and gas extraction	Inshore and offshore (mostly offshore in recent years); local to regional-scale effects.	Direct removal of species and substrate; smothering/physical alterations to habitat/substrate type (i.e. replacement of soft with hard substrate); chronic and acute toxic pollution events; noise pollution (Table 2).
Water extraction for cooling and desalination	Inshore, generally localized effects.	Fish and plankton killed during intake and processing (impingement and entrainment). Brine and heated water (thermal pollution) can impact communities near outflows, changing behavior and physiology. Toxicants can also be released with the effluent.

relevant today. The second is pollution (see ‘Pollution pathways (both industrial and domestic)’), including sediments, industrial and municipal waste, domestic wastewater, animal/slaughterhouse waste, fecal matter, street dust, oil from automobiles and other contaminant sources, pharmaceuticals, light pollution, and noise pollution (Table 2). The third is the wholesale conversion of natural habitats into a different state (see ‘Ocean sprawl (both coastal and offshore)’), such as reclaimed land, seawalls, jetties, piers, marinas, groynes, breakwaters, port and harbor infrastructure, and bridges (collectively termed as ‘ocean sprawl’, Table 3). These three drivers are presented in the chronological order in which they often begin to occur, though their timing and relative scope can vary substantially among cities (Fig. 2). Further, the three drivers can have interactive effects, with potential additional consequences for marine ecosystems (see ‘Overlap, interactions and feedbacks’). Other factors relating to urbanization, such as elevated propagule pressure and invasion risk, can also be particularly intense in coastal cities (Carlton 1996, Ruiz et al. 1999, 2000, Mineur et al. 2012, but see Tan et al. 2018 and Wells et al. 2019), however, we discuss

these primarily as they relate to one or more of the three drivers presented below.

Resource exploitation (both living and non-living)

It is increasingly well documented that the overexploitation of living coastal and marine resources is one of the earliest observable forms of human disturbance within coastal ecosystems (Jackson et al. 2001, Pandolfi et al. 2003, Lotze et al. 2006). Moreover, coastal systems that have endured the longest period of intense human impacts and that contain the highest human populations are among the most degraded (Lotze et al. 2006). Yet, awareness of the magnitude of changes that previously occurred as a result of the exploitation of living and non-living marine resources is generally poor. This is due to exploitation usually commencing prior to regular monitoring of these systems, coupled with the pervasiveness of the shifting baseline syndrome, where a lack of knowledge of past ecological conditions facilitates a gradual ratcheting down of expectations as to what constitutes a healthy ecosystem (Pauly 1995, Sheppard 1995).

Table 2. Pathways and potential effects of pollution on marine life.

Pollutant type	Main urban pathways	Potential effects on marine life
Sediments	Construction sites (on the coast and within inland urban areas), dredging, land reclamation.	Turbidity resulting in less light for photosynthesis and visual predators/prey. Down welling sediments smother benthic organisms and create a substrate unsuitable for settling larvae.
Nitrogen and phosphorus	Industrial discharge, human and animal waste, detergents, mariculture.	Eutrophication leading to both micro and macro algal blooms, reduced water clarity (see 'sediments'), shifts toward noxious cyanobacteria and reduced fertilization success in corals.
Plastics (macro and micro), lost and abandoned fishing gear	Resin pellets and discarded end-user products. Fishing activities.	Ingestion and/or entanglement, leading to internal blockages/injuries, toxic poisoning, starvation due to false 'stomach filling', suffocation, lacerations, infections, reduced ability to swim.
Compounds from oil	Motor vehicles, shipping, industry.	Impairment of growth and developmental rates, reduced reproductive output and recruitment rates, increased susceptibility to disease. Carcinogenic.
Heavy/trace metals	Industrial and vehicle emissions, leaching from landfills, urban runoff, sewage.	Can inhibit fertilization, recruitment, development, growth in marine microorganisms, invertebrates and vertebrates. Carcinogenic. Prone to undergo food chain magnification.
Tributyltin	Antifouling paint used in the maritime industry.	Causes imposex, and reduces growth and larval success, in various crustaceans and molluscs. Biomagnifies, leading to endocrine disruption in fishes, marine mammals and humans.
PCBs and PBDEs	Discharge from industry, especially electronics. Used in plastics, fire retardants and lubricants.	Prone to biomagnification. Interferes with neurological and hormonal systems of marine organisms and humans. Can lead to decreases in reproductive capabilities and pose immunotoxic risk in marine mammals.
Pharmaceuticals	Industrial, hospital and domestic waste.	Interferes with reproduction and development in both animals and plants. Perturbs fish physiology.
Bacteria and viruses	Sewage (from land and boats/ships), aquaculture.	Diseases, especially acute gastrointestinal illnesses, e.g. salmonellosis. Viruses can cause hepatitis and respiratory infections.
Light	Streets, private and commercial buildings, vehicle headlights, airports.	Encourages unwanted fouling, affects migration and predator-prey behavior. Disrupts larval settlement. De-synchronization of broadcast spawning from lunar phase (e.g. corals).
Noise	Boat traffic, construction, machine operation.	Disrupts behavior (e.g. ability to find food, mates or avoid predators), reduces growth and fecundity.

Coastal population growth and development has impacted a wide variety of living marine resources (Table 1). For instance, oyster reefs and maerl beds have dramatically declined or been extirpated in coastal ecosystems around the world due to destructive fishing methods aimed at providing food and/or building material for increasingly urbanized populations (Airoldi and Beck 2007, Claudet and Fraschetti 2010). Human population growth facilitated the establishment and expansion of industrialized commercial harvesting for marine mammals, turtles and fin-fish species, ultimately resulting in the decline or loss of marine megafauna, and of diadromous and large demersal fish species (Lotze et al. 2005, Thurstan et al. 2010, Van Houtan and Kittinger 2014). Targeted fin-fish assemblages, although constrained by environmental factors (e.g. availability of suitable habitat), have been shown to decline in abundance and richness along increasing gradients of human pressure or proximity to urban centres in a range of habitats (e.g. coral reefs: Williams et al. 2008, Brewer et al. 2009, Aswani and Sabetian 2010; surf zones of exposed sandy beaches: Vargas-Fonseca et al. 2016). Fishing effort also impacts intertidal species abundance, for example, the majority of known sandy beach invertebrate fishery stocks are fully exploited, overexploited or depleted due to commercial, subsistence or recreational harvesting (Defeo and de Alava 1995, Defeo 2003).

Overexploitation often follows a predictable spatio-temporal pattern that is tied to urban growth. This is particularly evident among exploited sessile species. On the east coast of the United States, historical oyster fishery collapses demonstrated sequential depletion beginning in urbanized estuaries and spreading along the coast away from urban centres (Kirby 2004). Many European native oyster reefs adjacent to urban conurbations became ecologically extinct prior to the mid-20th century (Korringa 1946, Airoldi and Beck 2007, Thurstan et al. 2013). Oyster *Ostrea angasi* reefs in South Australia disappeared less than 200 years after the first records of commercial oyster landings from this region by early Europeans (Alleway and Connell 2015). A total of five species of giant clam were historically recorded in the coastal seas around Singapore, but now only two remain, and these only exist in very low abundances (Neo and Todd 2012). The intensification of giant clam exploitation in the 19th century, followed by extensive coastal development from the 1960s onwards, are considered to be the main drivers in the decline and extirpation of these charismatic invertebrates (Guest et al. 2008, Neo and Todd 2012).

The historical legacy effects of overexploitation, combined with pollution and coastal development, means that the present day commercial exploitation of living marine resources adjacent to urbanized regions, at least in more economically

Table 3. Types of human-made structures comprising ocean-sprawl, their functions and potential impacts. Note: All of these structures require some alteration and/or loss of natural habitat.

Structure type	Function	Potential effects on marine habitats
Reclaimed land and artificial islands	Alleviation of coastal squeeze and expansion of land for industry and development.	Directly results in habitat loss, and fragmentation. Sedimentation during construction, altered hydrodynamics interferes with connectivity at landscape and local scales.
Artificial coastal defenses	Engineered to protect shorelines from shoreline erosion, flooding and impacts from waves.	Reduced intertidal extent resulting in steeper slopes. Footprint of the structure removes existing natural habitat but effects may extend beyond structure (halo effect). Change in substrate material and altered hydrodynamics could result in different colonizing assemblages.
Commercial ports, docks and marinas	Industry, services and recreation.	Elevated risk of species invasions, contaminants (oil, antifouling coatings, noise, light), disturbances associated with shipping (sediment resuspension, propeller injuries, etc.).
Oil shipping and refinery infrastructure	Non-renewable resource mining for energy.	Footprint of the structure removes existing natural habitat but effects may extend beyond structure (halo effect). Contaminants, risk of oil spills, noise and light pollution.
Tidal and wind energy infrastructure	Energy production.	Footprint of the structure removes existing natural habitat but effects may extend beyond structure (halo effect). Noise and light pollution, electromagnetic fields.
Submarine cables and pipelines	Telecommunications, power, water, oil.	Concrete mattresses are often used to stabilize and position cables on seafloor. Fragmentation of soft-sediment habitats due to introduction of hard substrates. Noise and light pollution during construction phase. Electromagnetic fields.

developed countries (MEDCs), is often far lower than its historical peak (Lotze et al. 2005, 2006). The search for resources has thus moved further offshore and into less exploited regions (Swartz et al. 2010, Anderson et al. 2011). Recreational fishing participation rates in MEDCs have also seen a decline in the last two decades as a result of factors related to urbanization, such as increased urban sprawl, demographic change, and a reduction in fishable water resources (Poudyal et al. 2011). In contrast, within less economically developed countries (LEDCs), small-scale and subsistence fishing often remains a significant source of livelihood for coastal

communities in or near urban areas (Smit et al. 2017). The maintenance of these traditional activities is, however, under pressure from factors such as declining water quality and coastal development (Smit et al. 2017), as well as enhanced access to education and alternative employment opportunities for children of fishing families (Teixeira et al. 2016). In some cases, urbanization may enhance economic opportunities for small-scale fishing communities. In southern Brazil, for example, the proximity of small-scale fishers to urban centres has expanded opportunities for subsistence fishers to access additional markets, as the presence of high numbers

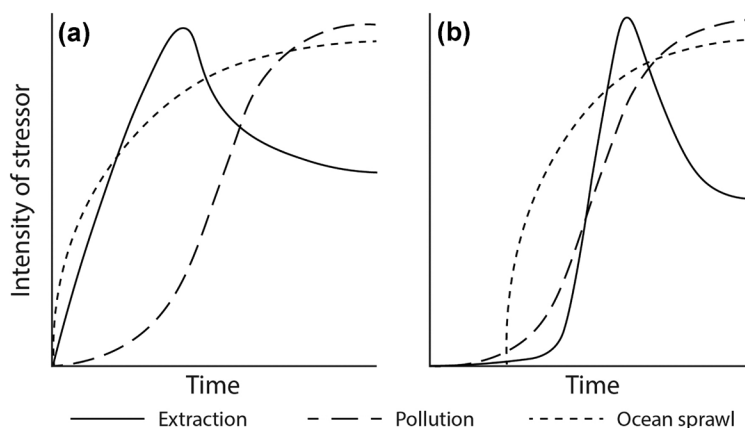


Figure 2. Trajectories of the three key drivers of marine urbanization over time are difficult to hindcast (or forecast) and are likely to be city-specific. However, they will almost certainly overlap, potentially creating non-linear interactions that are even more challenging to predict (and are not represented here). For illustration purposes only: (a) the exploitation of living resources could accelerate rapidly during the early development of many coastal cities, yet decrease in intensity as the resource is overexploited or inaccessible due to other factors, such as contaminants. Conversely, ocean sprawl may be more likely to follow an asymptotic trajectory, which reaches saturation as an increasingly large percentage of natural habitats are converted by the installation of artificial structures. (b) A possible alternative configuration of driver trajectories in a younger city with a shorter but equally intense history of marine urbanization.

of fishers enables them to supply enough fish to meet supply chain demand (Hellebrandt 2008).

Urbanization also coincides with increases in the exploitation of non-living resources, including the extraction of marine aggregates (sand, gravel, rocks) for use in construction and beach renourishment, mineral resources for industrial applications, and the extraction of energy resources (oil and natural gas, and wave and tidal resources). Nearshore aggregate dredging may occur for mud, rock, shells, corals or sand for construction purposes, or for the heavy or precious minerals they contain (Charlier and Charlier 1992). Potential negative effects arising from the extraction of coastal marine aggregates include an increased risk of flood events and coastal erosion. For example, aggregate extraction from the coasts of Kiribati in the South Pacific resulted in beach structure being degraded, exposing coastal conurbations to enhanced risk of flood events (Webb 2005, Holland and Woodruff 2006). Similarly, beach mining, nearshore dredging and quarrying have contributed significantly to coastal erosion in the Marshall Islands (Holland and Woodruff 2006), France, and Bali (Charlier and Charlier 1992). The extraction of sand for the renourishment of urban beaches is commonly undertaken for aesthetic and erosion control purposes (Fletemeyer et al. 2018). Knowledge of the direct and indirect effects of this activity on the local biota and ecological processes remains incomplete (Peterson and Bishop 2005), but beach renourishment has been shown to negatively impact nearshore coral reefs (Hernández-Delgado and Rosado-Matías 2017), marine invertebrate prey availability and nesting behavior in sea turtles (Peterson and Bishop 2005). Coastal urbanization also facilitates the expansion of maritime port operations, which often dredge nearshore channels to maintain deep-water access for commodity and passenger transport (Lemay 1998). Dredging and mining represent a major area of overlap between exploitation and pollution (Fig. 1) due to the release of toxicants and sediments that occurs during these operations.

The establishment of oil and natural gas rigs can be broken down into four stages: seismic exploration, exploratory drilling and installation, operation and decommissioning (Khan and Islam 2008). Each of these stages involves some form of extractive activity, although the consequences for marine life are particularly strong during the installation and decommissioning stages. The installation and decommissioning of rig infrastructure may also degrade or destroy the seabed (Macreadie et al. 2011). However, their establishment introduces a source of hard substrate, potentially increasing local biodiversity, as well as non-native species, which can alter community dynamics at local or regional levels (Burt et al. 2009, Feary et al. 2011, Macreadie et al. 2011). The establishment of renewable energy infrastructure presents many of the same ecological issues and opportunities as oil and gas, yet the installation of some structures, such as tidal barrages, has the potential for generating significant physical and ecological impacts at the local scale, including the loss of intertidal habitats, modification of water flow and sediment resuspension (Gao et al. 2013, Hooper and Austen 2013).

Pollution pathways (both industrial and domestic)

Urbanization and pollution are tightly linked; whereas air and soil pollution are major concerns for terrestrial conurbations, contaminated water and sediments are additional and often critical pollution issues for coastal cities (Table 2). Originating from both point (e.g. wastewater discharge) and non-point (e.g. wind-blown debris and dust) sources, pollution impacts marine life at individual, population and ecosystem levels, frequently bioaccumulating and then biomagnifying up the trophic pyramid (Erftemeijer et al. 2012, Johnston et al. 2015, Langston 2017). Chronic marine pollution effects tend to be sub-lethal (Browne et al. 2015), but they can interact with other stressors in ways that ultimately cause mortality (Yaakub et al. 2014a, Bårdsen et al. 2018).

Urban sediment pollution, commonly the result of runoff from construction work and disturbance via dredging (Rogers 1990, Eggleton and Thomas 2004, Erftemeijer et al. 2012), as well as other sources such as beach nourishment and land-use changes that alter catchment runoff (Colosio et al. 2007, Zhang et al. 2010), affects marine life in multiple ways. The resulting increase in turbidity reduces light penetration, photosynthesis (Falkowski et al. 1990), and the maximum depth at which photosynthetic organisms can grow (Heery et al. 2018a). Suspended sediments also reduce fish hatching success and larval survival (Auld and Schubel 1978), impede zooplankton feeding (Sew et al. 2018), affect mobile fauna that rely on visual cues (Weiffen et al. 2006), and alter a wide range of benthic ecosystem processes and patterns (Airoldi 2003), including the settlement and successful recruitment of organisms, the diversity of species, and competitive interactions – such as those between foundation macrophyte species and low-lying algal turfs (Gorgula and Connell 2004, Russell and Connell 2005, Gorman and Connell 2009, Knott et al. 2009, Bauman et al. 2015). Smothering by sediment further reduces light and physically interferes with the functioning of benthic organisms like corals (Rogers 1990, Junjie et al. 2014), seagrasses (Erftemeijer and Lewis 2006), and certain life stages of kelps (Devinny and Volse 1978, Geange et al. 2014).

High nutrient concentrations are frequently attendant with sediments but, in urban settings, inputs come also from wastewater treatment plants, industrial discharges, storm-water runoff, dust from land, domestic detergent use and human sewage (McClelland et al. 1997, Braga et al. 2000, Atkinson et al. 2003, Cole et al. 2004, Gaw et al. 2014, Vikas and Dwarakish 2015) and are particularly hazardous in bays and harbors with limited circulation (Gomez et al. 1990). Resultant eutrophication can have positive feedbacks on nutrient loads and localized acidification (Howarth et al. 2011) and leads to many undesirable ecological effects (Bell 1991, Orth et al. 2017), for example phytoplankton blooms and/or shifts toward noxious cyanobacteria, macroalgal blooms that can outcompete foundation species such as corals, and increases in the occurrence and severity of marine diseases (Bowen and Valiela 2001, Balestri et al. 2004, Lapointe et al. 2005, Reopanichkul et al. 2009, Haapkylä et al. 2011,

Redding et al. 2013). Human sewage and wastewater creates additional problems due to the release of fecal coliforms, antibiotics and other pharmaceuticals (Jiang et al. 2001a, Shibata et al. 2004, Watkinson et al. 2007, Rose et al. 2009, Jia et al. 2011, Rizzo et al. 2013, Gaw et al. 2014).

Toxic pollutants, including organochlorine compounds (e.g. PCBs and HCH), heavy metals, tributyltin (TBT), polybrominated diphenyl ethers (PBDEs) and compounds from oil (e.g. petrogenic PAHs, plastics and microplastics), are strongly associated with industrial activities and urban run-off (Kennish 1997, Shazili et al. 2006, Todd et al. 2010, Cole et al. 2011, Tayeb et al. 2015), as well as from shipping and other sea-based sources (Tornero and Hanke 2016). Many of these substances bioaccumulate in animals (Tanabe 1988, Wolff et al. 1993, Bayen et al. 2003) interfering with cellular and biochemical functions and disrupting hormonal, reproductive, neurological and nervous systems (Portmann 1975, Wolff et al. 1993, Frigo et al. 2002, Bosch et al. 2016). Lead, cadmium, copper, tin, nickel and iron are among the metals commonly found in sediments near industrial areas (Williamson and Morrissey 2000, Buggy and Tobin 2008, Amin et al. 2009). Copper is especially toxic to marine invertebrates, including poriferans, cnidarians, molluscs and arthropods (Reichelt-Brushett and Harrison 1999, 2000, Johnston and Keough 2000, Brown et al. 2004, Rainbow 2017). The impacts of lead and cadmium on economically important invertebrates such as oysters and crabs are also well established in the literature (Ramachandran et al. 1997), however, recent studies suggest deleterious effects from a wide range of metals (Langston 2017), particularly when combined with other anthropogenic stressors (Burton and Johnston 2010). Other industrial discharges that are known to have negative effects, albeit usually localized, include brine from desalination plants and heat from industrial cooling. Often the most deleterious impacts from these discharges are toxicants (especially metals, hydrocarbons and anti-fouling compounds) that enter the sea with the effluent (Lattemann and Höpner 2008, Roberts et al. 2010).

