Application of management tools to integrate ecological principles with the design of marine infrastructure

Katherine Dafforn[1,2], Mariana Mayer Pinto[1,2], Rebecca Morris[3], Nathan Waltham[4]

[1]Evolution & Ecology Research Centre, University of New South Wales, Sydney, NSW 2052, Australia

[2]Sydney Institute of Marine Sciences, Mosman, NSW 2088, Australia

[3] Centre for Research on the Ecological Impacts of Coastal Cities, University of Sydney, Sydney, NSW 2006, Australia

[4]TropWATER, James Cook University, Townsville, QLD 4811, Australia

Corresponding author: Katherine Dafforn, +61 2 93858701, k.dafforn@unsw.edu.au, School of BEES, University of NSW, Sydney, NSW 2052, Australia.

Abstract

Globally the coastal zone is suffering the collateral damage from continuing urban development and construction, expanding resource sectors, increasing population, regulation to river flow, and on-going land change and degradation. While protection of natural coastal habitat is recommended, balancing conservation with human services is now the challenge for managers. Marine infrastructure such as seawalls, marinas and offshore platforms is increasingly used to support and provide services, but has primarily been designed for engineering purposes without consideration of the ecological consequences. Increasingly developments are seeking alternatives to hard engineering and a range of ecological solutions has begun to replace or be incorporated into marine and coastal infrastructure. But too often, hard engineering remains the primary strategy because the tools for managers to implement ecological solutions are either lacking or not supported by policy and stakeholders. Here we outline critical research needs for marine urban development and emerging strategies that seek to mitigate the impacts of marine infrastructure. We present case studies to highlight the strategic direction necessary to support management decisions internationally.

Keywords: marine urban development; offshore energy installations; policy; marine spatial planning; eco-engineering; managed realignment

Introduction

Continuing human population growth and corresponding expansion of coastal cities has contributed to a modern day multi-use seascape including natural and engineered habitat features (e.g. Lee et al., 2006; Waltham and Connolly, 2011). Along with essential ecological services for fisheries production (Nagelkerken et al., 2013), the modern day seascape is also expected to provide services essential for humans, such as residential living, recreation, commercial, navigation, wastewater disposal and tourism activities (Dennison, 2008). Costanza et al (1997) estimated these marine and coastal services to be worth in the order of US$31.5 trillion yr^{-1}. The challenge for coastal managers is to now balance ecological biodiversity and habitat protection at the same time as approving expansion of coastal centres and development.

To move forward in the management of marine developments, we require a clear definition of what constitutes "marine infrastructure". We propose that the term includes basic recreational infrastructure (e.g. marinas, pilings, pontoons, boat ramps, swimming enclosures), coastal and foreshore defence infrastructure (e.g. seawalls, groynes, breakwaters), offshore energy installations (e.g. gas and oil extraction, wind farms), fisheries infrastructure (artificial reefs, offshore aquaculture facilities) and residential infrastructure (canal estates, bridge crossings). Currently these "marine infrastructure" are differentially managed, and lack comprehensive or consistent guidelines and regulations for their planning, construction and restoration.

Clear objectives for the management of marine developments will be essential in the future as the construction of infrastructure is forecast to increase considerably with the increasing urbanization of space and predicted climatic changes (Asif and Muneer, 2007; Dugan et al., 2011; Pérez-Alberti et al., 2013; Troell et al., 2009). For example, a significant amount of urban shorelines are occupied by marinas and recreational infrastructure (Table 1). In Australia, Sydney Harbour alone comprises almost 40 marinas that support around 35,000 vessels (Widmer et al., 2002). Furthermore, up to 70% of coastlines have been modified to protect coastal cities globally (reviewed by Dafforn et al., 2015; Dugan et al., 2011) (Table 1) and the footprint of marine developments is spreading seaward with an increasing number of offshore energy platforms. Globally, there are around 10,000 operational fixed platforms and 395 operational floating platforms (Ferentinos, 2013), and Australia's largest offshore oil and gas field in the Bass Strait supports 23 operational platforms (Table 1). This proliferation of human-made structures in the marine environment is ecologically significant because of the increasing range of impacts associated with their construction, operation and decommissioning (Dafforn et al., 2015; Dugan et al., 2011).

Important marine habitats have suffered from the collateral damage of coastal development (Browne and Chapman, 2011). For example, the desire for residential real estate with waterfrontage has contributed to the global construction of over 4000 km linear of residential canal estates, covering 270 km^2, of intertidal wetland habitats (Waltham and Connolly, 2011). In addition, in the UK up to 8600 km^2 seabed will be lost to wind farm developments (Wilson et al., 2010). This represents a significant amount of sedimentary habitat that provides important ecosystem functions such as biogeochemical cycling (Freckman et al., 1997). Similarly sub-lethal effects such as reduced reproductive potential, disorientation and avoidance, changes to productivity, and the facilitation of non-indigenous species (Dafforn et al., 2008; Dafforn et al., 2009; Piola and Johnston, 2008, 2009) have been associated with disturbances from the construction and operation of marine infrastructure (reviewed by Dafforn et al., 2015). Physical disturbances arise from the addition or removal of construction materials and the associated sediment resuspension (Lozano-Minguez et al., 2011). Chemical disturbances are often linked to estuarine infrastructures, such as marinas, which create hotspots of contamination from antifouling paints (Schiff et al., 2007). Residential canal estates have also been shown to accumulate heavy metal and pesticide contaminants following urban runoff, and therefore sequester pollutants which effectively protects downstream sensitive coastal wetland habitats (Waltham et al., 2011). Similarly, high levels of contamination have been linked to increasing the length of artificial channels (Papadopoulou-Vrynioti et al., 2013).

Given the extent of marine development and future predictions it will be essential that managers develop strategies that balance engineering needs with ecosystem requirements. This needs to be comprehensive in the types of infrastructure considered so that common principles can be applied and a variety of stakeholders considered. Here we provide recommendations for managing marine development and provide decision-making support in the form of a conceptual diagram for new and existing infrastructure. We identify potential management strategies for marine development that offer opportunities to restore natural conditions or build with nature to create multi-purpose structures. We also outline how building into the sea can be managed through marine spatial planning strategies and give examples of the tools available to support this, including in situations where ecosystem repair is possible. Finally, we review global and local policy and legislation that could be used to drive the implementation of ecological principles into marine developments and explore offset policies that could provide funding for further research.