Urban noise pollution usually originates from boat traffic and in-water construction (Middel and Verones 2017) while urban light pollution comes from street lights, buildings, shipping, airports and vehicle headlights (Hölker et al. 2010). For some fish and marine mammals, noise pollution inhibits communication, affects predator-prey interactions, and has negative effects on growth and reproduction (Slabbekoorn et al. 2010, Houghton et al. 2015). It may also impact various other taxa that are sensitive to sound, such as oysters (Charifi et al. 2017), clams (Mosher 1972, Peng et al. 2016), mussels (Roberts et al. 2015), cephalopods (André et al. 2011, Fewtrell and McCauley 2012), shrimp and other invertebrates (Solan et al. 2016). Night lighting comprises both direct glare and overall increased illumination, and can disrupt marine ecosystems in a number of ways (Hölker et al. 2010). Organisms that use light to navigate, such as birds and sea turtles, may become disorientated (Davies et al. 2014), as may fish and fish larvae.

Artificial lighting has also been reported to affect predator and prey behavior, disrupt larvae settlement, alter distribution patterns and de-synchronize broadcast spawning species from normal lunar phases (Becker et al. 2013, de Soto et al. 2013, Wale et al. 2013, Navarro-Barranco and Hughes 2015, Bolton et al. 2017).

A gradient of decreasing levels of various pollutants with increasing distance from urban sources has been described multiple times, particularly for: heavy metals (Qiao et al. 2013), sediments (Todd et al. 2004), marine debris (Evans et al. 1995, Andrades et al. 2016), and PAHs (Assunção et al. 2017). Whereas the effects of urban (land-based) light and noise pollution and some contaminants are limited to a few decimeters to kilometers from the source (Zaghden et al. 2005, Burton and Johnston 2010), other pollutants have impacts that extend much further (Heery et al. 2017). For example, PCBs have been found in Arctic waters far from any urban or industrial centres, albeit at very low levels (Gioia et al. 2008). An important example of urban pollution being transported huge distances but still having a substantial negative impact is marine debris, especially plastics. Like other forms of marine debris, plastics have a very high dispersal potential (Carlton et al. 2017), mainly because they can take decades to biodegrade (Moore 2008) and are often buoyant. They can maintain their structural integrity for many years, resulting in negative effects, via ingestion or entanglement, to animals ranging from seabirds, turtles and marine mammals to crustaceans and cnidarians (Azzarello and Van Vleet 1987, Moser and Lee 1992, Bjørndal et al. 1994, Jones 1995, Laist 1997, Lamb et al. 2018, Mecali et al. 2018) far from their point of origin. Due to ultraviolet rays, mechanical and microbial degradation, plastics eventually fragment into microplastics (Thompson et al. 2004, Barnes et al. 2009) that are bioavailable to suspension feeding marine organisms, including zooplankton (Browne et al. 2008, Wright et al. 2013, Barboza et al. 2018, Botterell et al. 2018).

Ocean sprawl (both coastal and offshore)

‘Ocean sprawl’ is a term used to describe the proliferation of human-made hard structures in the marine environment (Duarte et al. 2013, Firth et al. 2016, Table 3). This encompasses offshore infrastructure (e.g. wind farms, oil and gas platforms, aquaculture facilities, submarine cables/pipes) and coastal infrastructure such as artificial shore defences (e.g. seawalls, breakwaters, groynes), as well as facilities associated with ports, docks and marinas. Ocean sprawl is a fundamental and dominant feature of urbanized marine environments (Bulleri and Chapman 2010, Duarte et al. 2013, Dafforn et al. 2015, Firth et al. 2016) with artificial structures comprising the bulk of shorelines in many coastal cities (Bulleri et al. 2005, Todd and Chou 2005, Dafforn et al. 2015, Lai et al. 2015) and modifying habitats well into the subtidal zone (Airoldi and Beck 2007, Heery et al. 2017, Heery and Sebena 2018, Macura et al. 2019).

As a habitat, artificial shorelines are quite distinct from natural rocky shores (Connell and Glasby 1999,

Rilov and Benayahu 2000, Perkol-Finkel and Benayahu 2004, Bulleri et al. 2005, Moschella et al. 2005, Clynick et al. 2008, Lam et al. 2009, Bulleri and Chapman 2010, Lai et al. 2018). One of the most obvious differences is the slope of hard substrates; while shoreline armoring structures such as seawalls are generally very steep, natural rocky shores tend to be more gently sloping with longer and wider intertidal areas (Gabriele et al. 1999, Knott et al. 2004, Andersson et al. 2009, Chapman and Underwood 2011, Firth et al. 2015). The smaller area of intertidal zone typical of seawalls is probably an important contributor to species loss (Chapman and Underwood 2011, Perkins et al. 2015) as it can lead to greater overlap in the distribution of individuals (Klein et al. 2011) or to superimposed distributions of species that would not normally occur (Lam et al. 2009, Loke et al. 2019b). Wave impact is also more intense on steep shores (Gaylord 1999, Cuomo et al. 2010), potentially dislodging intertidal organisms and/or impeding their settlement (Blockley and Chapman 2008, Iveša et al. 2010). Compared to natural hard-bottom habitats, seawalls are topographically 'simple' (Loke et al. 2014) – having few microhabitats, such as pits, rock-pools, overhangs and crevices (Chapman 2003, Chapman and Bulleri 2003, Moreira et al. 2007), which are important for the persistence of many intertidal and benthic species (Chapman and Underwood 2011, Loke and Todd 2016, Loke et al. 2017). When considering these multiple effects in combination, it is unsurprising that many direct comparisons between rocky shores and seawalls often reveal the latter host lower species richness, reduced functional and genetic diversity, and different community compositions (Chapman 2003, Bulleri et al. 2005, Moschella et al. 2005, Fauvelot et al. 2009, Lai et al. 2018).

The consequences of ocean sprawl at large spatial scales are not yet well understood, but they are likely to be considerable given its prominence and extent (Lotze et al. 2006, Airoidi and Beck 2007). In some heavily urbanized regions, entire habitats have been lost as artificial structures proliferate over vast distances (Dong et al. 2016). Even where coastal transformation is not ubiquitous, clusters of artificial structures can serve as corridors that facilitate species invasions (Airoidi et al. 2015) and alter ecological connectivity, with significant effects on marine assemblages (Bishop et al. 2017). The spatial scale of impacts from artificial structures depends on the type of structure, local hydrodynamic conditions, and a variety of other parameters (summarized by Heery et al. 2017). For instance, fluxes of exogenous detritus from artificial structures typically affect marine communities within meters to tens of meters only (Heery and Sebens 2018), while infrastructure that creates major impediments to circulation and sediment transport tends to impact marine assemblages across a much larger area (Bishop et al. 2017).

Overlap, interactions and feedbacks

The three key drivers described above are not limited to urban areas, yet their relative magnitude and spatial and temporal overlap is often augmented near high-density coastal

development (Jiang et al. 2001b, Kennish 2002, Finkl and Charlier 2003, Mayer-Pinto et al. 2015). This overlap can have important consequences for marine organisms and communities, as effects from multiple anthropogenic stressors are often cumulative and non-linear in the marine environment (Adams 2005, Crain et al. 2008, 2009), leading to complex changes in ecosystem condition (Conversi et al. 2015, Halpern et al. 2015, Möllmann et al. 2015). It can also feedback to influence the key drivers themselves, which are each the result of dynamic, interacting socio-economic and biophysical forces (*sensu* Alberti et al. 2003), and closely interrelated in the coupled social-ecological systems that characterize coastal cities (Liu et al. 2007, Alberti 2008, Grimm et al. 2008a, Pickett et al. 2011). Such feedbacks and interactions are widely recognized as shaping urban ecosystem function (Wu 2014, McPhearson et al. 2016), and are central in nearly all current models of urban ecosystem dynamics (Pickett et al. 2001, Alberti et al. 2003, Grimm et al. 2013). In this section, we highlight some known and likely interactions among the three drivers (exploitation, pollution and ocean sprawl) of marine urbanization. Each interaction fits conceptually within the overlapping regions of the Venn diagram in Fig. 1.

One of the best examples of complex interactions and feedbacks among the drivers of marine urbanization and ecosystems is the relationship between habitat conversion, contaminants and invasion risk. Artificial structures associated with port infrastructure and shoreline protection tend to both concentrate environmental contaminants by altering hydrodynamic patterns and reducing water movement (Waltham et al. 2011, Rivero et al. 2013), and by facilitating increased contaminant influx, for instance from antifouling paints (Schiff et al. 2004, 2007, Warnken et al. 2004, Sim et al. 2015). Copper emissions from antifouling paints then have both direct and indirect consequences for marine organisms (Rygg 1985, Perrett et al. 2006). The toxin enters the food web by accumulating in algal tissues (Johnston et al. 2011) or being consumed directly by non-selectively feeding animals, which can additionally accelerate the leaching and burial process in adjacent sediments (Turner 2010). While toxic effects from copper negatively impact many marine organisms and reduce diversity (Rygg 1985), differential responses to copper contamination among invertebrates (Piola and Johnston 2006) combined with the novel colonization habitat that is provided by floating docks and other marina structures can disproportionately favor non-indigenous taxa, thus facilitating marine invasions (Piola and Johnston 2008, Dafforn et al. 2009, Piola et al. 2009, Airoidi and Bulleri 2011, Edwards and Stachowicz 2011, Cordell et al. 2013, McKenzie et al. 2012).

The trajectory of marine resource exploitation in urban areas is also closely tied to that of pollution pathways and ocean sprawl (Inglis and Kross 2000, Jiang et al. 2001b, Cundy et al. 2003) (Fig. 2). In the early developmental stages of many cities, shoreline habitats were converted by artificial structures to facilitate resource exploitation industries and

the economic growth they fueled (Squires 1992). Overwater structures that housed cannery facilities and seafood markets were prominent drivers of early waterfronts in San Francisco (Walker 2001), Singapore (Chang and Huang 2011), and many other coastal cities globally (West 1989, Portman et al. 2011). Various shoreline armoring structures were also part of facilities for resource exploitation industries, such as oil and gas (Minca 1995), and remain important drivers in adaptation plans for protecting these industries from future sea level rise (French et al. 1995, Ng and Mendelsohn 2005). Pollution associated with resource exploitation and habitat conversion continues to be problematic in many urban and suburban areas, for instance surrounding shellfish aquaculture farms, oil refineries, port infrastructure and dredged waterways that harbor contaminants (Board 1997, Pereira et al. 1999, Jones et al. 2001, Strand and Asmund 2003, Tolosa et al. 2004, Medeiros et al. 2005, Casado-Martínez et al. 2006, Paissé et al. 2008, Knott et al. 2009), and alters system dynamics via multiple biogeophysical pathways, trophic levels and functional groups (Paissé et al. 2008, Weis et al. 2017).

As coastal cities grow, and effects from various aspects of marine urbanization increasingly overlap (Fig. 2), the system's potential for feedbacks appears to intensify (Fernando 2008, Grimm et al. 2008b). For instance, as impervious surfaces proliferate on land, increased delivery of stormwater can accelerate the accumulation of contaminants in receiving waterbodies (Lee et al. 2006, Jartun et al. 2008, 2009, Jartun and Pettersen 2010, Walsh et al. 2012). Similarly, as resource exploitation and shoreline alteration expand, so too does the spatial extent and magnitude of marine debris and contaminants (Garcia-Sanda et al. 2003, Wake 2005, Ng and Song 2010, Märkl et al. 2017), which can in turn impact exploitable marine resources (Islam and Tanaka 2004). Additional biogeochemical and ecological feedbacks have also been important historically, in some cases leading to losses in a system's capacity to absorb urban impacts over time (Cloern 2001, Nyström et al. 2012). For instance, the loss of oyster reefs due to overharvesting and eutrophication is thought to have reduced the filtration capacity of urban estuaries in the United States (Zimmerman and Canuel 2000, Kemp et al. 2005, Wilberg et al. 2011, zu Ermgassen et al. 2013), potentially inhibiting their ability to accommodate further pollution influx. Similar feedbacks surrounding challenges such as harmful algal blooms and marine diseases may be increasingly likely as ecosystems are further altered by marine urbanization (Prins et al. 1997, Sunda et al. 2006, Heisler et al. 2008, Crain et al. 2009). However, such feedbacks can be difficult to predict and may obfuscate efforts to effectively anticipate ecosystem response to further environmental change (Elmqvist et al. 2003).

Key ecological patterns

The convergence of exploitation, pollution and ocean sprawl that typifies urban marine environments may lead to shifts in

ecosystem characteristics and several key ecological patterns, which are just beginning to emerge in the literature.

Homogenized systems, comprising heterogeneous mosaics

A common theme in the terrestrial urban ecology literature is the spatial heterogeneity that occurs across landscapes as a result of urbanization (Pickett et al. 1997, Dow 2000, Cadenasso et al. 2007, Pickett and Cadenasso 2008). The resulting 'mosaics' of habitat types, biophysical characteristics, and land use are temporally dynamic and influenced by multiple interacting social and ecological drivers (Pickett et al. 2017). At the same time, there are considerable similarities across cities in the underlying processes and trajectory of urbanization, leading to an overall homogenization among urban ecosystems regionally and globally (Alberti 2005, McKinney 2006). Even though research supporting these concepts is far more comprehensive in terrestrial environments, there are several indications of comparable patterns among urban marine ecosystems based on the current literature (Dafforn et al. 2015).

Most coastal cities are positioned in estuaries and bays that were historically dominated by soft sediments. As artificial structures are added to these sedimentary environments, a checkerboard of hard and soft habitats is created, with each supporting distinct biotic assemblages (Connell and Glasby 1999, Glasby 2000, Connell 2001, Barros et al. 2001). This can alter ecosystem dynamics in several ways. In some regions, artificial structures support a larger standing stock of benthic macroalgae and other hard-bottom organisms, which then enter adjacent sediments as detritus and may alter sedimentary community dynamics (Boehlert and Gill 2010, Heery 2018, Heery and Sebens 2018). Artificial structures has been shown to act as 'stepping stones' for dispersal, particularly of non-indigenous taxa (Bulleri and Airoidi 2005, Glasby et al. 2007, Vaselli et al. 2008, Sheehy and Vik 2010, Airoidi et al. 2015, Foster et al. 2016) and alter genetic population structure of marine fauna (Fauvelot et al. 2012). Marine species vary in dispersal potential, and many taxa encounter barriers to dispersal at relatively small spatial scales (Darling et al. 2009, Costantini et al. 2013, Maas et al. 2018, Sefbom et al. 2018). Dispersal limitation can therefore also interact with local stressors and abiotic conditions to result in compositionally very different assemblages across patches of hard substrata (Bulleri and Chapman 2004, Munari 2013). This may be accentuated where urban habitat conversion has significantly altered hydrodynamic patterns, created other additional barriers to dispersal and subsequent settlement (Bishop et al. 2017) or changed the configuration of habitats at the landscape scale (Loke et al. 2019c).

Spatially heterogeneous mosaics also form in urbanized seascapes as a result of fine-scale gradients in nutrient enrichment and sediment pollution (Airoidi 2003, Baum et al. 2015, Ling et al. 2018), particularly in low flow environments and enclosed estuaries and embayments (Balls 1994, Dauer et al. 2000). For instance, physical disturbance from

swing moorings, which are ubiquitous in shallow sedimentary environments in Sydney Harbor, leads to depressed concentrations of metal contaminants within a highly localized area (Hedge et al. 2017). This may result in complex, fine-scale spatial patterns in microbial, meiofaunal and macrofaunal taxa that are sensitive to metal contamination (Coull and Chandler 1992, Stark 1998, Lindegarth and Hoskin 2001, Mucha et al. 2003, Gillan et al. 2005, Sun et al. 2012). It is likely this is complicated further by localized gradients in other abiotic conditions, such as granularity, that commonly occur in the vicinity of artificial structures (Martin et al. 2005, Seitz et al. 2006). While swing moorings and other structures that increase physical disturbance and scour increase sediment grain size (Hedge et al. 2017), structures such as pilings that reduce flow speeds and increase deposition tend to reduce the grain size of nearby sediments (Heery et al. 2018b). Grain size, contaminant concentrations, and a variety of other flow-related metrics are known to have strong effects on sedimentary composition and diversity (Mannino and Montagna 1997, Hewitt et al. 2005), which likely varies considerably in urban seascapes over small spatial scales.

Studies of marine diversity and connectivity relative to urbanization remain relatively limited, and there is need for expanded work in this area. In particular, study designs that allow for the assessment of alpha, beta and gamma diversity could be helpful for beginning to distinguish between the ecological processes that shape marine assemblages in spatially heterogeneous urban seascapes. In their eDNA study on seagrass beds, Kelly et al. (2016) found decreases in beta diversity even while species richness increased with the intensity of urbanization. Landscape-scale homogenization in urban assemblages has some precedents in freshwater and terrestrial systems (McKinney and Lockwood 1999, Holway and Suarez 2006, Urban et al. 2006, Groffman et al. 2017), but less so in the marine literature (Balata et al. 2007). For instance, by creating urban freshwater reservoirs/dams many cities have inadvertently fragmented their catchments and resulted in biotic homogenization (Olden and Rooney 2006, Olden et al. 2008). The straightening or 'linearization' of shorelines through armoring (Dyl 2009) could homogenize intertidal communities at certain scales, though this has not been demonstrated empirically. Sedimentation may also cause marine communities to become more homogenous under certain conditions (Balata et al. 2007). However, more thorough characterization of diversity measures relative to resource exploitation, pollution and ocean sprawl should advance understanding of ecological processes in urban marine environments.

Loss of foundation species

Urban stressors can be particularly detrimental for sensitive foundation species such as oysters, reef-building corals, seagrasses, mangroves and canopy-forming kelps, which structure marine ecosystems via the provisioning of biogenic habitat (Dayton 1972, Bertness and Callaway 1994). Even though the dynamics of decline vary among taxa and across locations

(Terrados et al. 1998, Waycott et al. 2009, Polidoro et al. 2010, Heery et al. 2018a), loss in foundation species is generally tied to one or more of the three major drivers of marine urbanization (Rogers 1990, Hastings et al. 1995, Airoidi 2003, Balestri et al. 2004, Kirby 2004, Connell et al. 2008, Strain et al. 2014, Yaakub et al. 2014a, Alleway and Connell 2015). In temperate areas, nutrient-rich, high sedimentation conditions can limit the recruitment and survival of canopy-forming kelps while supporting opportunistic, turf-forming algal species that can act as kelp competitors (Airoidi 1998, Benedetti-Cecchi et al. 2001, Gorgula and Connell 2004, Russell and Connell 2005, Coleman et al. 2008, Gorman and Connell 2009). Similarly, in the tropics, sediment pollution has multiple negative effects on corals. These decrease coral cover and disproportionately impact competitive, branching coral genera such as *Acropora*, which ultimately lowers reef complexity in urban areas (Heery et al. 2018a). Ocean sprawl can also be an important driver of foundation species loss. For instance, despite the numerous ecosystem services they provide to urban communities (Benzeev et al. 2017), mangrove forests are cleared in many coastal areas to make way for urban development (Harper et al. 2007, Martinuzzi et al. 2009, Lai et al. 2015, Richards and Friess 2016). Where urban mangroves are left intact, they are vulnerable to deleterious effects from artificial structures constructed nearby; mangrove forests adjacent to seawalls tend to be narrower, with less leaf litter and fewer saplings than those without seawalls (Heatherington and Bishop 2012). Coral reefs and seagrass beds are also frequently built over (Chou 2006, Burt et al. 2013, Yaakub et al. 2014b). Furthermore, urban losses in foundation species often involve feedbacks that prevent subsequent population recovery (Altieri and Witman 2006, de Boer 2007, Moore et al. 2014). For instance, seagrass loss can be tied to sediment pollution and eutrophication (Waycott et al. 2009, Orth et al. 2017) and deforestation and altered hydrodynamic regimes from coastal construction (da Silva et al. 2004), as well as possible indirect effects from top to down reductions in grazers that control seagrass epiphyte loads (Duffy et al. 2005, Myers et al. 2007). The reduction of seagrass bed cover can lead to destabilization of sedimentary substrata, which then further increases turbidity (de Boer 2007) and potentially inhibits recolonization (Moore et al. 2014).

There is increasing evidence that multiple, often interacting, urban-related drivers affect both foundation species and ecological response to foundation species loss (Lenihan and Peterson 1998, Jackson 2008, Claudet and Fraschetti 2010, Nyström et al. 2012, Strain et al. 2014, Ferrario et al. 2016, Orth et al. 2017), although studies evaluating multiple urban stressors simultaneously are rare (O'Brien et al. 2019). The abundance of kelps and other important habitat-forming macroalgae is negatively correlated with human population density in several regions, including temperate coasts in Australia and North America (Connell et al. 2008, Scherner et al. 2013, Feist and Levin 2016), and this is likely linked to gradients in sedimentation and nutrients (Fowles et al. 2018).

Yet, ocean sprawl may also be an important factor in macroalgal community dynamics. Reduced topographic complexity, changes in substrate type, and altered substrate profiles are all factors that can limit kelp abundance (Toohey 2007, Schroeter et al. 2015) and correlate with urban habitat conversion. Artificial structures not only support distinct macroalgal assemblages compared with natural rocky shores (Glasby 1999) – the kelps that inhabit them also support distinct epifaunal and microbial communities and erode at different rates (Marzinelli et al. 2009, 2018, Mayer-Pinto et al. 2018). Habitat conversion thus likely influences ecological processes in urban areas where canopy-forming kelps persist. The interaction of resource extraction, pollution and ocean sprawl as drivers of foundation species loss, and the ecological responses to this loss, are important future areas of research. Importantly, these processes are highly dynamic, with ecological legacies from past impacts, and future scenarios linked to rising temperatures and pCO₂, that are challenging to ascertain (Ramalho and Hobbs 2012, Davis et al. 2017, Gao et al. 2017, Heldt et al. 2018, Fig. 2).

Changes in biodiversity and productivity

Patterns of biodiversity in urban marine environments are complex. Resource extraction, sediment pollution and habitat modification are important drivers of marine biodiversity declines globally (Sala and Knowlton 2006), and there are many examples from the literature of reduced species richness and altered community composition at heavily urbanized sites (Pearson and Rosenberg 1978, Long et al. 1995, Lindegarth and Hoskin 2001, Lotze et al. 2006, Airolidi and Beck 2007, Poquita-Du 2019). Even though the diversity of marine assemblages in some regions is negatively correlated with human population density (Schermer et al. 2013, Neo et al. 2017), this pattern is not universal, and varies considerably between regions, cities, the taxa and type of diversity considered, and the methods used. For instance, using eDNA from water samples, Kelly et al. (2016) found that species richness was positively correlated with land-based urbanization in intertidal seagrass beds. Similarly, while some studies have reported higher species diversity on artificial shorelines than on their natural counterparts (Chou and Lim 1986, Connell and Glasby 1999, Munsch et al. 2015), others have found artificial shorelines to be relatively depauperate (Firth et al. 2013, Aguilera et al. 2014, Lai et al. 2018).

There are similar complexities surrounding productivity in urban marine environments. In nutrient-rich marine estuaries, like those in most coastal cities, climate variables, such as major precipitation events and interannual fluctuations in weather patterns, tend to be particularly important drivers of temporal patterns in primary production (Mallin et al. 1993, Rodrigues and Pardal 2015), as these events deliver land-based sources of nitrogen to coastal waters. However, the relationship between nutrient load and primary production is highly variable (Borum and Sand-Jensen 1996), and urban-related increases in nutrient loads can have different effects depending on tidal regimes, the system's trophic structure,

as well as other factors (Alpine and Cloern 1992, Monbet 1992). Nutrient loading therefore does not manifest comparable, elevated marine production across cities. Moreover, broader ecosystem responses to primary production also vary across urban marine ecosystems. In some locations, nutrient enrichment can trigger micro- and macroalgal blooms that are highly detrimental to important foundation species (McGlathery 2001) while, in other places, the same process may increase secondary production (Leslie et al. 2005) and species richness (Whittaker and Heegaard 2003).

Novel assemblages

Novel assemblage structure tends to emerge as species move and change in abundance and dynamics in response to environmental change (Hobbs et al. 2018). The most obvious manifestation of this phenomenon in urban marine environments is among sessile assemblages on artificial shorelines. Conversion from natural shores to hard artificial structures creates new habitats for colonization and supports novel assemblages of hard-bottom organisms (Chou and Lim 1986, Connell and Glasby 1999, Bulleri et al. 2005, Moschella et al. 2005, Clynick et al. 2008, Lam et al. 2009, Airolidi et al. 2015, Munsch et al. 2015). These assemblages differ from nearby rocky shores with respect to composition (Chapman 2003, Bulleri and Chapman 2010, Airolidi et al. 2015, Lai et al. 2018) and genetic diversity (Fauvelot et al. 2009). Differences in species abundance between artificial and natural rocky shores may be biased towards some functional groups, such as motile primary consumers (Chapman 2003, Pister 2009). However, human-made habitats in urban areas also provide a foothold for a variety of non-indigenous species, many of which are non-motile (Glasby et al. 2007, Vaselli et al. 2008, Ruiz et al. 2009, Sheehy and Vik 2010, Simkanin et al. 2012, Airolidi et al. 2015, Foster et al. 2016).

Ruderal species and potential synanthropes

On land, urbanization is strongly associated with the proliferation of ruderal and synanthropic species (McKinney 2006). Ruderal species, those that grow in contaminated soils or human wastes, typically include a variety of weedy plant species (Haigh 1980), while 'synanthropes' is a term typically applied to mid-level consumers, such as raccoons and coyotes, that have higher densities and abundances in cities than in adjacent rural areas (McKinney 2002). Although not well studied, there is evidence of analogue taxa exploiting urban marine environments. Polluted sediments in urban areas appear to generate opportunities for certain marine microbes (Córdova-Kreylos et al. 2006, Cetecioglu et al. 2009, Nogueira et al. 2015). For instance, *Alteromonadales*, *Burkholderiales*, *Pseudomonadales*, *Rhodobacterales* and *Rhodocyclales* bacteria that are involved in the degradation of hydrocarbons, were found to be more abundant in polluted urban mangrove forests in Brazil (Marcial Gomes et al. 2008). Some macroalgae also respond opportunistically to polluted urban waters (Valiela et al. 1990, Raven and Taylor

2003). For instance, transplant experiments have demonstrated that the photosynthetic capacity of sea lettuce *Ulva lactuca* increases while that of canopy-forming brown seaweed *Sargassum stenophyllum* decreases in response to urban waters (Schermer et al. 2012). Differential photosynthetic responses to copper contaminants among different species of *Ulva* may connote a competitive advantage in contaminated urban areas (Han et al. 2008). Similarly, the combination of elevated sediment and nutrient loads increases the cover of filamentous turf-forming macroalgae in field manipulations (Gorgula and Connell 2004) and is thought to be central to turf proliferation in metropolitan areas (Airoldi 1998, Connell et al. 2008, Strain et al. 2014).

Evidence for synanthropic marine consumer species is more limited. Most of the studies on fish distribution patterns in urban areas and relative to coastal population density suggest primarily negative impacts of urbanization on major fish groups (Toft et al. 2007, Williams et al. 2011, Kornis et al. 2017, Munsch et al. 2017, Cinner et al. 2018). Although several well-recognized terrestrial synanthropes, including raccoons and rats, are known to forage in intertidal habitats (Carlton and Hodder 2003), degraded intertidal resources in urban areas are unlikely to be a major driver of synanthropic distribution patterns for these species. There is at least one record, however, of rats occurring in higher densities on artificial breakwaters than on natural shorelines (Aguilera 2018). Heery et al. (2018c) found that deep-dwelling giant Pacific octopus were more common in urban than in rural areas of Puget Sound (northeast Pacific), and suggested this may be a function of the amount of marine debris in the urban benthos, which octopus utilize as shelter (Katsanevakis and Verriopoulos 2004, Katsanevakis et al. 2007). Artificial structures, such as docks and buoys, are widely used as haul out sites by pinnipeds (Heath and Perrin 2009) and could similarly influence localized pinniped distribution patterns in urban areas (DeAngelis et al. 2008). Duarte et al. (2013) noted that floating structures associated with coastal development could play a key role in facilitating jellyfish blooms, by expanding the available habitat for polyp recruitment. These lines of evidence suggest that, where synanthropic distribution patterns do exist among marine consumers, ocean sprawl may be an important underlying mechanism (Heery et al. 2018c).

In addition to ruderal macrophytes and synanthropic consumers, the interacting drivers of marine urbanization appear to facilitate the establishment of opportunistic sessile invertebrates, many of which are non-indigenous. Opportunistic responses to multiple urban drivers may provide a particular advantage. For instance, the bryozoans, *Bugula neritina* and *Watersipora subtorquata*, and the ascidian, *Botrylloides violaceus*, have particularly high tolerances for copper toxicity (Piola and Johnston 2006), which could partially explain their successful invasion of urban marine environments beyond their endemic range (Piola et al. 2009, McKenzie et al. 2011, Osborne et al. 2018). In addition, larval dispersal for these taxa is aided by shipping activities between coastal cities, and

they readily utilize artificial structures, such as floating docks, as habitat for settlement (Lambert and Lambert 1998, 2003, Piola and Johnston 2008, Dafforn et al. 2009, Piola et al. 2009, Airoldi and Bulleri 2011, Edwards and Stachowicz 2011, Gittenberger and van der Stelt 2011, McKenzie et al. 2012, Simkanin et al. 2012, Cordell et al. 2013, Zhan et al. 2015). In this way, simultaneous positive responses to multiple urban drivers may help to facilitate invasion success in urban areas, although the strength of these responses likely vary between cities, taxonomic groups, and latitudes (Canning-Clode et al. 2011).

Acclimatization and adaptation

Urbanization is considered a major selective pressure (Alberti 2015, Donihue and Lambert 2015) leading to phenotypic changes at both the organismal and species levels (Alberti et al. 2017a). These changes are either phenotypically plastic (i.e. within-lifetime) responses such as acclimatization, or (population-level) adaptation via genetic change over multiple generations (Alberti et al. 2017b, Johnson and Munshi-South 2017). Recent advances in understanding evolutionary responses to urbanization have been driven largely by work in terrestrial systems (Partecke et al. 2006, Miranda et al. 2013, Johnson and Munshi-South 2017). However, there is ample precedent for rapid evolutionary change and phenotypic plasticity in response to anthropogenic stressors in the marine environment (Todd 2008, Sanford and Kelly 2011).

All three of the key drivers of marine urbanization are known to structure population genetics among a variety of marine taxa (examples – resource exploitation: Smith et al. 1991, Hauser et al. 2002; pollution: Suchanek 1993, López-Barea and Pueyo 1998, Nacci et al. 1999, Ma et al. 2000, Virgilio et al. 2003, Virgilio and Abbiati 2004, McMillan et al. 2006, Galletly et al. 2007, Moraga and Tanguy 2009; ocean sprawl: Street and Montagna 1996, Fauvelot et al. 2012). In many cases, resource exploitation, pollution and ocean sprawl lead to population bottlenecks and reduced genetic diversity (Nevo et al. 1986, Maltagliati 2002, Fauvelot et al. 2009, Ungheresse et al. 2010, Neo and Todd 2012, Pinsky and Palumbi 2014). Yet evidence of micro-evolution in urban marine environments has been limited. Some of the best examples come from the ecotoxicology literature (Medina et al. 2007). For instance, McKenzie et al. (2011) showed heritable copper tolerance in the bryozoan *Watersipora subtorquata*. Similarly, Galletly et al. (2007) found a significant genotype \times environment interaction in hatching success of the ascidian, *Styela plicata*, under different copper concentrations, yet hatching success at high concentrations had a different genetic basis than that at low concentrations, suggesting different genetic mechanisms for adaptation depending on pollution levels.

Trait plasticity in response to marine urbanization has been much more widely documented. Many marine organisms exhibit substantial capacity for acclimatization that may provide a fitness advantage; this could include changes in morphology, physiology, behavior and/or life history

(West-Eberhard 1989, Foo and Byrne 2016). Goiran et al. (2017) observed melanism in sea snakes inhabiting urban sites that they proposed facilitates the excretion of trace pollutants. Phenotypically plastic responses to light in corals are well documented and can benefit colonies where sediment pollution and associated turbidity is prevalent (Todd et al. 2003, Hoogenboom et al. 2008, Ow and Todd 2010). Some marine invertebrates also exhibit transgenerational plasticity, wherein parents alter the phenotypes of gametes in response to factors such as copper and salinity to maximize gamete performance (Marshall 2008, Jensen et al. 2014). Several other examples of trait plasticity from natural rocky shores may be additionally relevant in the abiotically stressful environments created by seawalls and other artificial structures (Strain et al. 2018). For example, dogwhelks *Nucella lapillus* and other gastropods have larger feet in high wave energy environments so they can adhere better to the substrate (Etter 1988, Trussell 1997), potentially an advantage on steep seawalls that intensify wave shock. Similarly, local adaptation for thermal tolerance in acorn barnacles *Semibalanus balanoides* (Bertness and Gaines 1993) and acclimatization to high temperatures in various intertidal gastropods (Williams and Morritt 1995, Marshall et al. 2010) may facilitate survival in novel thermal environments associated with ocean sprawl.

Urbanization-driven trait changes can have important effects on community interactions (Palkovacs et al. 2012, Alberti et al. 2017a), yet much work remains to understand the nature of these effects in the marine environment, as well as their ultimate consequences for functioning in urban marine ecosystems. This work needs to be conducted across multiple organismal scales to account for potential urban-related acclimatization at the level of holobionts – host–microbial assemblages that function as an ecological unit (Ziegler et al. 2016, Evans et al. 2017). Further, the heritability of urban-driven adaptation should be considered through both genetic and epigenetic approaches, as acclimatization responses can be inherited via transgenerational maternal effects and methylation patterns (Sun et al. 2014, Suarez-Ulloa et al. 2015).

Climate change and marine urbanization

The effects of climate change interacting with marine urbanization range from reasonably established to complex and speculative possibilities. Atmospheric warming from greenhouse gases leads to the thermal expansion of the oceans and melting of glacial and polar ice, and is well-documented as the cause of current and predicted sea-level rise (Neumann et al. 2015). Increases in the severity, and possibly occurrence, of major storms have also been attributed to global warming (Walsh et al. 2016). This combination of rising seas and extreme weather pose direct flooding and erosion threats to coastlines and, together with coastal development, represent the main drivers of the current proliferation of sea defenses (Dafforn et al. 2015). Elevated temperatures, altered rainfall patterns, and other changes associated with climate change (Duffy et al. 2015, Donat et al. 2016) pose challenges for

marine organisms that inhabit coastal defense structures (Ng et al. 2017), as well as for marine communities that provide sources of food and natural defenses for coastal cities, such as coral reefs and mangrove forests (Ward et al. 2016, Hoegh-Guldberg et al. 2017). Of course, coastal cities are also part of the problem as they contribute to climate change via high levels of greenhouse gas emissions, energy consumption and changes in land use, hydrology and biodiversity (Grimm et al. 2008a), but these additional impacts of marine urbanization are beyond the scope of the current review.

One of the better studied interactions between urbanization and climate change is ‘coastal squeeze’, first reported by Doody (2004), but later refined and defined by Pontee (2013, p. 206) as: ‘one form of coastal habitat loss, where intertidal habitat is lost due to the high water mark being fixed by a defence or structure (i.e. the high water mark residing against a hard structure such as a sea wall) and the low water mark migrating landwards in response to SLR’ (sea level rise). Loss and/or fragmentation of tidal wetlands means a concomitant reduction in ecosystem services, including flood and erosion abatement, biodiversity support, water quality, carbon sequestration and benefits to coastal fisheries (Torio and Chmura 2013). Managed retreat (or realignment), where infrastructure is relocated inland to escape the effects of erosion and flooding (Alexandrea et al. 2012), can alleviate coastal squeeze by moving back or removing hard artificial defences, thereby eliminating the fixed high water mark back-stop. However, the distances required for coastal habitats to successfully move inland can be considerable – potentially being meters per year depending on rate of sea level rise (Pethick 2001).

Temperature is a critical stressor on rocky shores (Helmuth and Hofmann 2001) but little is known regarding the thermal landscape of artificial coast defenses (Zhao et al. 2019). The homogeneity of artificial structures may create thermal barrens that challenge intertidal organisms (Perkins et al. 2015) or, alternatively, provide refugia from thermally-limited predators. Helmuth et al. (2006), based on a comprehensive study of the spatial and temporal patterns in the body temperature of the mussel *Mytilus californianus* on natural rocky shores, concluded that interacting factors such as tidal regime and wave splash can create complex thermal mosaics of temperature that are potentially more important locally than those of large-scale (e.g. latitudinal) climate effects. Hence, it will be difficult to predict or measure the broader impacts of global warming on the intertidal area of seawalls and similar structures. Climate associated shifts in patterns of rainfall and runoff, e.g. heavier rainfall and/or more prolonged rainfall (Wallace et al. 2014), could overwhelm drainage systems leading to peaks in the influx of pollutants. These unusual pollution spikes would likely be concurrent with increased sedimentation, eutrophication and low salinity, all of which could moderate species and community response and the toxicity of pollutants (Pearson and Rosenberg 1978, Šolić and Krstulović 1992, Verslycke et al. 2003).

Climate change is also likely to impact natural coastal defenses. Healthy coral reefs and mangrove forests are effective

at protecting coastlines from wave impact and associated erosion in tropical and subtropical regions, but both are vulnerable to climate change. Extended periods of warmer than average sea temperatures causes coral bleaching that, when severe, kills colonies (Hoegh-Guldberg 1999) resulting in the loss of wave-absorbing reef complexity (Alvarez-Filip et al. 2009, Graham and Nash 2013). As mangroves live within a narrow band of suitable habitat determined by local tidal regimes, they are susceptible to sea level rise if it exceeds the rate of soil accumulation, leading to shoreline retreat (Lovelock et al. 2015). Many tropical and subtropical towns and cities benefit from the protection that coral reefs and mangroves provide (Ferrario et al. 2014), and their loss can lead directly to the installation of alternative coastal defense measures, of which hard armour such as seawall, rip-rap and gabion are frequently chosen. There is also strong potential for additive or synergistic effects as coral reefs and mangroves near urban areas are likely to be heavily exploited as well as impacted by pollution (Wells and Ravilious 2006). In addition to these rather more predictable consequences of climate change, urban marine environments – as part of urban ecosystems – are shaped by a multitude of interacting social and ecological drivers (Alberti et al. 2003) and are likely to exhibit non-linear dynamics characteristic of complex adaptive systems (Scheffer et al. 2001, Alberti 2008). The three major drivers of marine urbanization have gradually altered urban marine ecosystems in ways that may have reduced their capacity to absorb disturbance; for instance to a 100-year storm event, a sudden change in socio-economic variables such as a rapid loss in food security, a major marine disease epidemic, or various other pulse perturbations. Without considerably more research, it is unclear how urban marine ecosystems will respond to such disturbances, whether they are susceptible to future phase shifts, and what such shifts might mean for ecosystem functions and ecosystem services. While these should be focal points of future research (discussed below), approaches such as scenario planning (Peterson et al. 2003) that integrate and accommodate uncertainties directly into management of urban marine environments would be highly beneficial (Alberti et al. 2003).

Ecological engineering

It is predicted that by the next decade approximately three quarters of the world's population will reside in coastal zones (Small and Nicholls 2003, Bulleri and Chapman 2015). Coastal land is therefore in high demand and development and reclamation are occurring at unprecedented scales (Yeung 2001, Duarte et al. 2008, Duan et al. 2016, Chee et al. 2017, Sengupta et al. 2018). In addition, the risks of climate change, as outlined in the previous section, have resulted in an urgent need for greater shoreline protection, especially in low-elevation coastal zones (LECZ) (*sensu* Neumann et al. 2015). For instance, in China, Japan and Korea alone, 28% of the global population are currently living in LECZ and it is predicted that by 2070, 37 million

people and assets worth \$13 trillion are going to be exposed to coastal hazards such as storms, flooding and climate variability (Nicholls et al. 2013). Strategies that mitigate risk and help coastal cities adapt to sea level rise and climate change are already being implemented in many parts of the world (Zimmerman and Faris 2010, Hayes et al. 2018) and are predicted to increase in the coming decades (Neumann et al. 2015, Dangendorf et al. 2017). Such strategies, though multifaceted, include expanded coastal armoring (French and Spencer 2001, Hinkel et al. 2014), the integration of new stormwater capture and treatment systems, and a wide variety of other modifications to increase the resilience of urban infrastructure (Zimmerman and Faris 2010).