Engineered and ecological solutions for marine infrastructure and developments

To effectively manage new and existing marine infrastructure requires investment in strategies that integrate ecological principles with the engineering designs of these structures and provide a range of solutions for different scenarios (Cooper and McKenna, 2008) (Table 2). Traditionally, the objectives of marine infrastructure and development have been achieved with hard engineering solutions. In situations where hard structures cannot be avoided, such as in the foundations of offshore energy platforms and boating infrastructure, there is the potential for eco- or 'green' engineering to mitigate the impacts of these structures and maximise potential ecological outcomes (Table 2). This can potentially be achieved by designing structures that provide important ecosystem services, including pollution reduction, habitat provision for target species, recreation and education (Dafforn et al., 2015). Eco-engineering, the combination of engineering and ecological principles to reduce environmental impacts from built structures (Chapman and Underwood, 2011), is an emerging field with global significance, but where marine developments have the capacity to prioritise ecological solutions, soft engineering approaches are thought of as being better for the environment than the 'hard' approach. This is because soft engineering involves the manipulation of natural habitats, rather than hardening the coast with artificial structures (Abel et al., 2011). Soft engineering strategies include beach nourishment and beach drainage, and managed retreat and are most appropriate replacements for hard defence structures (Table 2). These strategies provide coastal protection, but in addition maintain important amenities. However, soft engineering strategies should be considered temporary because they require continued human intervention (Cooper and McKenna, 2008). Coastal defence can be more ecologically sustainable when strategies include restoration of habitat such as mangroves and salt marshes that provide a natural buffer to increased wave energy and storm surges (Gedan et al., 2011; Hoang Tri et al., 1998) (Table 2). These engineered and ecological strategies available for marine infrastructure and developments provide a range of options for managers to implement depending on local conditions and community expectations. Here we outline examples of these strategies from Australia and other countries and provide a conceptual diagram for marine development decision-making outlining opportunities to better manage coastal and marine areas with alternative strategies (Fig. 1).

1) Eco-engineering

Retrofitting existing structures

Existing structures may pose an ecological risk through their removal. For example the physical disturbance resulting from removal of an offshore platform may be more ecologically costly than allowing them to remain and be used for a new purpose. Similarly, heritage structures such as seawalls can be enhanced with green engineering (see Fig. 1, Fig. 2A). Seawalls in Sydney, Australia have been engineered to enhance biodiversity through the addition of complexity and microhabitats with measured success (Browne and Chapman, 2011). Early green engineering of seawall designs that aimed to increase biodiversity by increasing the slope and complexity or by adding habitat met with varying degrees of success. Adding blocks and boulders to increase the slope of seawalls resulted in no increases in biodiversity on the seawalls and assemblages remained different to those on natural reef. However, increasing the surface complexity of seawalls resulted in increased colonisation by mobile invertebrates not normally found on the surfaces of the structures. Creating cavities in or on these structures added to this complexity and in some designs the additional habitat created conditions that facilitated colonisation by rockpool species. Green engineering of seawalls continue to progress with the recent development of the “flowerpot 2.0” design (Morris, unpublished data, Fig. 2E). This research has involved a number of stakeholders, including universities and local government, and, while the designs have previously focussed on heritage listed sandstone seawalls in Sydney Harbour (Browne and Chapman, 2014; Browne and Chapman, 2011; Chapman and Blockley, 2009; Chapman and Underwood, 2011), the potential to expand this research to other existing and new structures is considerable.The ecological principles that have been implemented in the design of ‘green’ roofs and walls in terrestrial systems (Oberndorfer et al., 2007) can similarly be expanded and manipulated to suit a marine setting. For example, seeding of marine structures with threatened species has been experimentally tested on breakwalls in the Mediterranean (Perkol-Finkel et al., 2012). This experiment had great success, with the transplanted habitat-forming seaweed *Cystoseira barbata* having greater survival (>30%) on artificial structures compared to adjacent native habitat. These results are encouraging and provide an important example on how coastal infrastructure can be used to provide services beyond just coastal protection, in this case, the provision of habitat for the growth of threatened species.

The potential for artificial structures to provide for multiple uses is also being explored for offshore platforms during both their operational and decommissioning phases (Fig. 2B). The ecological costs associated with platform removal has been a driving factor behind the rigs-to-reef program which aims to create artificial reefs from the underwater scaffolding of offshore platforms that are no longer operational (Macreadie et al., 2011) (Fig. 2F). Economic considerations have prompted the development of open offshore aquaculture that utilises the existing scaffolding of e.g. wind farms to avoid additional construction costs of a separate facility (Buck et al., 2004). Further, the application of eco-engineering in offshore structures through the manufacture of holes in wave energy foundations has been tested off the Swedish coast for the potential to enhance fish and crustacean abundance for fisheries management and species conservation (Langhamer and Wilhelmsson, 2009). These efforts to reduce the footprint and concentrate marine development are promising, but there is a range of enhancements yet to be tested on existing structures and the potential to extend ecological principles to new marine developments from the planning and design stages remains in its infancy.

Ecological principles for new marine developments

New developments in the United Kingdom have started to incorporate strategies that mimic more closely the complexity of natural habitats. Examples include the "Bioblock" (a purpose-built boulder designed to provide a range of microhabitats) has been incorporated into new breakwaters in Wales and has proven successful in facilitating the colonisation of native species (Firth et al., 2014). Engineers are also giving more consideration to features and materials that can not only improve performance and durability, but also reduce ecological stress and encourage the development of natural communities (e.g. ECOncrete®) (Coombes et al., 2013; Firth et al., 2014). The benefits of incorporating natural habitat elements and materials, such as riparian vegetation, wood debris and oyster reefs, into techniques of shoreline stabilization is an increasing practice worldwide as an alternative to hard armouring of the coasts (Cooper and McKenna, 2008; Gedan et al., 2011). This approach is hypothesised to provide better shoreline protection against erosion while maintaining important ecosystems services and functions. Rocks, or other natural hard materials, for instance, can be placed in specific ways and locations designed to reduce wave energy, consequently reducing erosion, while providing habitat for marshes and/or allowing for the development of beaches (Pires et al., 2013; Pires et al., 2009; Smith, 2006) (Fig. 2C, G). However, if not designed based on ecological and engineering needs, tailored for the site where they will be installed, these 'living shorelines' will not be successful (Fig. 1).