If the past is any indication, future proliferation of marine urbanization will further facilitate the formation of novel assemblages of marine organisms on an unprecedented scale. Currently, there is considerable debate in ecology regarding the concept of 'novel ecosystems' (Hobbs et al. 2014, Murcia et al. 2014), i.e. ecosystems shaped by human intervention that are distinct from their historical state, and that cannot be returned to their historical trajectory (Hallett et al. 2013). It is presently unclear whether urban marine ecosystems meet all criteria of 'novel ecosystems' (Morse et al. 2014), but their trajectory is undeniably shaped by the way in which coastal cities develop and modify the marine environment (Dafforn et al. 2015). Given the potential of marine assemblages to provide ecosystem services to urban populations, as well as recent success in the realm of eco-shoreline design (Toft et al. 2013, Morris et al. 2019), it may be more helpful to consider urban marine ecosystems and their future trajectory within the framework of 'designed ecosystems' (Higgs 2017) or 'reconciliation ecology' (Rosenzweig 2003a). While both of these frameworks arose with the realization that some systems have been so severely altered and/or degraded it is practically impossible to apply conventional restoration practices (or expect the system to shift back towards a 'historic' or 'pre-disturbed' state), conceptually they are fundamentally different in their intent, starting point and developmental trajectory (Hunter and Gibbs 2007, Higgs 2017). For instance, 'designed ecosystems' often involve large-scale intervention efforts to create and sustain the system whereas 'reconciliation ecology' is less reliant on long-term intervention and more based on the idea that 'if you build it, they will come' (Rosenzweig 2003b, p. 6). 'Ecological engineering', i.e. the design and engineering of urban infrastructure congruent with ecological principles, can be viewed as straddling between these frameworks, as it often requires huge initial intervention but with less emphasis on subsequent management and maintenance (see recent review by Loke et al. 2019a).

Ecological engineering is currently being trialed, or attempted in earnest, in many locations around the world (Chapman and Blockley 2009, Mitsch 2012, Strain et al. 2018). Nature-based or soft-engineering approaches using 'green infrastructure' for coastal defense are preferred over hard engineering approaches in many coastal cities as they have been shown to be more cost-effective in the longer term

and can serve multiple functions in addition to flood risk reduction (Temmerman et al. 2013, Spalding et al. 2014, Reguero et al. 2018). However, these solutions are often not adopted due to feasibility (e.g. mangrove planting at sites with high wave energy or flow) or socio-economic reasons (e.g. lack of political will, support or resources). In addition, hard artificial coastal defenses have frequently already been constructed and cannot realistically be removed. Given that more human-made shorelines are expected to be built in the foreseeable future, it is critical to find ways to increase their ecological and social value while maintaining their engineering function (Borsje et al. 2011, Loke et al. 2019a). The ecological engineering of human-made shoreline structures is a new but dynamic field, and there is often a tradeoff between taking time to understand these habitats as a system, and the urgency or desire to implement practical solutions (Morris et al. 2019). Knowledge of urban shoreline ecosystems and of strategies that effectively enhance ecosystem functioning and services should improve over time, as ecological enhancement and blue/green infrastructure projects become more common and are applied in a broader variety of urban marine environments (Pontee et al. 2016). Developing and maintaining research collaborations with industry will be essential to ensure that lessons from each of these projects are shared and translated into subsequent designs and engineering solutions (Mayer-Pinto et al. 2017). Further, partnerships with city governments and planners will be needed if ecological enhancement projects are to be applied concurrently with broader improvements in water quality and at a sufficient scale to have long-standing benefits, and then carefully monitored over time.

Critical challenges and research directions

Awareness of the impacts of exploitation, marine pollution and ocean sprawl, as well as of eco-engineering countermeasures, is growing (Chapman and Underwood 2011, Morris et al. 2016, Lotze et al. 2018, Strain et al. 2019). However, there remain many emerging issues, knowledge gaps and research needs at numerous scales for understanding the dynamics of urban marine ecosystems (Airoldi et al. 2005, Kueffer and Kaiser-Bunbury 2014) and building urban marine ecology as a discipline. Here, we offer some critical research questions and areas for investigation that have yet to be fully addressed.

1. What are the interactive effects of multiple stressors in urbanized coastal areas, including feedbacks and changes over time?
2. Stronger characterization of spatial and temporal patterns of biodiversity in urbanized marine environments.
3. What are the mechanisms driving marine synanthropy?
4. Key marine urban ecosystem functions, their most essential drivers, and likely future trajectories – including implications for current and future provisioning of ecosystem services.

5. Assessment of the evidence for urban-driven trait selection in the marine environment.
6. What ecological enhancement approaches (ecological engineering, green- and blue-infrastructure, etc.) are most effective in urban settings?

There are also numerous questions related to the key ecological processes discussed in the section ‘Key ecological patterns’ that need to be elucidated, especially disentangling co-varying stressors and determining the long-term responses of organisms and populations to marine urbanization. Ultimately, all aspects of coastal city design: architecture, urban planning and civil and municipal engineering, will need to prioritize the marine environment if the negative effects of urbanization are to be minimized. In particular, planning strategies that account for the interactive effects of drivers and accommodate complex system dynamics should enhance the ecological and human functions of future urban marine ecosystems.

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References

- Adams, S. M. 2005. Assessing cause and effect of multiple stressors on marine systems. – *Mar. Pollut. Bull.* 51: 649–657.
- Aguilera, M. A. 2018. Artificial defences in coastal marine ecosystems in Chile: opportunities for spatial planning to mitigate habitat loss and alteration of the marine community structure. – *Ecol. Eng.* 120: 601–610.
- Aguilera, M. A. et al. 2014. Spatial variability in community composition on a granite breakwater versus natural rocky shores: lack of microhabitats suppresses intertidal biodiversity. – *Mar. Pollut. Bull.* 87: 257–268.
- Airoldi, L. 1998. Roles of disturbance, sediment stress and substratum retention on spatial dominance in algal turf. – *Ecology* 79: 2759–2770.
- Airoldi, L. 2003. The effects of sedimentation on rocky coast assemblages. – *Oceanogr. Mar. Biol.* 41: 161–236.
- Airoldi, L. and Beck, M. W. 2007. Loss, status and trends for coastal marine habitats of Europe. – *Oceanogr. Mar. Biol. Annu. Rev.* 45: 345–405.
- Airoldi, L. and Bulleri, F. 2011. Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. – *PLoS One* 6: 22985.
- Airoldi, L. et al. 2005. An ecological perspective on the deployment and design of low-crested and other hard coastal defence structures. – *Coast. Eng.* 52: 1073–1087.

- Airoldi, L. et al. 2015. Corridors for aliens but not for natives: effects of marine urban sprawl at a regional scale. – *Divers. Distrib.* 21: 755–768.
- Alberti, M. 2005. The effects of urban patterns on ecosystem function. – *Int. Regional Sci. Rev.* 28: 168–192.
- Alberti, M. 2008. *Advances in urban ecology: integrating humans and ecological processes in urban ecosystems.* – Springer.
- Alberti, M. 2015. Eco-evolutionary dynamics in an urbanizing planet. – *Trends Ecol. Evol.* 30: 114–126.
- Alberti, M. et al. 2003. Integrating humans into ecology: opportunities and challenges for studying urban ecosystems. – *BioScience* 53: 1169–1179.
- Alberti, M. et al. 2017a. Urban driven phenotypic changes: empirical observations and theoretical implications for eco-evolutionary feedback. – *Phil. Trans. R. Soc. B* 372: 20160029.
- Alberti, M. et al. 2017b. Global urban signatures of phenotypic change in animal and plant populations. – *Proc. Natl Acad. Sci. USA* 114: 8951–8956.
- Alexander, K. S. et al. 2012. Managed retreat of coastal communities: understanding responses to projected sea level rise. – *J. Environ. Plann. Manage.* 55: 409–433.
- Alleway, H. K. and Connell, S. D. 2015. Loss of an ecological baseline through the eradication of oyster reefs from coastal ecosystems and human memory. – *Conserv. Biol.* 29: 795–804.
- Alpine, A. E. and Cloern, J. E. 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. – *Limnol. Oceanogr.* 37: 946–955.
- Altieri, A. H. and Witman, J. D. 2006. Local extinction of a foundation species in a hypoxic estuary: integrating individuals to ecosystem. – *Ecology* 87: 717–730.
- Alvarez-Filip, L. et al. 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. – *Proc. R. Soc. B* 276: 3019–3025.
- Amin, B. et al. 2009. Anthropogenic impacts on heavy metal concentrations in the coastal sediments of Dumai, Indonesia. – *Environ. Mon. Assess.* 148: 291–305.
- Anderson, S. C. et al. 2011. Rapid global expansion of invertebrate fisheries: trends, drivers and ecosystem effects. – *PLoS One* 6: e14735.
- Andersson, M. H. et al. 2009. Epibenthic colonization of concrete and steel pilings in a cold-temperate embayment: a field experiment. – *Helgoland Mar. Res.* 63: 249.
- Andrades, R. et al. 2016. Origin of marine debris is related to disposable packs of ultra-processed food. – *Mar. Pollut. Bull.* 109: 192–195.
- André, M. et al. 2011. Low-frequency sounds induce acoustic trauma in cephalopods. – *Front. Ecol. Environ.* 9: 489–493.
- Assunção, M. A. et al. 2017. Aliphatic and polycyclic aromatic hydrocarbons in surface sediments collected from mangroves with different levels of urbanization in southern Brazil. – *Mar. Poll. Bull.* 119: 439–445.
- Aswani, S. and Sabetian, A. 2010. Implications of urbanization for artisanal parrotfish fisheries in the western Solomon Islands. – *Conserv. Biol.* 24: 520–530.
- Atkinson, S. et al. 2003. Estrogens from sewage in coastal marine environments. – *Environ. Health Perspect.* 111: 531–535.
- Auld, A. H. and Schubel, J. R. 1978. Effects of suspended sediment on fish eggs and larvae: a laboratory assessment. – *Estuar. Coast. Mar. Sci.* 6: 153–164.
- Azzarello, M. Y. and Van Vleet, E. S. 1987. Marine birds and plastic pollution. – *Mar. Ecol. Prog. Ser.* 37: 295–303.
- Balata, D. et al. 2007. Sediment disturbance and loss of beta diversity on subtidal rocky reefs. – *Ecology* 88: 2455–2461.
- Balestri, E. et al. 2004. Variability in patterns of growth and morphology of *Posidonia oceanica* exposed to urban and industrial wastes: contrasts with two reference locations. – *J. Exp. Mar. Biol. Ecol.* 308: 1–21.
- Balls, P. W. 1994. Nutrient inputs to estuaries from nine Scottish east coast rivers; influence of estuarine processes on inputs to the North Sea. – *Estuar. Coast. Shelf Sci.* 39: 329–352.
- Barboza, L. G. A. 2018. Marine microplastic debris: an emerging issue for food security, food safety and human health. – *Mar. Pollut. Bull.* 133: 336–348.
- Bårdsen, B. J. et al. 2018. Multiple stressors: modeling the effect of pollution, climate and predation on viability of a sub-arctic marine bird. – *Ecosphere* 9: e02342.
- Barnes, D. K. A. et al. 2009. Accumulation and fragmentation of plastic debris in global environments. – *Phil. Trans. R. Soc. B* 64: 1985–1998.
- Barros, F. et al. 2001. The influence of rocky reefs on structure of benthic macrofauna in nearby soft-sediments. – *Estuar. Coast. Shelf Sci.* 52: 191–199.
- Baum, G. et al. 2015. Local and regional impacts of pollution on coral reefs along the Thousand Islands north of the megacity Jakarta, Indonesia. – *PLoS One* 10: e0138271.
- Baum, G. et al. 2016. Under pressure: investigating marine resource-based livelihoods in Jakarta Bay and the Thousand Islands. – *Mar. Pollut. Bull.* 110: 778–789.
- Bauman, A. G. et al. 2015. Coral settlement on a highly disturbed equatorial reef system. – *PLoS One* 10: e0127874.
- Bayen, S. et al. 2003. Occurrence of polychlorinated biphenyls and polybrominated diphenyl ethers in green mussels (*Perna viridis*) from Singapore, Southeast Asia. – *Environ. Toxicol. Chem.* 22: 2432–2437.
- Becker, A. et al. 2013. Potential effects of artificial light associated with anthropogenic infrastructure on the abundance and foraging behaviour of estuary-associated fishes. – *J. Appl. Ecol.* 50: 43–50.
- Bell, P. R. F. 1991. Status of eutrophication in the Great Barrier Reef Lagoon. – *Mar. Pollut. Bull.* 23: 89–93.
- Benedetti-Cecchi, L. et al. 2001. Predicting the consequences of anthropogenic disturbance: large-scale effects of removing dominant species on rocky shores. – *Mar. Ecol. Prog. Ser.* 214: 137–150.
- Benzeev, R. et al. 2017. Quantifying fisheries ecosystem services of mangroves and tropical artificial urban shorelines. – *Hydrobiologia* 803: 225–237.
- Bertness, M. D. and Callaway, R. 1994. Positive interactions in communities. – *Trends Ecol. Evol.* 9: 191–193.
- Bertness, M. D. and Gaines, S. D. 1993. Larval dispersal and local adaptation in acorn barnacles. – *Evolution* 47: 316–320.
- Bishop, M. J. et al. 2017. Effects of ocean sprawl on ecological connectivity: impacts and solutions. – *J. Exp. Mar. Biol. Ecol.* 492: 7–30.
- Bjorndal, K. A. et al. 1994. Ingestion of marine debris by juvenile sea turtles in coastal Florida habitats. – *Mar. Pollut. Bull.* 28: 154–158.
- Blockley, D. J. and Chapman, M. G. 2008. Exposure of seawalls to waves within an urban estuary: effects on intertidal assemblages. – *Austral Ecol.* 33: 168–183.
- Bloom, D. E. 2011. 7 billion and counting. – *Science* 333: 562–569.

- Board, M. 1997. Contaminated sediments in ports and waterways: cleanup strategies and technologies. – National Academies Press.
- Boehlert, G. W. and Gill, A. B. 2010. Environmental and ecological effects of ocean renewable energy development: a current synthesis. – *Oceanography* 23: 68–81.
- Bolton, D. et al. 2017. Coastal urban lighting has ecological consequences for multiple trophic levels under the sea. – *Sci. Total Environ.* 576: 1–9.
- Borsje, B. W. et al. 2011. How ecological engineering can serve in coastal protection. – *Ecol. Eng.* 37: 113–122.
- Borum, J. and Sand-Jensen, K. 1996. Is total primary production in shallow coastal marine waters stimulated by nitrogen loading? – *Oikos* 76: 406–410.
- Bosch, A. C. et al. 2016. Heavy metals in marine fish meat and consumer health: a review. – *J. Sci. Food Agri.* 96: 32–48.
- Botterell, Z. L. et al. 2018. Bioavailability and effects of microplastics on marine zooplankton: a review. – *Environ. Poll.* 245: 98–110.
- Bowen, J. L. and Valiela, I. 2001. The ecological effects of urbanization of coastal watersheds: historical increases in nitrogen loads and eutrophication of Waquoit Bay estuaries. – *Can. J. Fish. Aquat. Sci.* 58: 1489–1500.
- Braga, E. S. et al. 2000. Eutrophication and bacterial pollution caused by industrial and domestic wastes at the Baixada Santista estuarine system-Brazil. – *Mar. Pollut. Bull.* 40: 165–173.
- Brewer, T. D. et al. 2009. Thresholds and multiple scale interaction of environment, resource use and market proximity on reef fishery resources in the Solomon Islands. – *Biol. Conserv.* 142: 1797–1807.
- Brown, R. J. et al. 2004. Differential sensitivity of three marine invertebrates to copper assessed using multiple biomarkers. – *Aquat. Toxicol.* 66: 267–278.
- Browne, M. A. et al. 2008. Ingested microscopic plastic translocates to the circulatory system of the mussel, *Mytilus edulis* (L.). – *Environ. Sci. Technol.* 42: 5026–5031.
- Browne, N. K. et al. 2015. Fluctuations in coral health of four common inshore reef corals in response to seasonal and anthropogenic changes in water quality. – *Mar. Environ. Res.* 105: 39–52.
- Buggy, C. J. and Tobin, J. M. 2008. Seasonal and spatial distribution of metals in surface sediment of an urban estuary. – *Environ. Pollut.* 155: 308–319.
- Bulleri, F. and Airoidi, L. 2005. Artificial marine structures facilitate the spread of a non-indigenous green alga, *Codium fragile* ssp. *tomentosoides*, in the north Adriatic Sea. – *J. Appl. Ecol.* 42: 1063–1072.
- Bulleri, F. and Chapman, M. G. 2004. Intertidal assemblages on artificial and natural habitats in marinas on the north-west coast of Italy. – *Mar. Biol.* 145: 381–391.
- Bulleri, F. and Chapman, M. G. 2010. The introduction of coastal infrastructure as a driver of change in marine environments. – *J. Appl. Ecol.* 47: 26–35.
- Bulleri, F. and Chapman, M. G. 2015. Artificial physical structures. – In: Crowe, T. P. and Frid, C. L. J. (eds), *Marine ecosystems: human impacts on biodiversity, functioning and services*. Cambridge Univ. Press, pp. 167–197.
- Bulleri, F. et al. 2005. Intertidal assemblages on seawalls and vertical rocky shores in Sydney Harbour, Australia. – *Austral Ecol.* 30: 655–667.
- Burt, J. A. 2014. The environmental costs of coastal urbanization in the Arabian Gulf. – *City* 18: 760–770.
- Burt, J. A. et al. 2009. Are artificial reefs surrogates of natural habitats for corals and fish in Dubai, United Arab Emirates? – *Coral Reefs* 28: 663–675.
- Burt, J. A. et al. 2013. The continuing decline of coral reefs in Bahrain. – *Mar. Poll. Bull.* 72: 357–363.
- Burton, G. A. and Johnston, E. L. 2010. Assessing contaminated sediments in the context of multiple stressors. – *Environ. Toxicol. Chem.* 29: 2625–2643.
- Cadenasso, M. L. et al. 2007. Spatial heterogeneity in urban ecosystems: reconceptualizing land cover and a framework for classification. – *Front. Ecol. Environ.* 5: 80–88.
- Canning-Clode, J. et al. 2011. The effects of copper pollution on fouling assemblage diversity: a tropical–temperate comparison. – *PLoS One* 6: e18026.
- Carlton, J. T. 1996. Biological invasions and cryptogenic species. – *Ecology* 77: 1653–1655.
- Carlton, J. T. and Hodder, J. 2003. Maritime mammals: terrestrial mammals as consumers in marine intertidal communities. – *Mar. Ecol. Prog. Ser.* 256: 271–286.
- Carlton, J. T. et al. 2017. Tsunami-driven rafting: transoceanic species dispersal and implications for marine biogeography. – *Science* 357: 1402–1406.
- Casado-Martínez, M. C. et al. 2006. Using sediment quality guidelines for dredged material management in commercial ports from Spain. – *Environ. Int.* 32: 388–396.
- Cetecioglu, Z. et al. 2009. Biogeographical distribution and diversity of bacterial and archaeal communities within highly polluted anoxic marine sediments from the Marmara Sea. – *Mar. Pollut. Bull.* 58: 384–395.
- Chang, T. C. and Huang, S. 2011. Reclaiming the city: waterfront development in Singapore. – *Urban Stud.* 48: 2085–2100.
- Chapman, M. G. 2003. Paucity of mobile species on constructed seawalls: effects of urbanization on biodiversity. – *Mar. Ecol. Prog. Ser.* 264: 21–29.
- Chapman, M. G. and Blockley, D. J. 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. – *Oecologia* 161: 625–635.
- Chapman, M. G. and Bulleri, F. 2003. Intertidal seawalls – new features of landscape in intertidal environments. – *Landscape Urban Plan.* 62: 159–172.
- Chapman, M. G. and Underwood, A. J. 2011. Evaluation of ecological engineering of ‘armoured’ shorelines to improve their value as habitat. – *J. Exp. Mar. Biol. Ecol.* 400: 302–313.
- Charifi, M. et al. 2017. The sense of hearing in the Pacific oyster, *Magallana gigas*. – *PLoS One* 12: e0185353.
- Charlier, R. H. and Charlier, C. C. 1992. Ocean non-living resources: historical perspective on exploitation, economics and environmental impact. – *Int. J. Environ. Stud.* 40: 123–134.
- Charlier, R. H. et al. 2005. Panorama of the history of coastal protection. – *J. Coast. Res.* 21: 79–111.
- Chee, S. Y. et al. 2017. Land reclamation and artificial islands: walking the tightrope between development and conservation. – *Global Ecol. Conserv.* 12: 80–95.
- Chou, L. M. 2006. Marine habitats in one of the world’s busiest harbours. – In: Wolanski, E. (ed.), *The environment in Asia Pacific harbours*. Springer, pp. 377–391.
- Chou, L. M. and Lim, T. M. 1986. A preliminary study of the coral community on artificial and natural substrates. – *Malayan Nat. J.* 39: 225–229.
- Cinner, J. E. et al. 2018. Gravity of human impacts mediates coral reef conservation gains. – *Proc. Natl Acad. Sci. USA* 115: E6116–6125.
- Claudet, J. and Fraschetti, S. 2010. Human-driven impacts on marine habitats: a regional meta-analysis in the Mediterranean Sea. – *Biol. Conserv.* 143: 2195–2206.

- Cloern, J. E. 2001. Our evolving conceptual model of the coastal eutrophication problem. – *Mar. Ecol. Prog. Ser.* 210: 223–253.
- Clynick, B. G. et al. 2008. Fish assemblages associated with urban structures and natural reefs in Sydney, Australia. – *Austral Ecol.* 33: 140–150.
- Cole, M. L. et al. 2004. Assessment of a $\delta^{15}\text{N}$ isotopic method to indicate anthropogenic eutrophication in aquatic ecosystems. – *J. Environ. Qual.* 33: 124–132.
- Cole, M. et al. 2011. Microplastics as contaminants in the marine environment: a review. – *Mar. Pollut. Bull.* 62: 2588–2597.
- Coleman, M. A. et al. 2008. Absence of a large brown macroalga on urbanized rocky reefs around Sydney, Australia and evidence for historical decline. – *J. Phycol.* 44: 897–901.
- Colosio, F. et al. 2007. Effects of beach nourishment on sediments and benthic assemblages. – *Mar. Pollut. Bull.* 54: 1197–1206.
- Connell, S. D. 2001. Urban structures as marine habitats: an experimental comparison of the composition and abundance of subtidal epibiota among pilings, pontoons and rocky reefs. – *Mar. Environ. Res.* 52: 115–125.
- Connell, S. D. and Glasby, T. M. 1999. Do urban structures influence local abundance and diversity of subtidal epibiota? A case study from Sydney Harbour, Australia. – *Mar. Environ. Res.* 47: 373–387.
- Connell, S. D. et al. 2008. Recovering a lost baseline: missing kelp forests from a metropolitan coast. – *Mar. Ecol. Prog. Ser.* 360: 63–72.
- Conversi, A. et al. 2015. A holistic view of marine regime shifts. – *Phil. Trans. R. Soc. B* 370: 20130279.
- Cordell, J. R. et al. 2013. Ecological implications of invasive tunicates associated with artificial structures in Puget Sound, Washington, USA. – *Biol. Invas.* 15: 1303–1318.
- Córdova-Kreylos, A. L. et al. 2006. Diversity, composition and geographical distribution of microbial communities in California salt marsh sediments. – *Appl. Environ. Microb.* 72: 3357–3366.
- Cornelissen, G. et al. 2008. The contribution of urban runoff to organic contaminant levels in harbor sediments near two Norwegian cities. – *Mar. Pollut. Bull.* 56: 563–573.
- Costantini, F. et al. 2013. Quantifying spatial genetic structuring in mesophotic populations of the precious coral *Corallium rubrum*. – *PLoS One* 8: e61546.
- Coull, B. C. and Chandler, G. T. 1992. Pollution and meiofauna: field, laboratory and mesocosm studies. – *Oceanogr. Mar. Biol. Annu. Rev.* 30: 191–271.
- Crain, C. M. et al. 2008. Interactive and cumulative effects of multiple human stressors in marine systems. – *Ecol. Lett.* 11: 1304–1315.
- Crain, C. M. et al. 2009. Understanding and managing human threats to the coastal marine environment. – *Ann. N. Y. Acad. Sci.* 1162: 39–62.
- Creel, L. 2003. Ripple effects: population and coastal regions. – Population Reference Bureau, Washington, DC, pp. 1–7.
- Cundy, A. B. et al. 2003. Reconstructing historical trends in metal input in heavily-disturbed, contaminated estuaries: studies from Bilbao, Southampton Water and Sicily. – *Appl. Geochem.* 18: 311–325.
- Cuomo, G. et al. 2010. Breaking wave loads at vertical seawalls and breakwaters. – *Coast. Eng.* 57: 424–439.
- da Silva, J. F. et al. 2004. Seagrasses and sediment response to changing physical forcing in a coastal lagoon. – *Hydrol. Earth Syst. Sci.* 8: 151–159.
- Dafforn, K. A. et al. 2009. Shallow moving structures promote marine invader dominance. – *Biofouling* 25: 277–287.
- Dafforn, K. A. et al. 2015. Marine urbanization: an ecological framework for designing multifunctional artificial structures. – *Front. Ecol. Environ.* 13: 82–90.
- Dallimer, M. et al. 2011. Temporal changes in greenspace in a highly urbanized region. – *Biol. Lett.* 7: 763–766.
- Dangendorf, S. et al. 2017. Reassessment of 20th century global mean sea level rise. – *Proc. Natl Acad. Sci. USA* 114: 5946–5951.
- Darling, J. A. et al. 2009. Human-mediated transport determines the non-native distribution of the anemone *Nematostella vectensis*, a dispersal-limited estuarine invertebrate. – *Mar. Ecol. Prog. Ser.* 380: 137–146.
- Dauer, D. M. et al. 2000. Relationships between benthic community condition, water quality, sediment quality, nutrient loads and land use patterns in Chesapeake Bay. – *Estuaries* 23: 80–96.
- Davies, T. W. et al. 2014. The nature, extent and ecological implications of marine light pollution. – *Front. Ecol. Environ.* 12: 347–355.
- Davis, K. L. et al. 2017. Ecological performance of construction materials subject to ocean climate change. – *Mar. Environ. Res.* 131: 177–182.
- Dayton, P. K. 1972. Toward an understanding of community resilience and the potential effects of enrichments to the benthos at McMurdo Sound, Antarctica. – In: Parker, B. C. (ed.), *Proceedings of the colloquium on conservation problems in Antarctica*. Allen Press, Lawrence, Kansas, USA, pp. 81–96.
- de Boer, W. F. 2007. Seagrass–sediment interactions, positive feedbacks and critical thresholds for occurrence: a review. – *Hydrobiologia* 591: 5–24.
- de Soto, N. A. et al. 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. – *Sci. Rep.* 3: 2831.
- DeAngelis, M. L. et al. 2008. Preliminary observations of the effectiveness of non-lethal deterrence methods for California sea lions and pacific harbor seals along the coast of California. – In: Timm, R. M. and Madon, M. B. (eds), *Proc. 23rd Vertebr. Pest Conf.*, pp. 181–185.
- Defeo, O. 2003. Marine invertebrate fisheries in sandy beaches: an overview. – *J. Coast. Res. Special Issue* 35: 56–65.
- Defeo, O. and de Alava, A. 1995. Effects of human activities on long-term trends in sandy beach populations: the wedge clam *Donax hanleyanus* in Uruguay. – *Mar. Ecol. Prog. Ser.* 123: 73–82.
- Devinny, J. S. and Volsse, L. A. 1978. Effects of sediments on the development of *Macrocystis pyrifera* gametophytes. – *Mar. Biol.* 48: 343–348.
- Donat, M. G. et al. 2016. More extreme precipitation in the world's dry and wet regions. – *Nat. Clim. Change* 6: 508–513.
- Dong, Y. et al. 2016. The marine 'great wall' of China: local- and broad-scale ecological impacts of coastal infrastructure on intertidal macrobenthic communities. – *Divers. Distrib.* 22: 731–744.
- Donihue, C. M. and Lambert, M. R. 2015. Adaptive evolution in urban ecosystems. – *Ambio* 44: 194–203.
- Doody, J. P. 2004. 'Coastal squeeze' – an historical perspective. – *J. Coast. Conserv.* 10: 129–138.
- Dow, K. 2000. Social dimensions of gradients in urban ecosystems. – *Urban Ecosyst.* 4: 255–275.
- Duan, H. et al. 2016. Characterization and environmental impact analysis of sea land reclamation activities in China. – *Ocean Coast. Manage.* 130: 128–137.

- Duarte, C. M. et al. 2008. The charisma of coastal ecosystems: addressing the imbalance. – *Estuar. Coast.* 31: 233–238.
- Duarte, C. M. et al. 2013. Is global ocean sprawl a cause of jellyfish blooms? – *Front. Ecol. Environ.* 11: 91–97.
- Duffy, J. E. et al. 2005. Ecosystem consequences of diversity depend on food chain length in estuarine vegetation. – *Ecol. Lett.* 8: 301–309.
- Duffy, P. B. et al. 2015. Projections of future meteorological drought and wet periods in the Amazon. – *Proc. Natl Acad. Sci. USA* 112: 13172–13177.
- Dyl, J. 2009. Lessons from history: coastal cities and natural disaster. – *Manage. Environ. Qual. Int. J.* 20: 460–473.
- Dyson, K. and Yocom, K. 2015. Ecological design for urban waterfronts. – *Urban Ecosyst.* 18: 189–208.
- Edwards, K. F. and Stachowicz, J. J. 2011. Spatially stochastic settlement and the coexistence of benthic marine animals. – *Ecology* 92: 1094–1103.
- Eggleton, J. and Thomas, K. V. 2004. A review of factors affecting the release and bioavailability of contaminants during sediment disturbance events. – *Environ. Int.* 30: 973–980.
- Elmqvist, T. et al. 2003. Response diversity, ecosystem change and resilience. – *Front. Ecol. Environ.* 1: 488–494.
- Ertfemeijer, P. L. and Lewis III, R. R. 2006. Environmental impacts of dredging on seagrasses: a review. – *Mar. Pollut. Bull.* 52: 1553–1572.
- Ertfemeijer, P. L. A. et al. 2012. Environmental impacts of dredging and other sediment disturbances on corals: a review. – *Mar. Pollut. Bull.* 64: 1737–1765.
- Etter, R. J. 1988. Asymmetrical developmental plasticity in an intertidal snail. – *Evolution* 42: 322–334.
- Evans, S. M. et al. 1995. Domestic waste and TBT pollution in coastal areas of Ambon Island (Eastern Indonesia). – *Mar. Pollut. Bull.* 30: 109–115.
- Evans, J. S. et al. 2017. Introduced ascidians harbor highly diverse and host-specific symbiotic microbial assemblages. – *Sci. Rep.* 7: 11033.
- Falkowski, P. G. et al. 1990. Irradiance and corals. – In: Dubinski, Z. (ed.), *Ecosystems of the world 25: coral reefs*. Elsevier, pp. 89–107.
- Fauvelot, C. et al. 2009. Lower genetic diversity in the limpet *Patella caerulea* on urban coastal structures compared to natural rocky habitats. – *Mar. Biol.* 156: 2313–2323.
- Fauvelot, C. et al. 2012. Do artificial structures alter marine invertebrate genetic makeup? – *Mar. Biol.* 159: 2797–2807.
- Feary, D. A. et al. 2011. Artificial marine habitats in the Arabian Gulf: review of current use, benefits and management implications. – *Ocean Coast. Manage.* 54: 742–749.
- Feist, B. E. and Levin, P. S. 2016. Novel indicators of anthropogenic influence on marine and coastal ecosystems. – *Front. Mar. Sci.* 3: 113.
- Fernando, H. J. S. 2008. Polimetrics: the quantitative study of urban systems (and its applications to atmospheric and hydro environments). – *Environ. Fluid Mech.* 8: 397–409.
- Ferrario, F. et al. 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. – *Nat. Commun.* 5: 3794.
- Ferrario, F. et al. 2016. The overlooked role of biotic factors in controlling the ecological performance of artificial marine habitats. – *J. Appl. Ecol.* 53: 16–24.
- Fewtrell, J. L. and McCauley, R. D. 2012. Impact of air gun noise on the behaviour of marine fish and squid. – *Mar. Pollut. Bull.* 64: 984–993.
- Finkl, C. W. and Charlier, R. H. 2003. Sustainability of subtropical coastal zones in southeastern Florida: challenges for urbanized coastal environments threatened by development, pollution, water supply and storm hazards. – *J. Coast. Res.* 19: 934–943.
- Firth, L. B. et al. 2013. The importance of water-retaining features for biodiversity on artificial intertidal coastal defence structures. – *Divers. Distrib.* 19: 1275–1283.
- Firth, L. B. et al. 2014. Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. – *Coast. Eng.* 87: 122–135.
- Firth, L. B. et al. 2015. Facing the future: the importance of substratum features for ecological engineering of artificial habitats in the rocky intertidal. – *Mar. Freshwater Res.* 67: 131–143.
- Firth, L. B. et al. 2016. Ocean sprawl: challenges and opportunities for biodiversity management in a changing world. – *Oceanogr. Mar. Biol. Annu. Rev.* 54: 189–262.
- Fletemeyer, J. et al. 2018. The impact of sand nourishment on beach safety. – *J. Coast. Res.* 34: 1–5.
- Foo, S. A. and Byrne, M. 2016. Acclimatization and adaptive capacity of marine species in a changing ocean. – *Adv. Mar. Biol.* 74: 69–116.
- Foster, V. et al. 2016. Identifying the physical features of marina infrastructure associated with the presence of non-native species in the UK. – *Mar. Biol.* 163: 173.
- Fowles, A. E. et al. 2018. Effects of urbanisation on macroalgae and sessile invertebrates in southeast Australian estuaries. – *Estuar. Coast. Shelf Sci.* 205: 30–39.
- French, J. R. and Spencer, T. 2001. Sea-level rise. – In: Warren, A. and French, J. R. (eds), *Conservation and the physical environment*. Wiley, pp. 305–347.
- French, G. T. et al. 1995. Sea-level rise and Nigeria: potential impacts and consequences. – *J. Coast. Res.* 14: 224–242.
- Frijo, D. E. et al. 2002. DDT and its metabolites alter gene expression in human uterine cell lines through estrogen receptor-independent mechanisms. – *Environ. Health Perspect.* 110: 1239–1245.
- Gabriele, M. et al. 1999. Sublittoral hard substrate communities of the northern Adriatic Sea. – *Cah. Biol. Mar.* 40: 65–76.
- Galletly, B. C. et al. 2007. Genetic mechanisms of pollution resistance in a marine invertebrate. – *Ecol. Appl.* 17: 2290–2297.
- Gao, G. et al. 2013. Modeling effects of a tidal barrage on water quality indicator distribution in the Severn Estuary. – *Front. Environ. Sci. Eng.* 7: 211–218.
- Gao, X. et al. 2017. Interactive effects of nutrient availability and temperature on growth and survival of different size classes of *Saccharina japonica* (Laminariales, Phaeophyceae). – *Phycologia* 56: 253–260.
- Garcia-Sanda, E. et al. 2003. Clean production in fish canning industries: recovery and reuse of selected wastes. – *Clean Technol. Environ.* 5: 289–294.
- Gaw, S. et al. 2014. Sources, impacts and trends of pharmaceuticals in the marine and coastal environment. – *Phil. Trans. R. Soc. B* 369: 20130572.
- Gaylord, B. 1999. Detailing agents of physical disturbance: wave-induced velocities and accelerations on a rocky shore. – *J. Exp. Mar. Biol. Ecol.* 239: 85–124.
- Geange, S. W. et al. 2014. Sediment load and timing of sedimentation affect spore establishment in *Macrocystis pyrifera* and *Undaria pinnatifida*. – *Mar. Biol.* 161: 1583–1592.
- Gillan, D. C. et al. 2005. Structure of sediment-associated microbial communities along a heavy-metal contamination gradient