Recent foreshore developments in North America have also implemented eco-engineering principles at the planning stage (Leonard and Kullmann, 2010). For example, construction engineers working on the Vancouver Convention Centre foreshore implemented solutions to reduce local impacts of seawalls to natural sedimentary habitats by building stepped structures ("habitat skirts"). Other foreshore sites in North America are also undergoing extensive redevelopment. The Elliott Bay Seawall project will stretch more than 2 km along the Seattle foreshore and aims to introduce novel designs that reduce the ecological impacts of shading from marine infrastructure. Innovations have included the creation of boardwalk windows and "skylights" designed to maximize light penetration beneath the structure. Furthermore, the "Living Breakwaters" project on Staten Island, New York aims to build ecological resiliency together with a buffer from destructive wave energy by creating habitat breakwaters and constructed reefs (http://www.rebuildbydesign.org). These developments are very new and while promising, we highlight that their capacity to maintain or restore natural assemblages requires more data (but see Goff, 2010).

Carefully designed survey and experimental work similar to the progressive work on existing seawall in Sydney Harbour (Chapman and Underwood, 2011) will be required to test the effectiveness of any eco-engineering strategy. Future marine developments are likely to continue and at an increasing spatial scale, but we have the potential to design for multi-purpose objectives from the beginning (Dafforn et al., 2015). Importantly, there is still a major research gap since most of these modifications to date have been made on intertidal structures. In subtidal habitats, besides the implementation of artificial reefs designed to enhance fisheries (Baine, 2001) or as restoration tools (Dupont, 2008), not much has been done regarding eco-engineering and this deserves attention in the future.

2) Soft engineering

Beach nourishment and drainage

Beach nourishment is a central management strategy in soft engineering, and is widely practiced across the world. 'Beach or shore nourishment' includes the deposition of sand onto beaches in the surf-zone, and dune protection (Hamm et al., 2002). The world leader in beach nourishment practices is the United States, where beach nourishment is the preferred method of coastal protection and therefore has the largest number of nourishment projects, as well as volumes replenished (Campbell and Benedet, 2004; Hanson et al., 2002). A shift from hard to soft coastal defence techniques may becoming a preference worldwide due to the maintenance of the aesthetic and recreational values of replenished beaches, which results in the economical benefits far outweighing the investment in coastal defence (Campbell and Benedet, 2004). In Europe, many different beach nourishment practices are employed across the different countries (Hanson et al., 2002) Fig. 2G). Hanson *et al.* (2002) identified Spain and the Netherlands as being the biggest nourishing countries in Europe, with nourishment practices being uncommon, or hard engineering more widely used in other areas such as France, Sweden, Greece and Ireland. In the United Kingdom, beach nourishment is used to complement hard coastal defence structures by replenishing beaches in front of seawalls to extend the life of the seawall. These beach fill schemes have been met with such success that there is an increasing demand for sand in the UK for future projects (Hanson et al., 2002). In Australia, coastal managers employed beach nourishment practices for 130 beaches between 2001 and 2011, mainly to protect coastal infrastructure and public beach amenity (Cooke et al., 2012). Nourishment occurred predominantly around the major urban centres of Australia in Sydney, Brisbane, Adelaide, Melbourne, the Gold Coast and Perth (Cooke et al., 2012). Only 17% of the Local Government Areas employing beach nourishment practices, however, monitor to assess the effectiveness or any impacts of the projects (Cooke et al., 2012). In contrast, in the United States biological monitoring is done at the dredge and fill sites as a requirement of the permit (Peterson and Bishop, 2005). This is a good approach, as nourishment practices needs knowledge of erosion rates, effects of storms and wave action in specific locations to be successful, and best practice involves regular monitoring to improve understanding of the ecological impacts of soft engineering (Cooke et al., 2012). Unfortunately, despite a requirement for monitoring in the U.S., knowledge of the ecological effects of beach nourishment is not as advanced as it could be due to poorly designed monitoring studies that lack scientific rigor (Peterson and Bishop, 2005). Worldwide monitoring with robust experimental design and analysis is needed to fully understand the impacts of beach nourishment, and its contribution in the long-term to coastal defence. Due to the need for continued human intervention, soft engineering has been considered a short-term solution to coastal defence (Cooper and McKenna, 2008). Recent research however is investigating the use of specially designed breakwater units ('Beachsaver Reef') to improve the retention of sand in beach nourishment projects (Morang et al., 2014).

Another soft engineering method for the retention and accretion of sand on beaches is the installation of beach drainage systems which artificially reduce the beach water table e.g. (Ciavola et al., 2008). This was first tested in the field in Australia by Chappell *et al.* (1979), who concluded that beach deposition could be aided by maintaining the beach water table at a low level though pumping at appropriate times, such as during long periods of swell. Beach drainage is often popular with coastal managers as it is less costly than other defence structures such as seawalls and groynes, has no visual impact, and thought to be more environmentally sustainable (Ciavola et al., 2008). Research into the efficacy and environmental impact of beach drainage however is scarce, and grey literature is the only information available for most sites (Ciavola et al., 2008). The literature that has reviewed or experimentally tested the use of beach drainage systems in the US, Denmark, Italy and UK (Ciavola et al., 2008; Turner and Leatherman, 1997; Vicinanza et al., 2010) has concluded that there is still not enough scientific data available to be sure that these systems have a positive effect with regards to coastal protection. In many cases, the systems were damaged in storms, not enough data was collected and there was a big variation in the success between different locations.

Managed realignment (managed retreat)

Managed retreat is one type of soft engineering approach that is increasingly being incorporated into coastal defence strategies and has become the preferred approach with regards to sea level rise and nature conservation in the United Kingdom with 51 projects implemented at the end of 2012 (Esteves, 2013). Thirty-five of these 51 projects are a result of breaching or removal of flood defences, and 14 of these projects in England have multiple objectives in addition to responding to sea level rise - the most common being the creation of intertidal habitat to offset habitat loss created by coastal squeeze; this is a statutory requirement under the EU Habitats Directive (see Supplementary Table S1, Esteves, 2013). The ecological consequences of managed retreat and a return to natural flooding processes are being tested, and experimental work from South Devon in the UK suggests that coastal grassland species will be robust to flooding with little terrestrial invertebrate mortality and shifts in aquatic invertebrate communities from freshwater to brackish water dominated (Hoggart et al., 2014).