- in the marine environment. – *Appl. Environ. Microb.* 71: 679–690.
- Gioia, R. et al. 2008. Polychlorinated biphenyls in air and water of the North Atlantic and Arctic Ocean. – *J. Geophys. Res.* 113: D19302.
- Gittenberger, A. and van der Stelt, R. C. 2011. Artificial structures in harbors and their associated ascidian fauna. – *Aquat. Invas.* 6: 413–420.
- Glasby, T. M. 1999. Differences between subtidal epibiota on pier pilings and rocky reefs at marinas in Sydney, Australia. – *Estuar. Coast. Shelf Sci.* 48: 281–290.
- Glasby, T. M. 2000. Surface composition and orientation interact to affect subtidal epibiota. – *J. Exp. Mar. Biol. Ecol.* 248: 177–190.
- Glasby, T. M. et al. 2007. Nonindigenous biota on artificial structures: could habitat creation facilitate biological invasions? – *Mar. Biol.* 151: 887–895.
- Goiran, C. et al. 2017. Industrial melanism in the seasnake *Emydocephalus annulatus*. – *Curr. Biol.* 27: 2510–2513.
- Gomez, E. D. et al. 1990. State of the marine environment in the East Asian Seas Region. – UNEP Regional Seas Reports and Studies No. 126.
- Gorgula, S. K. and Connell, S. D. 2004. Expansive covers of turf-forming algae on human-dominated coast: the relative effects of increasing nutrient and sediment loads. – *Mar. Biol.* 145: 613–619.
- Gorman, D. and Connell, S. D. 2009. Recovering subtidal forests in human-dominated landscapes. – *J. Appl. Ecol.* 46: 1258–1265.
- Graham, N. A. J. and Nash, K. L. 2013. The importance of structural complexity in coral reef ecosystems. – *Coral Reefs* 32: 315–326.
- Grimm, N. B. et al. 2008a. Global change and the ecology of cities. – *Science* 319: 756–760.
- Grimm, N. B. et al. 2008b. The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. – *Front. Ecol. Environ.* 6: 264–272.
- Grimm, N. et al. 2013. Viewing the urban socio-ecological system through a sustainability lens: lessons and prospects from the Central Arizona–Phoenix LTER Programme. – *LTSER HUEN*, pp. 217–246.
- Groffman, P. M. et al. 2017. Ecological homogenization of residential macrosystems. – *Nat. Ecol. Evol.* 1: 0191.
- Guest, J. R. et al. 2008. Can giant clam (*Tridacna squamosa*) populations be restored on Singapore's heavily impacted coral reefs? – *Aquat. Conserv. Mar. Freshwater Ecosyst.* 18: 570–579.
- Haapkylä, J. et al. 2011. Seasonal rainfall and runoff promote coral disease on an inshore reef. – *PLoS One* 6: e16893.
- Haigh, M. J. 1980. Ruderal communities in English cities. – *Urban Ecol.* 4: 329–338.
- Hallett, L. M. et al. 2013. Towards a conceptual framework for novel ecosystems. – In: Hobbs, R. J. et al. (eds), *Novel ecosystems: intervening in the new ecological world order*. Wiley, pp. 16–28.
- Halpern, B. S. et al. 2015. Spatial and temporal changes in cumulative human impacts on the world's ocean. – *Nat. Commun.* 6: 7615.
- Han, T. et al. 2008. Physiological responses of *Ulva pertusa* and *U. armoricana* to copper exposure. – *Aquat. Toxicol.* 86: 176–184.
- Harper, G. J. et al. 2007. Fifty years of deforestation and forest fragmentation in Madagascar. – *Environ. Conserv.* 34: 325–333.
- Hastings, K. et al. 1995. Seagrass loss associated with boat moorings at Rottneest Island, Western Australia. – *Ocean Coast. Manage.* 26: 225–246.
- Hauser, L. et al. 2002. Loss of microsatellite diversity and low effective population size in an overexploited population of New Zealand snapper (*Pagrus auratus*). – *Proc. Natl Acad. Sci. USA* 99: 11742–11747.
- Hayes, A. L. et al. 2018. The role of scientific expertise in local adaptation to projected sea level rise. – *Environ. Sci. Pol.* 87: 55–63.
- Heath, C. B. and Perrin, W. F. 2009. California, Galapagos and Japanese sea lions: *Zalophus californianus*, *Z. wolfebaeki* and *Z. japonicus*. – In: Perrin, W. F. et al. (eds), *Encyclopedia of marine mammals*, 2nd edn. Elsevier/Academic Press, Amsterdam, pp. 170–176.
- Heatherington, C. and Bishop, M. J. 2012. Spatial variation in the structure of mangrove forests with respect to seawalls. – *Mar. Freshwater Res.* 63: 926–933.
- Hedge, L. H. et al. 2017. Uncovering hidden heterogeneity: geostatistical models illuminate the fine scale effects of boating infrastructure on sediment characteristics and contaminants. – *Mar. Poll. Bull.* 119: 143–150.
- Heery, E. C. 2018. Reduced macrofauna diversity and abundance in response to red macroalgal detritus. – *J. Exp. Mar. Biol. Ecol.* 505: 1–8.
- Heery, E. C. and Sebens, K. P. 2018. Artificial structures as a source of elevated detrital loads for sedimentary environments. – *Bull. Mar. Sci.* doi: 10.5343/bms.2017.1165.
- Heery, E. C. et al. 2017. Identifying the consequences of ocean sprawl for sedimentary habitats. – *J. Exp. Mar. Biol. Ecol.* 492: 31–48.
- Heery, E. C. et al. 2018a. Urban coral reefs: degradation and resilience of hard coral assemblages in coastal cities of East and Southeast Asia. – *Mar. Pollut. Bull.* 135: 654–681.
- Heery, E. C. et al. 2018b. Not all artificial structures are created equal: pilings linked to greater ecological and environmental change in sediment communities than seawalls. – *Mar. Environ. Res.* 142: 286–294.
- Heery, E. C. et al. 2018c. Urbanization-related distribution patterns and habitat-use by the marine mesopredator, giant Pacific octopus (*Enteroctopus dofleini*). – *Urban Ecosyst.* 21: 707–719.
- Heisler, J. et al. 2008. Eutrophication and harmful algal blooms: a scientific consensus. – *Harmful Algae* 8: 3–13.
- Heldt, K. A. et al. 2018. Increasing use of human-dominated habitats as CO₂ emissions warm and acidify oceans. – *Estuar. Coast.* 41: 1660–1666.
- Hellebrandt, D. 2008. Urbanisation, global market and informality: a case study of small-scale fisheries in Southern Brazil. – Short paper submitted to the 'Cities in an Insecure World' event, held by the Development Studies Association – DSA, London School of Economics – LSE, and Overseas Development Institute – ODI, on 15th November 2008 at LSE.
- Helmuth, B. S. T. and Hofmann, G. E. 2001. Microhabitats, thermal heterogeneity and patterns of physiological stress in the rocky intertidal zone. – *Biol. Bull.* 201: 374–384.
- Helmuth, B. S. T. et al. 2006. Mosaic patterns of thermal stress in the rocky intertidal zone: implications for climate change. – *Ecol. Monogr.* 76: 461–479.
- Hernández-Delgado, E. A. and Rosado-Matías, B. J. 2017. Long-lasting impacts of beach renourishment on nearshore urban coral reefs: a glimpse of future impacts of shoreline erosion,

- climate change and sea level rise. – *Ann. Mar. Biol. Res.* 4: 1021.
- Hewitt, J. E. et al. 2005. The importance of small-scale habitat structure for maintaining beta diversity. – *Ecology* 86: 1619–1626.
- Higgs, E. 2017. Novel and designed ecosystems. – *Restor. Ecol.* 25: 8–13.
- Hinkel, J. et al. 2014. Coastal flood damage and adaptation costs under 21st century sea-level rise. – *Proc. Natl Acad. Sci. USA* 111: 3292–3297.
- Hobbs, R. J. et al. 2014. Novel ecosystems: concept or inconvenient reality? A response to Murcia et al. – *Trends Ecol. Evol.* 29: 645–646.
- Hobbs, R. J. et al. 2018. Movers and stayers: novel assemblages in changing environments. – *Trends Ecol. Evol.* 33: 116–128.
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. – *Mar. Freshwater Res.* 50: 839–866.
- Hoegh-Guldberg, O. et al. 2017. Coral reef ecosystems under climate change and ocean acidification. – *Front Mar Sci.* 4: 158.
- Hoffman, E. J. et al. 1983. Annual input of petroleum hydrocarbons to the coastal environment via urban runoff. – *CJFAS* 40: s41–s53.
- Hölker, F. et al. 2010. The dark side of light: a transdisciplinary research agenda for light pollution policy. – *Ecol. Soc.* 15: 13.
- Holland, P. and Woodruff, A. 2006. Managing non living resources in the Pacific through economics. 23rd Science, Technology and Resources Network (STAR) Conference, Honiara, Solomon Islands. – SOPAC Secretariat, Fiji Islands.
- Holway, D. A. and Suarez, A. V. 2006. Homogenization of ant communities in mediterranean California: the effects of urbanization and invasion. – *Biol. Conserv.* 127: 319–326.
- Hoogenboom, M. O. et al. 2008. Interactions between morphological and physiological plasticity optimize energy acquisition in corals. – *Ecology* 89: 1144–1154.
- Hooper, T. and Austen, M. 2013. Tidal barrages in the UK: ecological and social impacts, potential mitigation and tools to support barrage planning. – *Renew. Sust. Energ. Rev.* 23: 289–298.
- Houghton, J. et al. 2015. The relationship between vessel traffic and noise levels received by killer whales (*Orcinus orca*). – *PLoS One* 10: e0140119.
- Howarth, R. et al. 2011. Coupled biogeochemical cycles: eutrophication and hypoxia in temperate estuaries and coastal marine ecosystems. – *Front. Ecol. Environ.* 9: 18–26.
- Hunter Jr, M. L. and Gibbs, J. P. 2007. Fundamentals of conservation biology. – Blackwell, p. 497.
- Inglis, G. J. and Kross, J. E. 2000. Evidence for systemic changes in the benthic fauna of tropical estuaries as a result of urbanization. – *Mar. Pollut. Bull.* 41: 367–376.
- Islam, M. S. and Tanaka, M. 2004. Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis. – *Mar. Pollut. Bull.* 48: 624–649.
- Iveša, L. et al. 2010. Differential patterns of distribution of limpets on intertidal seawalls: experimental investigation of the roles of recruitment, survival and competition. – *Mar. Ecol. Prog. Ser.* 407: 55–69.
- Jackson, J. B. 2008. Ecological extinction and evolution in the brave new ocean. – *Proc. Natl Acad. Sci. USA* 105: 11458–11465.
- Jackson, J. B. et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. – *Science* 293: 629–637.
- Jartun, M. and Pettersen, A. 2010. Contaminants in urban runoff to Norwegian fjords. – *J. Soils Sediments* 10: 155–161.
- Jartun, M. et al. 2008. Runoff of particle bound pollutants from urban impervious surfaces studied by analysis of sediments from stormwater traps. – *Sci. Total Environ.* 396: 147–163.
- Jartun, M. et al. 2009. Painted surfaces—important sources of polychlorinated biphenyls (PCBs) contamination to the urban and marine environment. – *Environ. Pollut.* 157: 295–302.
- Jensen, N. et al. 2014. Adaptive maternal and paternal effects: gamete plasticity in response to parental stress. – *Funct. Ecol.* 28: 724–733.
- Jia, A. et al. 2011. Occurrence and source apportionment of sulfonamides and their metabolites in Liaodong Bay and the adjacent Liao River Basin, North China. – *Environ. Toxicol. Chem.* 30: 1252–1260.
- Jiang, S. et al. 2001a. Human adenoviruses and coliphages in urban runoff-impacted coastal waters of southern California. – *Appl. Environ. Microb.* 67: 179–184.
- Jiang, Y. et al. 2001b. Megacity development: managing impacts on marine environments. – *Ocean Coast. Manage.* 44: 293–318.
- Johnson, M. T. J. and Munshi-South, J. 2017. Evolution of life in urban environments. – *Science* 358: eaam8327.
- Johnston, E. L. and Keough, M. J. 2000. Field assessment of effects of timing and frequency of copper pulses on settlement of sessile marine invertebrates. – *Mar. Biol.* 137: 1017–1029.
- Johnston, E. L. et al. 2011. Bearing the burden of boat harbours: heavy contaminant and fouling loads in a native habitat-forming alga. – *Mar. Pollut. Bull.* 62: 2137–2144.
- Johnston, E. L. et al. 2015. Chemical contaminant effects on marine ecosystem functioning. – *J. Appl. Ecol.* 52: 140–149.
- Jones, M. M. 1995. Fishing debris in the Australian marine environment. – *Mar. Pollut. Bull.* 30: 25–33.
- Jones, K. W. et al. 2001. Dredged material decontamination demonstration for the port of New York/New Jersey. – *J. Hazard. Mater.* 85: 127–143.
- Junjie, R. K. et al. 2014. Impacts of sediments on coral energetics: partitioning the effects of turbidity and settling particles. – *PLoS One* 9: e107195.
- Katsanevakis, S. and Verriopoulos, G. 2004. Den ecology of *Octopus vulgaris* Cuvier, 1797, on soft sediment: availability and types of shelter. – *Sci. Mar.* 68: 147–157.
- Katsanevakis, S. et al. 2007. Effect of marine litter on the benthic megafauna of coastal soft bottoms: a manipulative field experiment. – *Mar. Pollut. Bull.* 54: 771–778.
- Kelly, R. P. et al. 2016. Genetic signatures of ecological diversity along an urbanization gradient. – *PeerJ* 4: e2444.
- Kemp, W. M. et al. 2005. Eutrophication of Chesapeake Bay: historical trends and ecological interactions. – *Mar. Ecol. Prog. Ser.* 303: 1–29.
- Kennish, M. J. 1997. Pollution impacts on marine biotic communities. – CRC Press.
- Kennish, M. J. 2002. Environmental threats and environmental future of estuaries. – *Environ. Conserv.* 29: 78–107.
- Khan, M. I. and Islam, M. R. 2008. Sustainable management techniques for offshore oil and gas operations. – *Energ. Sour. Part B* 3: 121–132.
- Kirby, M. X. 2004. Fishing down the coast: historical expansion and collapse of oyster fisheries along continental margins. – *Proc. Natl Acad. Sci. USA* 101: 13096–13099.
- Klein, J. C. et al. 2011. Urban structures provide new insights into interactions among grazers and habitat. – *Ecol. Appl.* 21: 427–438.

- Knott, N. A. et al. 2004. Epibiota on vertical and on horizontal surfaces on natural reefs and on artificial structures. – *J. Mar. Biol. Assoc. UK* 84: 1117–1130.
- Knott, N. A. et al. 2009. Contemporary ecological threats from historical pollution sources: impacts of large-scale resuspension of contaminated sediments on sessile invertebrate recruitment. – *J. Appl. Ecol.* 46: 770–781.
- Konishi, H. 2000. Formation of hub cities: transportation cost advantage and population agglomeration. – *J. Urban Econ.* 48: 1–28.
- Kornis, M. S. et al. 2017. Linking the abundance of estuarine fish and crustaceans in nearshore waters to shoreline hardening and land cover. – *Estuar. Coast.* 40: 1464–1486.
- Korringa, P. 1946. The decline of natural oyster beds. – *Basteria* 10: 36–41.
- Kueffer, C. and Kaiser-Bunbury, C. N. 2014. Reconciling conflicting perspectives for biodiversity conservation in the Anthropocene. – *Front. Ecol. Environ.* 12: 131–137.
- Kyttä, M. et al. 2013. Towards contextually sensitive urban densification: location-based softGIS knowledge revealing perceived residential environmental quality. – *Landscape Urban Plan.* 113: 30–46.
- Lai, S. et al. 2015. The effects of urbanisation on coastal habitats and the potential for ecological engineering: a Singapore case study. – *Ocean Coast. Manage.* 103: 78–85.
- Lai, S. et al. 2018. Biodiversity surveys and stable isotope analyses reveal key differences in intertidal communities between tropical seawalls and rocky shores. – *Mar. Ecol. Prog. Ser.* 587: 41–53.
- Laist, D. 1997. Impacts of marine debris: entanglement of marine life in marine debris including a comprehensive list of species with entanglement and ingestion records. – In: Coe, J. M. and Rogers, D. B. (eds), *Marine debris: sources, impacts and solutions*. Springer, pp. 99–139.
- Lam, N. W. Y. et al. 2009. Variations in intertidal assemblages and zonation patterns between vertical artificial seawalls and natural rocky shores: a case study from Victoria Harbour, Hong Kong. – *Zool. Studies* 48: 184–195.
- Lamb, J. B. et al. 2018. Plastic waste associated with disease on coral reefs. – *Science* 359: 460–462.
- Lambert, C. C. and Lambert, G. 1998. Non-indigenous ascidians in southern California harbors and marinas. – *Mar. Biol.* 130: 675–688.
- Lambert, C. C. and Lambert, G. 2003. Persistence and differential distribution of nonindigenous ascidians in harbors of the Southern California Bight. – *Mar. Ecol. Prog. Ser.* 259: 145–161.
- Langston, W. J. 2017. Toxic effects of metals and the incidence of metal pollution in marine ecosystems. – In: Furness, R. W. and Rainbow, P. S. (eds), *Heavy metals in the marine environment*. CRC Press, pp. 101–120.
- Lapointe, B. E. et al. 2005. Macroalgal blooms on southeast Florida coral reefs: II. Cross-shelf discrimination of nitrogen sources indicates widespread assimilation of sewage nitrogen. – *Harmful Algae* 4: 1106–1122.
- Lattemann, S. and Höpner, T. 2008. Environmental impact and impact assessment of seawater desalination. – *Desalination* 220: 1–15.
- Lee, S. Y. et al. 2006. Impact of urbanization on coastal wetland structure and function. – *Austral Ecol.* 31: 149–163.
- Lemay, M. H. 1998. Coastal and marine resources management in Latin America and the Caribbean. Technical study, December 1998 – No ENV-129. – Environment Division, Sustainable Development Department, Inter-American Development Bank, Washington, D.C.
- Lenihan, H. S. and Peterson, C. H. 1998. How habitat degradation through fishery disturbance enhances impacts of hypoxia on oyster reefs. – *Ecol. Appl.* 8: 128–140.
- Leslie, H. M. et al. 2005. Barnacle reproductive hotspots linked to nearshore ocean conditions. – *Proc. Natl Acad. Sci. USA* 102: 10534–10539.
- Li, H. 2003. Management of coastal mega-cities – a new challenge in the 21st century. – *Mar. Policy* 27: 333–337.
- Lindgarth, M. and Hoskin, M. 2001. Patterns of distribution of macro-fauna in different types of estuarine, soft sediment habitats adjacent to urban and non-urban areas. – *Estuar. Coast. Shelf Sci.* 52: 237–247.
- Ling, S. D. et al. 2018. Pollution signature for temperate reef biodiversity is short and simple. – *Mar. Pollut. Bull.* 130: 159–169.
- Liu, J. et al. 2007. Complexity of coupled human and natural systems. – *Science* 317: 1513–1516.
- Loke, L. H. L. and Todd, P. A. 2016. Structural complexity and component type increase intertidal biodiversity independently of area. – *Ecology* 97: 383–393.
- Loke, L. H. L. et al. 2014. Complexity for artificial substrates (CASU): software for creating and visualising habitat complexity. – *PLoS One* 9: e87990.
- Loke, L. H. L. et al. 2017. The effects of manipulating microhabitat size and variability on tropical seawall biodiversity: field and flume experiments. – *J. Exp. Mar. Biol. Ecol.* 492: 113–120.
- Loke, L. H. L. et al. 2019a. Chapter 29: shoreline defences. – In: Sheppard, C. (ed.), *World seas: an environmental evaluation, Vol III: ecological issues and environmental impacts*, 2nd edn. Elsevier.
- Loke, L. H. L. et al. 2019b. Area-independent effects of water-retaining features on intertidal biodiversity on eco-engineered seawalls in the tropics. – *Front. Mar. Sci.* 6: 16.
- Loke, L. H. L. et al. 2019c. Effects of habitat area and spatial configuration on biodiversity in an experimental intertidal community. – *Ecology* <<https://doi.org/10.1002/ecy.2757>>.
- Long, E. R. et al. 1995. Incidence of adverse biological effects within ranges of chemical concentrations in marine and estuarine sediments. – *Environ. Manage.* 19: 81–97.
- López-Barea, J. and Pueyo, C. 1998. Mutagen content and metabolic activation of promutagens by molluscs as biomarkers of marine pollution. – *Mutat. Res. Fund. Mol. M.* 399: 3–15.
- Lotze, H. K. et al. 2005. Human transformations of the Wadden Sea ecosystem through time: a synthesis. – *Helgol. Mar. Res.* 59: 84–95.
- Lotze, H. K. et al. 2006. Depletion degradation, and recovery potential of estuaries and coastal seas. – *Science* 312: 1806–1809.
- Lotze, H. K. et al. 2018. Public perceptions of marine threats and protection from around the world. – *Ocean Coast. Manage.* 152: 14–22.
- Lovelock, C. E. et al. 2015. The vulnerability of Indo-Pacific mangrove forests to sea-level rise. – *Nature* 526: 559–563.
- Ma, X. L. et al. 2000. Effect of pollution on genetic diversity in the bay mussel *Mytilus galloprovincialis* and the acorn barnacle *Balanus glandula*. – *Mar. Environ. Res.* 50: 559–563.
- Maas, D. L. et al. 2018. Rapid divergence of mussel populations despite incomplete barriers to dispersal. – *Mol. Ecol.* 27: 1556–1571.
- Macreadie, P. I. et al. 2011. Rigs-to-reefs: will the deep sea benefit from artificial habitat? – *Front. Ecol. Environ.* 9: 455–461.

- Macura, B. et al. 2019. Impact of structural habitat modifications in coastal temperate systems on fish recruitment: a systematic review. – *Environ. Evidence* 8: 14.
- Mallin, M. A. et al. 1993. Regulation of estuarine primary production by watershed rainfall and river flow. – *Mar. Ecol. Prog. Ser.* 93: 199–199.
- Maltagliati, F. 2002. Genetic monitoring of brackish-water populations: the Mediterranean toothcarp, *Aphanius fasciatus* (Cyprinodontidae), as a model. – *Mar. Ecol. Prog. Ser.* 235: 257–262.
- Mannino, A. and Montagna, P. A. 1997. Small-scale spatial variation of macrobenthic community structure. – *Estuaries* 20: 159–173.
- Marcial Gomes, N. C. et al. 2008. Exploring the diversity of bacterial communities in sediments of urban mangrove forests. – *FEMS Microbiol. Ecol.* 66: 96–109.
- Märkl, V. et al. 2017. Effect of leached cement paste samples with different superplasticiser content on germination and initial root growth of white mustard (*Sinapis alba*) and cress (*Lepidium sativum*). – *Water Air Soil Pollut.* 228: 111.
- Marshall, D. J. 2008. Transgenerational plasticity in the sea: context-dependent maternal effects across the life history. – *Ecology* 89: 418–427.
- Marshall, D. J. et al. 2010. Non-climatic thermal adaptation: implications for species' responses to climate warming. – *Biol. Lett.* 6: 669–673.
- Martin, D. et al. 2005. Ecological impact of coastal defence structures on sediment and mobile fauna: evaluating and forecasting consequences of unavoidable modifications of native habitats. – *Coast. Eng.* 52: 1027–1051.
- Martinuzzi, S. et al. 2009. Conversion and recovery of Puerto Rican mangroves: 200 years of change. – *For. Ecol. Manage.* 257: 75–84.
- Marzinelli, E. M. et al. 2009. Do modified habitats have direct or indirect effects on epifauna? – *Ecology* 90: 2948–2955.
- Marzinelli, E. M. et al. 2018. Coastal urbanisation affects microbial communities on a dominant marine holobiont. – *NPJ Biofilms Microbiomes* 4: 1.
- Mayer-Pinto, M. et al. 2015. Sydney Harbour: a review of anthropogenic impacts on the biodiversity and ecosystem function of one of the world's largest natural harbours. – *Mar. Freshwater Res.* 66: 1088–1105.
- Mayer-Pinto, M. et al. 2017. Building 'blue': an eco-engineering framework for foreshore developments. – *J. Environ. Manage.* 189: 109–114.
- Mayer-Pinto, M. et al. 2018. Artificial structures alter kelp functioning across an urbanised estuary. – *Mar. Environ. Res.* 139: 136–143.
- McClelland, J. W. et al. 1997. Nitrogen-stable isotope signatures in estuarine food webs: a record of increasing urbanization in coastal watersheds. – *Limnol. Oceanogr.* 42: 930–937.
- McGlathery, K. J. 2001. Macroalgal blooms contribute to the decline of seagrass in nutrient-enriched coastal waters. – *J. Phycol.* 37: 453–456.
- McGranahan, G. et al. 2007. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. – *Environ. Urban.* 19: 17–37.
- McKenzie, L. A. et al. 2011. Heritable pollution tolerance in a marine invader. – *Environ. Res.* 111: 926–932.
- McKenzie, L. A. et al. 2012. A widespread contaminant enhances invasion success of a marine invader. – *J. Appl. Ecol.* 49: 767–773.
- McKinney, M. L. 2002. Urbanization, biodiversity and conservation: the impacts of urbanization on native species are poorly studied, but educating a highly urbanized human population about these impacts can greatly improve species conservation in all ecosystems. – *Bioscience* 52: 883–890.
- McKinney, M. L. 2006. Urbanization as a major cause of biotic homogenization. – *Biol. Conserv.* 127: 247–260.
- McKinney, M. L. and Lockwood, J. L. 1999. Biotic homogenization: a few winners replacing many losers in the next mass extinction. – *Trends Ecol. Evol.* 14: 450–453.
- McMillan, A. M. et al. 2006. Genetic diversity and structure of an estuarine fish (*Fundulus heteroclitus*) indigenous to sites associated with a highly contaminated urban harbor. – *Ecotoxicology* 15: 539.
- McPhearson, T. et al. 2016. Advancing urban ecology toward a science of cities. – *BioScience* 66: 198–212.
- Mecali, A. et al. 2018. Episodic records of jellyfish ingestion of plastic items reveal a novel pathway for trophic transference of marine litter. – *Sci. Rep.* 8: 6105.
- Medeiros, P. M. et al. 2005. Natural and anthropogenic hydrocarbon inputs to sediments of Patos Lagoon Estuary, Brazil. – *Environ. Int.* 31: 77–87.
- Medina, M. H. et al. 2007. Micro-evolution due to pollution: possible consequences for ecosystem responses to toxic stress. – *Chemosphere* 67: 2105–2114.
- Middel, H. and Verones, F. 2017. Making marine noise pollution impacts heard: the case of cetaceans in the North Sea within life cycle impact assessment. – *Sustainability* 9: 1138.
- Minca, C. 1995. Urban waterfront evolution: the case of Trieste. – *Geography* 80: 225–234.
- Mineur, F. et al. 2012. Changing coasts: marine aliens and artificial structures. – In: Gibson, R. N. et al. (eds), *Oceanography and marine biology*. CRC Press, pp. 198–243.
- Miranda, A. C. et al. 2013. Urbanization and its effects on personality traits: a result of microevolution or phenotypic plasticity?. – *Global Change Biol.* 19: 2634–2644.
- Mitsch, W. J. 2012. What is ecological engineering? – *Ecol. Eng.* 45: 5–12.
- Möllmann, C. et al. 2015. Marine regime shifts around the globe: theory, drivers and impacts. – *Phil. Trans. R. Soc. B* 370: 20130260.
- Monbet, Y. 1992. Control of phytoplankton biomass in estuaries: a comparative analysis of microtidal and macrotidal estuaries. – *Estuaries* 15: 563–571.
- Moore, C. J. 2008. Synthetic polymers in the marine environment: a rapidly increasing, long-term threat. – *Environ. Res.* 108: 131–139.
- Moore, K. A. et al. 2014. Impacts of varying estuarine temperature and light conditions on *Zostera marina* (Eelgrass) and its interactions with *Ruppia maritima* (Widgeongrass). – *Estuar. Coast.* 37: 20–30.
- Moraga, D. and Tanguy, A. 2000. Genetic indicators of herbicide stress in the Pacific oyster *Crassostrea gigas* under experimental conditions. – *Environ. Toxicol. Chem.* 19: 706–711.
- Moreira, J. et al. 2007. Maintenance of chitons on seawalls using crevices on sandstone blocks as habitat in Sydney Harbour, Australia. – *J. Exp. Mar. Biol. Ecol.* 347: 134–143.
- Morris, R. L. et al. 2016. Eco-engineering in urbanised coastal systems: consideration of social values. – *Ecol. Manage. Restor.* 17: 33–39.
- Morris, R. L. et al. 2019. Design options, implementation issues and evaluating success of ecologically-engineered shorelines. – *Oceanogr. Mar. Biol. Annu. Rev.* 57: 137–196.

- Morse, N. B. et al. 2014. Novel ecosystems in the Anthropocene: a revision of the novel ecosystem concept for pragmatic applications. – *Ecol. Soc.* 19: 12.
- Moschella, P. S. et al. 2005. Low-crested coastal defence structures as artificial habitats for marine life: using ecological criteria in design. – *Coast. Eng.* 52: 1053–1071.
- Moser, M. L. and Lee, D. S. 1992. A fourteen-year survey of plastic ingestion by western North Atlantic seabirds. – *Colon. Waterbird.* 15: 83–94.
- Mosher, J. I. 1972. The responses of *Macoma balthica* (Bivalvia) to vibrations. – *J. Mollus. Stud.* 40: 125–131.
- Mucha, A. P. et al. 2003. Macrobenthic community in the Douro estuary: relations with trace metals and natural sediment characteristics. – *Environ. Pollut.* 121: 169–180.
- Munari, C. 2013. Benthic community and biological trait composition in respect to artificial coastal defence structures: a study case in the northern Adriatic Sea. – *Mar. Environ. Res.* 90: 47–54.
- Munsch, S. H. et al. 2015. Effects of shoreline engineering on shallow subtidal fish and crab communities in an urban estuary: a comparison of armored shorelines and nourished beaches. – *Ecol. Eng.* 81: 312–320.
- Munsch, S. H. et al. 2017. Effects of shoreline armouring and over-water structures on coastal and estuarine fish: opportunities for habitat improvement. – *J. Appl. Ecol.* 54: 1373–1384.
- Murcia, C. et al. 2014. A critique of the 'novel ecosystem' concept. – *Trends Ecol. Evol.* 29: 548–553.
- Myers, R. A. et al. 2007. Cascading effects of the loss of apex predatory sharks from a coastal ocean. – *Science* 315: 1846–1850.
- Nacci, D. et al. 1999. Adaptations of wild populations of the estuarine fish *Fundulus heteroclitus* to persistent environmental contaminants. – *Mar. Biol.* 134: 9–17.
- Navarro-Barranco, C. and Hughes, L. E. 2015. Effects of light pollution on the emergent fauna of shallow marine ecosystems: amphipods as a case study. – *Mar. Pollut. Bull.* 94: 235–240.
- Neo, M. L. and Todd, P. A. 2012. Population density and genetic structure of the giant clams *Tridacna crocea* and *T. squamosa* on Singapore's reefs. – *Aquatic Biol.* 14: 265–275.
- Neo, M. L. et al. 2017. Giant clams (Bivalvia: Cardiidae: Tridacninae): a comprehensive update of species and their distribution, current threats and conservation status. – *Oceanogr. Mar. Biol. Annu. Rev.* 55: 87–388.
- Neumann, B. et al. 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding – a global assessment. – *PLoS One* 10: e0118571.
- Nevo, E. et al. 1986. Genetic diversity and resistance to marine pollution. – *Biol. J. Linn. Soc.* 29: 139–144.
- Ng, W. S. and Mendelsohn, R. 2005. The impact of sea level rise on Singapore. – *Environ. Dev. Econ.* 10: 201–215.
- Ng, A. K. Y. and Song, S. 2010. The environmental impacts of pollutants generated by routine shipping operations on ports. – *Ocean Coast. Manage.* 53: 301–311.
- Ng, T. P. et al. 2017. Linking behaviour and climate change in intertidal ectotherms: insights from littorinid snails. – *J. Exp. Mar. Biol. Ecol.* 492: 121–131.
- Nicholls, R. J. 1995. Coastal megacities and climate change. – *GeoJournal* 37: 369–379.
- Nicholls, R. J. et al. 2013. Cost of adaptation to rising coastal water levels for the People's Republic of China, Japan and the Republic of Korea. – Asian Development Bank (2013), Mandaluyong City, Philippines.
- Nixon, S. W. 1995. Coastal marine eutrophication: a definition, social causes and future concerns. – *Ophelia* 41: 199–219.
- Nogueira, V. L. et al. 2015. Microbiomes and potential metabolic pathways of pristine and anthropized Brazilian mangroves. – *Reg. Stud. Mar. Sci.* 2: 56–64.
- Nyström, M. et al. 2012. Confronting feedbacks of degraded marine ecosystems. – *Ecosystems* 15: 695–710.
- O'Brien, A. L. et al. 2019. After decades of stressor research in urban estuarine ecosystems the focus is still on single stressors: a systematic literature review and meta-analysis. – *Sci. Total Environ.* doi: 10.1016/j.scitotenv.2019.02.131.
- Olden, J. D. and Rooney, T. P. 2006. On defining and quantifying biotic homogenization. – *Global Ecol. Biogeogr.* 15: 113–120.
- Olden, J. D. et al. 2008. Species invasions and the changing biogeography of Australian freshwater fishes. – *Global Ecol. Biogeogr.* 17: 25–37.
- Orth, R. J. et al. 2017. Submersed aquatic vegetation in Chesapeake Bay: sentinel species in a changing world. – *Bioscience* 67: 698–712.
- Osborne, K. L. et al. 2018. Differential copper toxicity in invasive and native ascidians of New England provides support for enhanced invader tolerance. – *Mar. Ecol. Prog. Ser.* 595: 135–147.
- Ow, Y. X. and Todd, P. A. 2010. Light-induced morphological plasticity in the scleractinian coral *Goniastrea pectinata* and its functional significance. – *Coral Reefs* 29: 797–808.
- Paissé, S. et al. 2008. Structure of bacterial communities along a hydrocarbon contamination gradient in a coastal sediment. – *FEMS Microbiol. Ecol.* 66: 295–305.
- Palkovacs, E. P. et al. 2012. Fates beyond traits: ecological consequences of human-induced trait change. – *Evol. Appl.* 5: 183–191.
- Pandolfi, J. M. et al. 2003. Global trajectories of the long-term decline of coral reef ecosystems. – *Science* 301: 955–958.
- Pardecke, J. et al. 2006. Stress and the city: urbanization and its effects on the stress physiology in European blackbirds. – *Ecology* 87: 1945–1952.
- Pauly, D. 1995. Anecdotes and the shifting baseline syndrome of fisheries. – *Trends Ecol. Evol.* 10: 430.
- Pearson, T. H. and Rosenberg, R. 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. – *Oceanogr. Mar. Biol. Annu. Rev.* 16: 229–311.
- Peng, C. et al. 2016. Effects of anthropogenic sound on digging behavior, metabolism, Ca²⁺/Mg²⁺ ATPase activity and metabolism-related gene expression of the bivalve *Sinonovacula constricta*. – *Sci. Rep.* 6: 24266.
- Pereira, W. E. et al. 1999. Sedimentary record of anthropogenic and biogenic polycyclic aromatic hydrocarbons in San Francisco Bay, California. – *Mar. Chem.* 64: 99–113.
- Perkins, M. J. et al. 2015. Conserving intertidal habitats: what is the potential of ecological engineering to mitigate impacts of coastal structures? – *Estuar. Coast. Shelf Sci.* 167: 504–515.
- Perkol-Finkel, S. and Benayahu, Y. 2004. Community structure of stony and soft corals on vertical unplanned artificial reefs in Eilat (Red Sea): comparison to natural reefs. – *Coral Reefs* 23: 195–205.
- Perrett, L. A. et al. 2006. Impact by association: direct and indirect effects of copper exposure on mobile invertebrate fauna. – *Mar. Ecol. Prog. Ser.* 326: 195–205.
- Peterson, C. H. and Bishop, M. J. 2005. Assessing the environmental impacts of beach nourishment. – *BioScience* 55: 887–896.
- Peterson, G. D. et al. 2003. Scenario planning: a tool for conservation in an uncertain world. – *Conserv. Biol.* 17: 358–366.

- Pethick, J. 2001. Coastal management and sea-level rise. – *Catena* 42: 307–322.
- Pickett, S. T. A. and Cadenasso, M. L. 2008. Linking ecological and built components of urban mosaics: an open cycle of ecological design. – *J. Ecol.* 96: 8–12.
- Pickett, S. T. A. et al. 1997. A conceptual framework for the study of human ecosystems in urban areas. – *Urban Ecosyst.* 1: 185–199.
- Pickett, S. T. A. et al. 2001. Urban ecological systems: linking terrestrial ecological, physical and socioeconomic components of metropolitan areas. – *Annu. Rev. Ecol. Syst.* 32: 127–157.
- Pickett, S. T. A. et al. 2011. Urban ecological systems: scientific foundations and a decade of progress. – *J. Environ. Manage.* 92: 331–362.
- Pickett, S. T. A. et al. 2017. Dynamic heterogeneity: a framework to promote ecological integration and hypothesis generation in urban systems. – *Urban Ecosyst.* 20: 1–14.
- Pinsky, M. L. and Palumbi, S. R. 2014. Meta-analysis reveals lower genetic diversity in overfished populations. – *Mol. Ecol.* 23: 29–39.
- Piola, R. F. and Johnston, E. L. 2006. Differential resistance to extended copper exposure in four introduced bryozoans. – *Mar. Ecol. Prog. Ser.* 311: 103–114.
- Piola, R. F. and Johnston, E. L. 2008. Pollution reduces native diversity and increases invader dominance in marine hard-substrate communities. – *Divers. Distrib.* 14: 329–342.
- Piola, R. F. et al. 2009. The influence of antifouling practices on marine invasions. – *Biofouling* 25: 633–644.
- Pister, B. 2009. Urban marine ecology in southern California: the ability of riprap structures to serve as rocky intertidal habitat. – *Mar. Biol.* 156: 861–873.
- Polidoro, B. A. et al. 2010. The loss of species: mangrove extinction risk and geographic areas of global concern. – *PLoS One* 5: e10095.
- Pontee, N. 2013. Defining coastal squeeze: a discussion. – *Ocean Coast. Manage.* 84: 204–207.
- Pontee, N. et al. 2016. Nature-based solutions: lessons from around the world. – *Proc. Inst. Civil Eng. Mar. Eng.* 169: 29–36.
- Poquita-Du, R. C. et al. 2019. Last species standing: loss of Pocilloporidae corals associated with coastal urbanization in a tropical city state. – *Mar. Biodiv.* doi: 10.1007/s12526-019-00939-x.
- Portman, M. E. et al. 2011. The connection between fisheries resources and spatial land use change: the case of two New England fish ports. – *Land Use Policy* 28: 523–533.
- Portmann, J. E. 1975. The bioaccumulation and effects of organochlorine pesticides in marine animals. – *Proc. R. Soc. B* 189: 291–304.
- Poudyal, N. C. et al. 2011. Modeling the impact of changes in land use and socio-cultural patterns from urbanization on recreational fishing. – In: Turunen, E. and Koskinen, A. (eds) *Urbanization and the global environment*. Nova Science Publishers, Hauppauge, NY, pp. 163–180.
- Prins, T. C. et al. 1997. A review of the feedbacks between bivalve grazing and ecosystem processes. – *Aquat. Ecol.* 31: 349–359.
- Qiao, Y. et al. 2013. Distribution and geochemical speciation of heavy metals in sediments from coastal area suffered rapid urbanization, a case study of Shantou Bay, China. – *Mar. Pollut. Bull.* 68: 140–146.
- Rainbow, P. S. 2017. Heavy metal levels in marine invertebrates. In *Heavy metals in the marine environment*. – CRC Press, pp. 67–79.
- Ramachandran, S. et al. 1997. Effect of copper and cadmium on three Malaysian tropical estuarine invertebrate larvae. – *Ecotox. Environ. Safe.* 36: 183–188.
- Ramalho, C. E. and Hobbs, R. J. 2012. Time for a change: dynamic urban ecology. – *Trends Ecol. Evol.* 27: 179–188.
- Raven, J. A. and Taylor, R. 2003. Macroalgal growth in nutrient-enriched estuaries: a biogeochemical and evolutionary perspective. – *Water Air Soil Pollut.* 3: 7–26.
- Redding, J. E. et al. 2013. Link between sewage-derived nitrogen pollution and coral disease severity in Guam. – *Mar. Pollut. Bull.* 73: 57–63.
- Reguero, B. G. et al. 2018. Comparing the cost effectiveness of nature-based and coastal adaptation: a case study from the Gulf Coast of the United States. – *PLoS One* 13: e0192132.
- Reichelt-Brushett, A. J. and Harrison, P. L. 1999. The effect of copper, zinc and cadmium on fertilization success of gametes from scleractinian reef corals. – *Mar. Pollut. Bull.* 38: 182–187.
- Reichelt-Brushett, A. J. and Harrison, P. L. 2000. The effect of copper on the settlement success of larvae from the scleractinian coral *Acropora tenuis*. – *Mar. Pollut. Bull.* 41: 385–391.
- Reopanichkul, P. et al. 2009. Sewage impacts coral reefs at multiple levels of ecological organization. – *Mar. Pollut. Bull.* 58: 1356–1362.
- Richards, D. R. and Friess, D. A. 2016. Rates and drivers of mangrove deforestation in Southeast Asia, 2000–2012. – *Proc. Natl Acad. Sci. USA* 113: 344–349.
- Rilov, G. and Benayahu, Y. 2000. Fish assemblage on natural versus vertical artificial reefs: the rehabilitation perspective. – *Mar. Biol.* 136: 931–942.
- Rivero, N. K. et al. 2013. Environmental and ecological changes associated with a marina. – *Biofouling* 29: 803–815.
- Rizzo, L. et al. 2013. Urban wastewater treatment plants as hotspots for antibiotic resistant bacteria and genes spread into the environment: a review. – *Sci. Total Environ.* 447: 345–360.
- Roberts, D. A. et al. 2010. Impacts of desalination plant discharges on the marine environment: a critical review of published studies. – *Water Res.* 44: 5117–5128.
- Roberts, L. et al. 2015. Sensitivity of the mussel *Mytilus edulis* to substrate-borne vibration in relation to anthropogenically generated noise. – *Mar. Ecol. Prog. Ser.* 538: 185–195.
- Rodrigues, E. T. and Pardal, M. Á. 2015. Primary productivity temporal fluctuations in a nutrient-rich estuary due to climate-driven events. – *Estuaries Coast.* 38: 1–12.
- Rogers, C. S. 1990. Responses of coral reefs and reef organisms to sedimentation. – *Mar. Ecol. Prog. Ser.* 62: 182–202.
- Rose, J. M. et al. 2009. Occurrence and patterns of antibiotic resistance in vertebrates off the Northeastern United States coast. – *FEMS Microbiol. Ecol.* 67: 421–431.
- Rosenzweig, M. L. 2003a. Reconciliation ecology and the future of species diversity. – *Oryx* 37: 194–205.
- Rosenzweig, M. L. 2003b. Win-win ecology: how the earth's species can survive in the midst of human enterprise. – Oxford Univ. Press.
- Ruiz, G. M. et al. 1999. Non-indigenous species as stressors in estuarine and marine communities: assessing invasion impacts and interactions. – *Limnol. Oceanogr.* 44: 950–972.
- Ruiz, G. M. et al. 2000. Global spread of microorganisms by ships. – *Nature* 408: 49.
- Ruiz, G. M. et al. 2009. Habitat distribution and heterogeneity in marine invasion dynamics: the importance of hard substrate