In the United States, around 3.7 million people live close to the high tide zone (Strauss et al., 2012). Increasingly, the strategy adopted by coastal states is to prevent new development in high risk areas to prevent “squeeze” on beaches and coastal ecosystems which would otherwise absorb wave energy (Kousky, 2014). New buildings in South Carolina need to be constructed inland of the primary dune area and North Carolina incorporates shoreline setback calculations when delimiting coastal developments (Abbott, 2013). In other states, local government are actively retreating and in San Francisco an approach combining retreat with restoration has involved removal of hard protection structures and the relocation of a highway and parking lot inland to allow for the restoration of sand dunes (SPUR, 2012). Furthermore, areas of the US that have been recognised as natural disaster zones due to storms and flooding are currently viewed as a “policy window” to allow for retreat and inundation and prevent rebuilding (Kousky, 2014).

In contrast to other global efforts, managed retreat is rarely implemented in Australia (Ryan et al., 2011), although it is often a cheaper management option to the upgrading or repair of existing hard defences (French, 2006). In 2012, the NSW Government removed from its policy recommending statewide sea level rise planning benchmarks to limit new developments in low-lying areas, instead supporting individual council management policies, relaxing the rules on the use of seawalls and encouraging temporary coastal protection works from minor storm events (Abel et al., 2011). If managed retreat is going to be successfully used in Australia, then resources should be allocated for research into the suitability and effectiveness of this strategy for use as coastal protection and the impact on biodiversity and ecosystem functioning. As the United Kingdom is the world leader in this research, coastal scientists and managers working in Australia can learn from the data already generated there. Where coastal development or reconstruction of hard coastal defences is occurring, managers need to consider whether alternative methods such as managed retreat are more appropriate. Scientific modelling (Rogers et al., 2014) may be a useful tool in helping identify whether managed retreat is a viable management option in specific areas.

Retreat will not be optimal everywhere (Fig. 1) —economically, socially, or politically—and once population and development cross certain thresholds, retreat will be exceedingly unlikely (Abel et al., 2011). But, with the predicted sea level rise, coastal managers should be considering all available options for coastal protection, and managed retreat may become increasingly important in the future. With increased sea levels, maintenance of sea defences in some areas may no longer be viable due to the high cost of repairing these structures; and managed retreat is often a cheaper alternative for coastal defence (French, 2006). Further, managed retreat may be an effective way to protect critically important saline coastal wetland habitat, such as mangroves and salt marsh (Rogers et al., 2014). We caution that the ecological and social consequences of managed retreat and manipulation of coastal flooding regimes are considered and should be rigorously assessed in line with national and international policy, and the needs of end users (Hoggart et al., 2014).

3) Coastal habitat restoration

Ecological restoration has been defined as “the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed” (SER, 2002). Active restoration of systems such as mangroves, salt-marshes, seaweeds, seagrasses and oyster reefs can also be used in shoreline stabilization practices since these systems reduce erosion, providing natural protection for the coastal zone against storms and waves (Fig. 1) (Beck et al., 2011; Foster et al., 2013; Orth et al., 2006; Pérez-Alberti et al., 2012). In a recent review and meta-analyses, Gedan *et al.* (2011) found that the presence of wetland vegetation reduces wave heights and property damage, being an efficient protection, although context-dependent, from erosion, storm surge and even small tsunami waves. Where opportunities for restoration of natural systems are absent then artificial structures have been used for restoration efforts (e.g. (Perkol-Finkel et al., 2012) described above). Artificial reefs, in particular, are increasingly being successfully used in large-scale restoration projects, e.g. kelp and oyster beds and coral reefs, ranging from areas of 61 ha in Southern California, USA, to regional marine parks in Hong Kong (see review by (Seaman, 2007). Such projects have been thoroughly planned and designed, having identified *a priori* the need for restoration and have gathered the necessary ecological information, taking into account the measurable objectives necessary for a successful implementation, such as the specification of effort units (e.g. of oysters and kelps). Furthermore, monitoring is being done and the ecology of organisms have been used to inform on the design of the reef structures (see (Seaman, 2007)).

Examples of restoration as alternatives to coastal armouring

Most marine restoration projects implemented as an alternative to coastal armouring have been done in the US (e.g. Davis et al., 2006; Piazza et al., 2005; Seaman, 2007), with few examples available in Asia, more specifically in Malaysia (Hashim et al., 2010; Kamali et al., 2010), Some examples of successful restoration of habitats is the use of experimental oyster reefs and salt-marshes in the reduction of coastline erosion. Those habitats were restored with the primary aim of coastal protection, while maintaining importance services to society. In order to test the 'living shoreline' approach, i.e. the employment of natural elements as appropriate for site conditions to protect shorelines from erosion, scientists removed a seawall, in Chesapeake Bay, US, replacing it by a living shoreline which consisted of areas of planted salt-marshes (Davis et al., 2006). Blocks of different types of habitats -made from natural elements, such as oyster reefs and woody debris - were also deployed in the area to evaluate whether structural differences of habitats would influence benthic and fish assemblages. The authors found that some species responded almost immediately to the restored shoreline (i.e. planted salt-marshes) and suggest that living shoreline designs should include multiple habitats elements to maximise diversity and functional value.

A further method for protecting foreshores is to introduce which encourage the growth of natural reefs that can help prevent erosion of the shoreline and improve water quality (Fig. 1, Fig. 2D,H). For example, in the United States oyster castles have been successfully employed where oyster spat attach to and grow on reef structures (Black, 2011; Kingsley-Smith et al., 2012). In Louisiana, experimental intertidal oyster shell reefs (25 X 1.0 X 0.7 m) were constructed within 5 m of eroding marsh shorelines to assess their potential as natural shoreline protection tools (Piazza et al., 2005). Reefs were created at low and high wave energy shorelines. The authors also determined whether the experimental reefs were sustainable over long-term. Results suggest that while the experimental reefs may be effective in low-energy shorelines, reducing erosion, they were not effective in high-energy environments. Such techniques can, however, be successfully used by coastal managers in low-energy areas, especially in areas where oyster reefs are threatened by human activities. Furthermore, results of this experiment also suggest that these types of experimental reefs are potentially sustainable, having high natural recruitment and growth of oysters.

In the UK, although coastal defence has been the main driver of intertidal habitat restoration, managed retreat has been generally used as the preferred method by coastal managers (Garbutt et al., 2006). This technique has been extensively discussed in the section above.

Examples of incorporating restoration into hard engineering

In Malaysia, hard and soft engineering techniques were used in coastal rehabilitation. A breakwater structure was built on a degraded mangrove area, at the muddy beach Sg Hj Dorani, so wave energy was reduced, protecting the transplanted seedlings of *Avicennia marina* (Hashim et al., 2010; Kamali et al., 2010). Monitoring surveys done 8 months after initial restoration revealed that approximately 30% of the saplings survived and sediment retention increased, indicating the efficiency of the restoration project in raising the beach elevation.

In Australia, although some successful restoration projects were done, e.g. the re-vegetation of the important habitat-forming seaweed *Phyllospora comosa* in areas of Sydney where this species had disappeared (Campbell et al., 2014), and the addition of artificial boulder fields on intertidal rocky shores (Chapman and Smith, 2012), restoration practices are not currently used for coastal stabilisation and/or protection. Regardless, these experiments provide examples on how habitat restoration can be done in a cost-effective manner, considering important ecological principles and interaction of species and similar techniques should be considered by coastal managers in the future.

Guiding restoration strategies

Practices of habitat restoration are increasingly becoming an integral part of conservation strategies worldwide e.g. (Bell et al., 2008; Suding et al., 2004). Despite this, most attempts to restore coastal habitats, such as mangroves and seagrasses, have been unsuccessful, with projects either failing completely or failing to meet the success criteria (Bell et al., 2008; Lewis III, 2005). This is probably due to the complex ecological interactions occurring in the systems; the level of human intervention in the particular area and/or the fact that the conceptual planning of projects has not been well thought and therefore the used restoration practices are insufficient to overcome the degraded state of the habitat(s) (Byers et al., 2006; Seaman, 2007; Suding, 2011). In addition, there is a lack of existing baseline data and long-term monitoring data, which provides important quantitative data to compare with following development activities and to measure conservations outcomes (Addison et al., 2015).

Successful restoration requires the establishment of clear goals and consequently how to gauge the success of the project (i.e. what will be considered a successful restored habitat or system; e.g. (Grayson et al., 1999; Seaman, 2007); innovative management (e.g. models that identify not only the stressors degrading the habitat/system, but also that incorporate alternative states of systems and the thresholds and feedbacks that might affect restoration success), and the disruption of feedbacks when the degraded system(s) have shifted to new states (e.g. coral reefs to algal beds) (Suding et al., 2004). Despite many of the problems identified in restoration projects that need to be urgently addressed, there have been some successful examples (on varying levels) on how coastline protection can be achieved through restoration of key stabilising natural habitats. Such projects have been designed taking into account important ecological processes and the maintenance of services and functions of the natural systems.

Importantly, although the use of artificial structures to create/restore new habitats where human activities has significantly impacted the environment is important, care still needs to be taken when adding hard structures into the marine environment, even when for restoration purposes. As briefly discussed above (and extensively discussed elsewhere, e.g. (Bulleri and Chapman, 2010; Dafforn et al., 2015), the addition of such structures on the seascape can cause significant losses of soft-sediment habitats, affecting the diversity and function of marine systems in general. The creation of new (hard) habitats, albeit important, does not offset the loss of soft-sediment communities and the (different) services they provide. Efforts need to be made, not only to understand how such losses can be minimised with the use of alternative techniques and practices, but also on the restoration of ecologically equivalent areas of those that have been lost.

Managing marine infrastructure and development with maritime spatial planning

The spatial scale to which such structures can affect the marine environment can range from 10s of metres to 1000s of kilometres. (Dafforn et al., 2015). Importantly, the spatial arrangement of how artificial structures are constructed can determine, not only the spatial scale of the impact, but also the type of impact caused. In many coastal areas, the result is a mosaic of natural and engineered habitats (Fig. 1). For instance, up to 8600 km^2 of seabed habitat in the United Kingdom is forecast to be lost due to urban development (Wilson et al., 2010), affecting several species and potentially decreasing the diversity of the area, but the consequences for ecosystem services provided by this habitat remains unknown. Furthermore, the spatial arrangement of marine artificial structures has the potential to affect the connectivity of marine organisms. The construction of coastal and offshore infrastructure results in the creation of islands of artificial substrates and modified habitats surrounded by natural habitats. The isolation of these islands may be compounded if the hydrodynamics and physical characteristics of the structures restrict the transportation of larvae and food (Floerl and Inglis, 2003). As climate change drives species range shifts, the designs of different artificial structures may restrict (e.g. breakwalls enclosing marinas) or enhance (e.g. dense configurations of pilings and pontoons) these movements (Thomas, 2011). In other cases, however, the design of the structures may enhance connectivity. Marine artificial structures that are built a few hundred metres apart and extending over entire coastlines (e.g. North Adriatic) can facilitate the introduction and dispersal of non-indigenous species, while offering unsuitable habitat to many natives (Airoldi and Bulleri, 2011; Bulleri and Airoldi, 2005). Spatial and conservation planning of the urban development in marine environments is therefore as important as in terrestrial and urban habitats, and should be used to prevent or mitigate the impacts of artificial structures.

Considering the potential damage that artificial structures can cause in the marine environment, where and when such structures are constructed should be regulated, taking into consideration essential ecosystem services provided by marine systems (Böhnke-Henrichs et al., 2013). Plans to expand development (industry, agricultural, farming) across northern Australia to meet increasing demands for food and energy (mining and port facilities) supplies in Australasia (CSIRO, 2009) means that the risk of collateral damage from anthropogenic stresses is imminent. Part of this development region includes the Great Barrier Reef (GBR); extending approximately 2,300km along the Queensland coastline, it is one of the natural wonders of the world and a marine ecosystem of globally significant biodiversity, with extensive environmental, cultural, social and economic values (GBRMPA, 2013). Recognised as a World Heritage Area and National Marine Park, the GBR has a series of inscribed international agreements, and national and state legislation/policies in place for its protection and management (GBRMPA, 2013). However, many functional characteristics of this complex habitat are under threat owing to loss of natural freshwater wetlands as nursery habitat, expansion of city centres for increasing population and port expansions following increasing mining activities (Brodie, 2014; Waltham and Sheaves, 2015).