- and artificial structure. – In: Wahl, M. (ed.), Patterns, dynamics, diversity and change. Springer, pp. 321–332.
- Russell, B. D. and Connell, S. D. 2005. A novel interaction between nutrients and grazers alters relative dominance of marine habitats. – *Mar. Ecol. Prog. Ser.* 289: 5–11.
- Rygg, B. 1985. Effect of sediment copper on benthic fauna. – *Mar. Ecol. Prog. Ser.* 25: 83–89.
- Sala, E. and Knowlton, N. 2006. Global marine biodiversity trends. – *Annu. Rev. Environ. Resour.* 31: 93–122.
- Sanford, E. and Kelly, M. W. 2011. Local adaptation in marine invertebrates. – *Annu. Rev. Mar. Sci.* 3: 509–535.
- Scheffer, M. et al. 2001. Catastrophic shifts in ecosystems. – *Nature* 413: 591–596.
- Scherner, F. et al. 2012. Photosynthetic response of two seaweed species along an urban pollution gradient: evidence of selection of pollution-tolerant species. – *Mar. Pollut. Bull.* 64: 2380–2390.
- Scherner, F. et al. 2013. Coastal urbanization leads to remarkable seaweed species loss and community shifts along the SW Atlantic. – *Mar. Pollut. Bull.* 76: 106–115.
- Schiff, K. et al. 2004. Copper emissions from antifouling paint on recreational vessels. – *Mar. Pollut. Bull.* 48: 371–377.
- Schiff, K. et al. 2007. Extent and magnitude of copper contamination in marinas of the San Diego region, California, USA. – *Mar. Pollut. Bull.* 54: 322–328.
- Schroeter, S. C. et al. 2015. Effects of reef physical structure on development of benthic reef community: a large-scale artificial reef experiment. – *Mar. Ecol. Prog. Ser.* 540: 43–55.
- Sefbom, J. et al. 2018. A planktonic diatom displays genetic structure over small spatial scales. – *Environ. Microbiol.* 20: 2783–2795.
- Seitz, R. D. et al. 2006. Influence of shallow-water habitats and shoreline development on abundance, biomass and diversity of benthic prey and predators in Chesapeake Bay. – *Mar. Ecol. Prog. Ser.* 326: 11–27.
- Sengupta, D. et al. 2018. Building beyond land: an overview of coastal land reclamation in 16 global megacities. – *Appl. Geogr.* 90: 229–238.
- Seto, K. C. et al. 2011. A meta-analysis of global urban land expansion. – *PLoS One* 6: e23777.
- Sew, G. et al. 2018. Effects of concentration and size of suspended particles on the ingestion, reproduction and mortality rates of the copepod, *Acartia tonsa*. – *Mar. Environ. Res.* 140: 251–264.
- Shazili, N. A. M. et al. 2006. Heavy metal pollution status in the Malaysian aquatic environment. – *Aquat. Ecosyst. Health* 9: 137–145.
- Sheehy, D. J. and Vik, S. F. 2010. The role of constructed reefs in non-indigenous species introductions and range expansions. – *Ecol. Eng.* 36: 1–11.
- Sheppard, C. 1995. The shifting baseline syndrome. – *Mar. Pollut. Bull.* 30: 766–767.
- Shibata, T. et al. 2004. Monitoring marine recreational water quality using multiple microbial indicators in an urban tropical environment. – *Water Res.* 38: 3119–3131.
- Sim, V. X. et al. 2015. Sediment contaminants and infauna associated with recreational boating structures in a multi-use marine park. – *PLoS One* 10: e0130537.
- Simkanin, C. et al. 2012. Anthropogenic structures and the infiltration of natural benthos by invasive ascidians. – *Mar. Ecol.* 33: 499–511.
- Slabbekoorn, H. et al. 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. – *Trends Ecol. Evol.* 25: 419–427.
- Small, C. and Nicholls, R. J. 2003. A global analysis of human settlement in coastal zones. – *J. Coast. Res.* 19: 584–599.
- Smit, J. E. et al. 2017. Unravelling complex interactions between urbanisation and coastal fisheries using a system dynamics approach. – In: Paper presented at the 5th system dynamics conference jointly hosted by the South African System Dynamics Chapter and Eskom Soc, Pretoria, 27–28 November 2017, Eskom Research and Innovation Centre, Rosherville, Johannesburg.
- Smith, P. J. et al. 1991. Loss of genetic diversity due to fishing pressure. – *Fish. Res.* 10: 309–316.
- Solan, M. et al. 2016. Anthropogenic sources of underwater sound can modify how sediment-dwelling invertebrates mediate ecosystem properties. – *Sci. Rep.* 6: 20540.
- Šolić, M. and Krstulović, N. 1992. Separate and combined effects of solar radiation, temperature, salinity and pH on the survival of faecal coliforms in seawater. – *Mar. Pollut. Bull.* 24: 411–416.
- Spalding, M. D. et al. 2014. The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. – *Ocean Coast. Manage.* 90: 50–57.
- Squires, D. F. 1992. Quantifying anthropogenic shoreline modification of the Hudson River and estuary from European contact to modern time. – *Coast. Manage.* 20: 343–354.
- Stark, J. S. 1998. Heavy metal pollution and macrobenthic assemblages in soft sediments in two Sydney estuaries, Australia. – *Mar. Freshwater Res.* 49: 533–540.
- Strain, E. M. A. et al. 2014. Identifying the interacting roles of stressors in driving the global loss of canopy-forming to mat-forming algae in marine ecosystems. – *Global Change Biol.* 20: 3300–3312.
- Strain, E. M. A. et al. 2018. Eco-engineering urban infrastructure for marine and coastal biodiversity: which interventions have the greatest ecological benefit?. – *J. Appl. Ecol.* 55: 426–441.
- Strain, E. M. A. et al. 2019. Urban blue: a global analysis of the factors shaping people's perceptions of the marine environment and ecological engineering in harbours. – *Sci. Total Environ.* 658: 1293–1305.
- Strand, J. and Asmund, G. 2003. Tributyltin accumulation and effects in marine molluscs from West Greenland. – *Environ. Pollut.* 123: 31–37.
- Street, G. T. and Montagna, P. A. 1996. Loss of genetic diversity in Harpacticoida near offshore platforms. – *Mar. Biol.* 126: 271–282.
- Suarez-Ulloa, V. et al. 2015. Environmental epigenetics: a promising venue for developing next-generation pollution biomonitoring tools in marine invertebrates. – *Mar. Pollut. Bull.* 98: 5–13.
- Suchanek, T. H. 1993. Oil impacts on marine invertebrate populations and communities. – *Am. Zool.* 33: 510–523.
- Sun, M. Y. et al. 2012. Bacterial communities are sensitive indicators of contaminant stress. – *Mar. Pollut. Bull.* 64: 1029–1038.
- Sun, P. Y. et al. 2014. Acclimation and adaptation to common marine pollutants in the copepod *Tigriopus californicus*. – *Chemosphere* 112: 465–471.
- Sunda, W. G. et al. 2006. Positive feedback and the development and persistence of ecosystem disruptive algal blooms 1. – *J. Phycol.* 42: 963–974.
- Swartz, W. et al. 2010. The spatial expansion and ecological footprint of fisheries (1950 to present). – *PLoS One* 5: e15143.
- Tan, W. T. et al. 2018. Do Singapore's seawalls host non-native marine molluscs? – *Aquat. Invas.* 13: 365–378.
- Tanabe, S. 1988. PCB problems in the future: foresight from current knowledge. – *Environ. Pollut.* 50: 5–28.

- Tayeb, A. et al. 2015. Impact of urban and industrial effluents on the coastal marine environment in Oran, Algeria. – *Mar. Pollut. Bull.* 98: 281–288.
- Teixeira et al. 2016. Effects of urbanization and the sustainability of marine artisanal fishing: a study on tropical fishing communities in Brazil. – In: Ergen, M. (ed.), *Sustainable urbanization*. Intech Open, pp. 87–114.
- Temmerman, S. et al. 2013. Ecosystem-based coastal defence in the face of global change. – *Nature* 504: 79.
- Terrados, J. et al. 1998. Changes in community structure and biomass of seagrass communities along gradients of siltation in SE Asia. – *Estuar. Coast.* 46: 757–768.
- Thompson, R. C. et al. 2004. Lost at sea: where is all the plastic? – *Science* 304: 838–838.
- Thurstan, R. H. et al. 2010. The effects of 118 years of industrial fishing on UK bottom trawl fisheries. – *Nat. Commun.* 1: 15.
- Thurstan, R. H. et al. 2013. Oyster (*Ostrea edulis*) extirpation and ecosystem transformation in the Firth of Forth, Scotland. – *J. Nat. Conserv.* 21: 253–261.
- Tian, B. et al. 2016. Drivers, trends and potential impacts of long-term coastal reclamation in China from 1985 to 2010. – *Estuar. Coast. Shelf Sci.* 170: 83–90.
- Todd, P. A. 2008. Morphological plasticity in scleractinian corals. – *Biol. Rev.* 83: 315–337.
- Todd, P. A. and Chou, L. M. 2005. A tale of survival: Labrador Park, Singapore. – *Coral Reefs* 24: 391–391.
- Todd, P. A. et al. 2003. Plastic corals from Singapore: 1. – *Coral Reefs* 22: 306–306.
- Todd, P. A. et al. 2004. Genotype × environment interactions in transplanted clones of the massive corals *Favia speciosa* and *Diploastrea heliophora*. – *Mar. Ecol. Prog. Ser.* 271: 167–182.
- Todd, P. A. et al. 2010. Impacts of pollution on marine life in Southeast Asia. – *Biodivers. Conserv.* 19: 1063–1082.
- Toft, J. D. et al. 2007. Fish distribution, abundance and behavior along city shoreline types in Puget Sound. – *N. Am. J. Fish. Manage.* 27: 465–480.
- Toft, J. D. et al. 2013. Ecological response and physical stability of habitat enhancements along an urban armored shoreline. – *Ecol. Eng.* 57: 97–108.
- Tolosa, I. et al. 2004. Aliphatic and aromatic hydrocarbons in coastal Caspian Sea sediments. – *Mar. Pollut. Bull.* 48: 44–60.
- Toohy, B. D. 2007. The relationship between physical variables on topographically simple and complex reefs and algal assemblage structure beneath an *Ecklonia radiata* canopy. – *Estuar. Coast. Shelf Sci.* 71: 232–240.
- Torio, D. D. and Chmura, G. L. 2013. Assessing coastal squeeze of tidal wetlands. – *J. Coast. Res.* 29: 1049–1061.
- Tornero, V. and Hanke, G. 2016. Chemical contaminants entering the marine environment from sea-based sources: a review with a focus on European seas. – *Mar. Pollut. Bull.* 112: 17–38.
- Trussell, G. C. 1997. Phenotypic plasticity in the foot size of an intertidal snail. – *Ecology* 78: 1033–1048.
- Turner, A. 2010. Marine pollution from antifouling paint particles. – *Mar. Pollut. Bull.* 60: 159–171.
- Ungherese, G. et al. 2010. Relationship between heavy metals pollution and genetic diversity in Mediterranean populations of the sandhopper *Talitrus saltator* (Montagu) (Crustacea, Amphipoda). – *Environ. Pollut.* 158: 1638–1643.
- United Nations, Department of Economic and Social Affairs, Population Division 2017. World population prospects: the 2017 revision, key findings and advance tables. – Working Paper No. ESA/P/WP/248.
- Urban, M. C. et al. 2006. Stream communities across a rural–urban landscape gradient. – *Divers. Distrib.* 12: 337–350.
- Valiela, I. et al. 1990. Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters. – *Biogeochemistry* 10: 177–197.
- Van Houtan, K. S. and Kittinger, J. N. 2014. Historical commercial exploitation and the current status of Hawaiian green turtles. – *Biol. Conserv.* 170: 20–27.
- Vargas-Fonseca, E. et al. 2016. Combined effects of urbanization and connectivity on iconic coastal fishes. – *Divers. Distrib.* 22: 1328–1341.
- Vaselli, S. et al. 2008. Hard coastal-defence structures as habitats for native and exotic rocky-bottom species. – *Mar. Environ. Res.* 66: 395–403.
- Verslycke, T. et al. 2003. The toxicity of metal mixtures to the estuarine mysid *Neomysis integer* (Crustacea: Mysidacea) under changing salinity. – *Aquat. Toxicol.* 64: 307–315.
- Vikas, M. and Dwarakish, G. S. 2015. Coastal pollution: a review. – *Aquat. Pr.* 4: 381–388.
- Virgilio, M. and Abbiati, M. 2004. Habitat discontinuity and genetic structure in populations of the estuarine species *Hediste diversicolor* (Polychaeta: Nereididae). – *Estuar. Coast.* 61: 361–367.
- Virgilio, M. et al. 2003. Relationships between sediments and tissue contamination and allozymic patterns in *Hediste diversicolor* (Polychaeta Nereididae) in the Pialassa lagoons (north Adriatic Sea). – *Oceanol. Acta* 26: 85–92.
- Wake, H. 2005. Oil refineries: a review of their ecological impacts on the aquatic environment. – *Estuar. Coast.* 62: 131–140.
- Wale, M. A. et al. 2013. Noise negatively affects foraging and anti-predator behaviour in shore crabs. – *Anim. Behav.* 86: 111–118.
- Walker, R. 2001. Industry builds the city: the suburbanization of manufacturing in the San Francisco Bay Area, 1850–1940. – *J. Hist. Geogr.* 27: 36–57.
- Wallace, J. M. et al. 2014. Global warming and winter weather. – *Science* 343: 729–730.
- Walsh, C. J. et al. 2012. Urban stormwater runoff: a new class of environmental flow problem. – *PLoS One* 7: e45814.
- Walsh, K. J. et al. 2016. Tropical cyclones and climate change. – *Wiley Interdiscip. Rev. Clim. Change* 7: 65–89.
- Waltham, N. J. et al. 2011. Contaminants in water, sediment and fish biomonitor species from natural and artificial estuarine habitats along the urbanized Gold Coast, Queensland. – *J. Environ. Monitor.* 13: 3409–3419.
- Ward, R. D. et al. 2016. Impacts of climate change on mangrove ecosystems: a region by region overview. – *Ecosyst. Health Sustain.* 2: e01211.
- Warnken, J. et al. 2004. Investigation of recreational boats as a source of copper at anchorage sites using time-integrated diffusive gradients in thin film and sediment measurements. – *Mar. Pollut. Bull.* 49: 833–843.
- Watkinson, A. J. et al. 2007. Antibiotic-resistant *Escherichia coli* in wastewaters, surface waters and oysters from an urban riverine system. – *Appl. Environ. Microb.* 73: 5667–5670.
- Waycott, M. et al. 2009. Accelerating loss of seagrasses across the globe threatens coastal ecosystems. – *Proc. Natl Acad. Sci. USA* 106: 12377–12381.
- Webb, A. P. 2005. Technical report – an assessment of coastal processes, impacts, erosion mitigation options and beach mining. Proj. Rep. 46, 47 pp., South Pac. Appl. Geosci. Comm., Suva.
- Weiffen, M. et al. 2006. Effect of water turbidity on the visual acuity of harbor seals (*Phoca vitulina*). – *Vision Res.* 46: 1777–1783.

- Weis, W. A. et al. 2017. Urbanization effects on different biological organization levels of an estuarine polychaete tolerant to pollution. – *Ecol. Indic.* 73: 698–707.
- Wells, S. and Ravilious, C. 2006. In the front line: shoreline protection and other ecosystem services from mangroves and coral reefs. – UNEP/Earthprint (No. 24).
- Wells, F. E. et al. 2019. A low number of introduced marine species in the tropics: a case study from Singapore. – *Manage. Biol. Invas.* 10: 23–45.
- West, N. 1989. Urban-waterfront developments: a geographic problem in search of a model. – *Geoforum* 20: 459–468.
- West-Eberhard, M. J. 1989. Phenotypic plasticity and the origins of diversity. – *Annu. Rev. Ecol. Evol. Syst.* 20: 249–278.
- Whittaker, R. J. and Heegaard, E. 2003. What is the observed relationship between species richness and productivity? Comment. – *Ecology* 84: 3384–3390.
- Wilberg, M. J. et al. 2011. Overfishing, disease, habitat loss and potential extirpation of oysters in upper Chesapeake Bay. – *Mar. Ecol. Prog. Ser.* 436: 131–144.
- Williams, G. A. and Morritt, D. 1995. Habitat partitioning and thermal tolerance in a tropical limpet, *Cellana grata*. – *Mar. Ecol. Prog. Ser.* 124: 89–103.
- Williams, I. D. et al. 2008. Assessing the importance of fishing impacts on Hawaiian coral reef fish assemblages along regional-scale human population gradients. – *Environ. Conserv.* 35: 261–272.
- Williams, I. D. et al. 2011. Differences in reef fish assemblages between populated and remote reefs spanning multiple archipelagos across the central and western Pacific. – *J. Mar. Biol.* 2011: 826234.
- Williamson, R. B. and Morrissey, D. J. 2000. Stormwater contamination of urban estuaries. 1. Predicting the build-up of heavy metals in sediments. – *Estuaries* 23: 56–66.
- Wolff, M. S. et al. 1993. Blood levels of organochlorine residues and risk of breast cancer. – *J. Natl Cancer Inst.* 85: 648–652.
- Wright, S. L. et al. 2013. The physical impacts of microplastics on marine organisms: a review. – *Environ. Pollut.* 178: 483–492.
- Wu, J. 2014. Urban ecology and sustainability: the state-of-the-science and future directions. – *Landscape Urban Plan.* 125: 209–221.
- Yaakub, S. M. et al. 2014a. Chronic light reduction reduces overall resilience to additional shading stress in the seagrass *Halophila ovalis*. – *Mar. Pollut. Bull.* 83: 467–474.
- Yaakub, S. M. et al. 2014b. Courage under fire: seagrass persistence adjacent to a highly urbanised city–state. – *Mar. Pollut. Bull.* 83: 417–424.
- Yeung, Y. M. 2001. Coastal mega-cities in Asia: transformation, sustainability and management. – *Ocean Coast. Manage.* 44: 319–333.
- Zaghden, H. et al. 2005. Hydrocarbons in surface sediments from the Sfax coastal zone, (Tunisia) Mediterranean Sea. – *Mar. Pollut. Bull.* 50: 1287–1294.
- Zhan, A. et al. 2015. Ascidiacs as models for studying invasion success. – *Mar. Biol.* 162: 2449–2470.
- Zhang, X. et al. 2010. Effects of landuse change on surface runoff and sediment yield at different watershed scales in the Loess Plateau. – *Int. J. Sediment Res.* 25: 283–293.
- Zhao, K. et al. 2019. Modelling surface temperature of granite seawalls in Singapore. – *Case Stud. Therm. Eng.* 13: 100395.
- Ziegler, M. et al. 2016. Coral microbial community dynamics in response to anthropogenic impacts near a major city in the central Red Sea. – *Mar. Pollut. Bull.* 105: 629–640.
- Zimmerman, A. R. and Canuel, E. A. 2000. A geochemical record of eutrophication and anoxia in Chesapeake Bay sediments: anthropogenic influence on organic matter composition. – *Mar. Chem.* 69: 117–137.
- Zimmerman, R. and Faris, C. 2010. Chapter 4: infrastructure impacts and adaptation challenges. – *Ann. N. Y. Acad. Sci.* 1196: 63–86.
- zu Ermgassen, P. S. et al. 2013. Quantifying the loss of a marine ecosystem service: filtration by the eastern oyster in US estuaries. – *Estuar. Coast.* 36: 36–43.