The declining health and resilience of Great Barrier Reef ecosystems in response to continuing landscape and climate change has recently attracted media and community attention (Brodie, 2014; Grech et al., 2013). These concerns led to a request from UNESCO (June 2011) for Australian government agencies to conduct a strategic assessment of the Great Barrier Reef World Heritage Area (GBRWHA). Central to this assessment was addressing exactly how future coastal development could continue while still satisfying conservation and protection obligations/responsibilities under the world heritage agreement. The assessment (draft released December 2013) highlighted weaknesses in knowledge and uncertainty in the design and implementation of coastal infrastructure projects that have led to repeated problems with the implementation and operation of coastal development and reductions to the extent of productive wetland habitats. These problems reflect adversely on developers and operators of coastal assets, even when complying with their legislative obligations; often there is no failure of governance or compliance, rather problems stem from incomplete knowledge and understanding of key values that prejudices effective decision making (Grech et al., 2013).

Spatial planning in the construction of artificial structures is essential to prevent and/or reduce impacts that urban development might have on the marine environment. Understanding some of the mechanisms on how artificial structures impact systems, such as how they facilitate the spread of invasive species or how they fragment marine habitats, is necessary to devise specific regulations on how and where such structures should be built (when no alternative option is available). Regulation and planning of the construction of artificial structures within the coastal seascape, taking into account their distribution and spatial scale, will allow a decrease in the footprint of such structures, with direct consequences to the diversity and functioning of marine systems and, consequently to human well-being. Strict guidelines could be set, incorporating anticipated development footprints, when unavoidable, as well as a context-specific spatial planning (i.e. each type of structure will have specific guidelines and recommendations). Development of an Australian Marine Spatial Information System (AMSIS) will be essential to support spatial planning of artificial structures in the coastal and offshore zone. This could incorporate data and support from the current AMSIS initiative by

Geoscience Australia and would benefit from a variety of long-term monitoring sources e.g. topographical maps, aerial photographs and satellite imagery to assess changes in marine systems as a result of urbanisation and development (Skilodimou et al., 2002). Comprehensive zoning plans for the marine and coastal zones of Australia will be needed to aid decision makers and ensure that spatial planning for marine artificial structures meets the needs of multiple stakeholders (see Fig. 1).

Managing marine infrastructure and development through policy

Although alternative to hard engineering (e.g. eco-engineering, soft/natural systems engineering) are not specifically integrated into many policies worldwide, the delivery of these projects can make a significant contribution to a large number of policy objectives, in particular the promotion of sustainable development and maintenance/rehabilitation of biodiversity and ecosystem functioning (Supplementary Table S1). According to the United Nations Convention on the Law of the Sea (UNCLOS), States are required to protect and preserve the marine environment (UNCLOS Article 194 (5); Ban et al., 2014) and at least 10% of the coastal and marine areas should be protected by 2020, through the Convention on Biological Diversity (CBD) Aichi target 11 (Ban et al., 2014). Many countries have national policies promoting the objectives of the CBD, focusing on sustainable development and conservation of biological diversity, for example the Environment Protection and Biodiversity Conservation Act 1999 in Australia, the National Environmental Policy Act 1970 in the U.S. and the National Environment Management Act 1998 in South Africa, amongst others (Supplementary Table S1). In addition, some countries have legislation committed specifically to the protection of marine biodiversity, such as the European Union's Marine Strategy Framework Directive (2008/56/EC) and China's Marine Environment Protection Law of the People's Republic of China 1982 (see Supplementary Table S1). Australia has a policy explicitly dedicated to the protection of Sydney Harbour Trust Land, the Sydney Harbour Trust Act 2001, the objectives of this act include the use of 'water sensitive urban design principles' in the development of future planning processes. The impact of coastal developments on the environment is controlled in many countries through the requirement of an Environmental Impact Statement to be completed before development. For example, in Australia all construction works require an Environmental Impact Statement to be approved under the Environmental Planning and Assessment Act 1979 (Supplementary Table S1), encouraging sustainable development which protects and conserves the natural environment (Article 5). Although these policies can and should be used to encourage research and application of alternatives to hard engineering, their objectives are very broad, therefore specific working documents are needed to complement the policies, giving direction to end-users on how e.g. eco-engineering can be implemented under certain legislation. This has been recognised in Europe, with the European Commission's release of a green infrastructure strategy in May 2013 (EC, 2013). The strategy outlines the contribution of green infrastructure to European policies, promoting the implementation of green infrastructure projects within existing legal, policy and financial instruments (EC, 2013). The document recognises that action needs to be taken at an EU level if green infrastructure is going to deliver at full potential, with a commitment to develop a framework to ensure that green infrastructure is considered as part of spatial planning and development, and a call for more research, with an aim to set up a financing facility for these projects (EC, 2013). This strategy exemplifies the next step for other countries worldwide to aid large scale implementation of eco-engineering through existing policies.

Marine development offset policies

In many cases urban development and/or its impacts are inevitable, due to social and economic reasons. To limit such effects, biodiversity offsets should be considered in the context of a mitigation hierarchy (Regnery et al., 2013). Such hierarchy includes a 4-step procedure: 1) to avoid development on hotspots of diversity or areas with threatened species; 2) to reduce the footprint of the development, i.e. to reduce the impacted area or the impact itself; 3) restoration or rehabilitation to remedy the effects of the development; and 4) the implementation of offset measurements to compensate for any residual effects (modified from McKenney and Kiesecker, 2010; Regnery et al., 2013). One of the major challenges to marine development offsetting is the lack of knowledge on long-term impacts of such developments on essential ecosystem services provided by marine systems. Losses and gains used in offset policies need to be measured in the same metric to demonstrate ecological equivalence and of the impacts of construction are not yet established, then the use of offsets is not appropriate. The inclusion of ecosystem services as specific 'targets' into management and conservation policies as well as offset policies, if applied in a hierarchical context, will ensure that important services provided by marine systems are not going to be lost.

Offset policy goals vary from 'no net loss' to 'net gain' and are potentially a powerful tool for balancing conservation and development (McKenney and Kiesecker, 2010), including the predicted urban sprawl in marine environments. Such policies are, however, not appropriate for impacts on areas that provide irreplaceable biodiversity, habitats or systems that may take decades or centuries to restore or for those habitats or systems for which restoration techniques are unknown (BBOP, 2009).

Nevertheless, offset policies might be successfully used to reduce the footprint of artificial structures when residual impacts of the construction still exist, after avoidance and mitigation measures. It is imperative, however, that this policy is applied not only as a last resource (i.e. when all prevention, reduction and restoration measurements are not sufficient to avoid an impact), but also with sound scientific knowledge attached to it. Although Australia has a very specific set of offsets policies under the Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act), such policies will only be successfully applied on coastal urban development regulations when suitable monitoring and long-term impact assessments of artificial structures is implemented. Furthermore, the application of such policies is hampered due to an inability to determine equivalence when discussing diversity and service (Gordon et al., 2011). Also, the ‘net gain’ or ‘no net loss’ goals are dependent on the baseline against which performances are measured (Gordon et al., 2011). Much research is needed in this area to develop, not only, better valuation techniques, but also ways of establishing equivalence among species, habitats and services that are appropriate, accurate and feasible.

Although ecosystem services are increasingly being incorporated into management and conservation policies (Chan et al., 2006; Nelson et al., 2009; Nelson et al., 2008), research on where and how these services are distributed, especially in marine environments is a massive gap in our research. In addition, the relationship among diversity, functioning and services need to be further elucidate, e.g. whether targeting biodiversity, for instance, is an efficient and appropriate proxy to ecosystem services and vice-versa. Also, adding value (social, economic or environmental) to specific areas, an essential step to develop not only offset policies, but also cost-benefit analyses, is still a challenge, with many ethical and moral issues involved (Naidoo and Ricketts, 2006).

A program of ongoing monitoring of major coastal structures is necessary, in order to determine exactly how the newly created habitat adds to the ecology of the receiving environment. Clear guidelines for marine development offsetting should be introduced into policy to direct funds towards future research. Monitoring and revision of offsetting policies will be necessary to match the progress in green engineering and increasing/changing pressures from marine developments

Managing marine infrastructure and development through stakeholder engagement

There is a growing amount of research on the integration of ecological principles into marine infrastructure and development, but application of this in coastal management is still in the early stages (Naylor et al., 2012). Communication between multiple stakeholders is crucial to an effective national marine policy for the application of appropriate hard, soft or eco-engineering strategies into the planning, design and construction of marine developments, coastal defence structures, offshore energy platforms and resource infrastructure. The issues surrounding the management of artificial structures are multi-disciplinary and therefore relevant stakeholders will include at a minimum coastal scientists, engineers, ecologists, economists and social scientists. Management of marine protected areas have benefited from the inclusion of local community stakeholders into decision-making processes (Apostolopoulou et al., 2012). We also advocate the identification of ‘knowledge brokers’ (e.g. Naylor et al., 2012) to act as intermediaries or interpreters that translate between producers and users of knowledge e.g. research and policy. Differences in the objectives of coastal scientists, managers and engineers can be a barrier to good communication, however the use of an ‘interpreter’ or ‘knowledge broker’ to translate information between scientists and end users may be a way to overcome this (Holmes and Clark, 2008; Naylor et al., 2012).

Effective communication between scientists, engineers and managers will ultimately ensure that ecological enhancements are incorporated in a way that allows the design to be tested in a scientifically robust way. This data can then be used to increase the knowledge of the environmental benefits of ecological enhancements, informing research-driven policy. The publication of end user focussed guidance documents has been found to be an effective way to link science and policy in the United Kingdom (Naylor et al., 2012). End user focussed guidelines exist in Australia for seawalls (NSWDECC, 2009), but soft engineering e.g. managed realignment and other eco-engineering management options need to be included, as well as an operational framework for implementation of ecological enhancements under current legislation and funding instruments. Furthermore, knowledge brokers to facilitate collaboration between coastal managers, scientists and engineers and improve communication between scientists and end users should be used in more projects in Australia to mediate knowledge transfer between the stakeholders involved (Holmes and Clark, 2008). The allocation of funds to support such role is still, however, a main challenge. In addition, the establishment of a science advisory committee to act as a boundary organisation can further facilitate knowledge transfer and collaboration between stakeholders (Holmes and Clark, 2008; Owens et al., 2006). The organisation of a state, or a national working group would establish an infrastructure for effective communication between the government and international research groups. The primary role of the working group would be the promotion of the high quality research of Australia's marine scientists, providing independent advice to the government. The working group would be responsible for creating international links with other research groups worldwide, to develop a best practice for coastal management. As sea levels rise and coastal urbanisation increases, research into sustaining coastal biodiversity is a scientific priority; therefore a legislative or policy driver stipulating the consideration of ecological enhancement in coastal development in Australia is needed.

Public support for urban conservation is crucial. Successful managed retreat projects, for instance require support from community members (Kousky, 2014). Frequently, coastal property owners armour the coastline with hard structures to prevent erosion of the land and damage to their property. Although the armouring of a few scattered properties has little impact on the environment, the proliferation of hard structures along the coastline can have profound effects on the marine system (Kousky, 2014). Science communication and public education is essential for an effective marine urban policy and the application of ecological enhancement in coastal management. The research involves redesigning structures that people come into contact with, and end users, like councils, value the opinion of the community. For the public to make an informed decision about coastal research, scientists need to be able to communicate their work in a way that is informative, but easily accessible. All scientists should be trained to be able to communicate effectively across a broad range of groups, from outreach in schools to adults, and should engage regularly with the public. Collaboration with council and industry partners will help public education through, for example, setting up interpretive signs at ecologically enhanced sites. Promoting public awareness of key environmental issues can aid the acceptance and support of a project, encouraging the community to raise concerns about these environmental problems with councils and other organisations to help develop improvement within their area. Also, effective communication will aid property-owners to make informed choices for their land.

Future directions

The basis for management decisions about existing and future marine infrastructure and development should be supported by scientifically rigorous, long term, data. However, more often the precautionary approach is taken and monitoring follows construction or land use and climate changes (Waltham and Sheaves, 2015). We argue that priority should be given to the implementation of suitable impact assessments and long-term monitoring programs to the construction of any artificial structure on coastal and oceanic systems, including those on private land. Assessments should include not only possible long-term effects of marine infrastructure and development at a local scale, but also analyses and predictions on magnitude and long-term effects on regional scales, e.g. impacts on connectivity of systems (Waltham and Sheaves, 2015) and introduction of invasive species (Dafforn et al., 2015). To that end, regular monitoring needs to be incorporated into the operational framework for Local Government Areas. Research efforts should be concentrated in determining basic mechanisms on how these different strategies impact (or add value to) marine habitats as well as further understanding links between diversity, functioning and ecosystem services. These assessments need also to include modes to prevent, minimise or mitigate possible impacts.

Concurrently, research is needed to investigate the possible uses of biodiversity offsets in the marine environment to develop a framework that can be implemented with sufficient baseline data. In the United Kingdom, a report was recently issued investigating the scope for application of biodiversity offsets to the marine environment, using hypothetical case studies for a windfarm and tidal barrage project to develop understanding of how offsets may be planned (Dickie et al., 2013). A similar approach may be a useful starting point for the application of offsets to marine developments in Australia and internationally. Regulations and guidelines on urban development in the marine environment need, however, to be integrated on a national level. Impacts of these infrastructure and developments might occur over large spatial scales, which are beyond political and social boundaries; therefore, legislation should reflect such impacts.

Acknowledgements

The authors would like to acknowledge support from the Australian Research Council LP140100753 for KAD. MMP received research support from UNSW.

References

Abbott, T., 2013. Shifting shorelines and political winds – The complexities of implementing the simple idea of shoreline setbacks for oceanfront developments in Maui, Hawaii. Ocean Coast. Manage. 73, 13-21.
Abel, N., Gorddard, R., Harman, B., Leitch, A., Langridge, J., Ryan, A., Heyenga, S., 2011. Sea level rise, coastal development and planned retreat: analytical framework, governance principles and an Australian case study. Environ. Sci. Policy 14, 279-288.
Addison, P., Flander, L., Cook, C., 2015. Are we missing the boat? Current uses of long-term biological monitoring data in the evaluation and management of marine protected areas. J. Environ. Manage. 149, 148-156.
Airoldi, L., Beck, M.W., 2007. Loss, status and trends for coastal marine habitats of Europe. Oceanogr. Mar. Biol. 45, 345-405.
Airoldi, L., Bulleri, F., 2011. Anthropogenic disturbance can determine the magnitude of opportunistic species responses on marine urban infrastructures. PLoS ONE 6, e22985.
Amin, M.F.H.M., 2014. Use of Alternative Energies in the Australian Offshore Sector, Australian Maritime College. University of Tasmania, Tasmania.
Apostolopoulou, E., Drakou, E.G., Pediaditi, K., 2012. Participation in the management of Greek Natura 2000 sites: Evidence from a cross-level analysis. J. Environ. Manage. 113, 308-318.
Asif, M., Muneer, T., 2007. Energy supply, its demand and security issues for developed and emerging economies. Renew. Sust. Energ. Rev. 11, 1388-1413.
Baine, M., 2001. Artificial reefs: a review of their design, application, management and performance. Ocean Coast. Manage. 44, 241-259.
Ban, N.C., Maxwell, S.M., Dunn, D.C., Hobday, A.J., Bax, N.J., Ardron, J., Gjerde, K.M., Game, E.T., Devillers, R., Kaplan, D.M., 2014. Better integration of sectoral planning and management approaches for the interlinked ecology of the open oceans. Mar. Policy 49, 127-136.
BBOP, 2009. Biodiversity Offset Design Handbook. Business Biodiversity Offsets Programme Washington, DC, USA.
Beck, M.W., Brumbaugh, R.D., Airoldi, L., Carranza, A., Coen, L.D., Crawford, C., Defeo, O., Edgar, G.J., Hancock, B., Kay, M.C., 2011. Oyster reefs at risk and recommendations for conservation, restoration, and management. Bioscience 61, 107-116.
Bell, S.S., Tewfik, A., Hall, M.O., Fonseca, M.S., 2008. Evaluation of seagrass planting and monitoring techniques: implications for assessing restoration success and habitat equivalency. Restor. Ecol. 16, 407-416.
Black, J.A., 2011. Oyster Reef Restoration in North Carolina: Recommendations for Improvements in Techniques and Monitoring. Duke University.
Böhnke-Henrichs, A., Baulcomb, C., Koss, R., Hussain, S.S., de Groot, R.S., 2013. Typology and indicators of ecosystem services for marine spatial planning and management. J. Environ. Manage. 130, 135-145.
Brodie, J., 2014. Dredging the Great Barrier Reef: Use and misuse of science. Estuar. Coast. Shelf Sci. 142, 1-3.
Browne, M., Chapman, M., 2014. Mitigating against the loss of species by adding artificial intertidal pools to existing seawalls. Mar. Ecol. Prog. Ser. 497, 119-129.
Browne, M.A., Chapman, M.G., 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. Environ. Sci. Technol. 45, 8204-8207.
BSEE, 2013. Outer Continental Shelf Platform Activity, Bureau of Safety and Environmental Enforcement.
Buck, B.H., Krause, G., Rosenthal, H., 2004. Extensive open ocean aquaculture development within wind farms in Germany: the prospect of offshore co-management and legal constraints. Ocean Coast. Manage. 47, 95-122.

Bulleri, F., Airoldi, 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., Chapman, M.G., 2010. The introduction of coastal infrastructures as a driver of change in marine environments. J. Appl. Ecol. 47, 26-35.

Byers, J.E., Cuddington, K., Jones, C.G., Talley, T.S., Hastings, A., Lambrinos, J.G., Crooks, J.A., Wilson, W.G., 2006. Using ecosystem engineers to restore ecological systems. Trends Ecol. Evol. 21, 493-500.

Campbell, A.H., Marzinelli, E.M., Vergés, A., Coleman, M.A., Steinberg, P.D., 2014. Towards restoration of missing underwater forests. PloS one 9, e84106.

Campbell, T., Benedet, L., 2004. Beach nourishment magnitudes and trends in the US. J. Coast. Res. 39.

Chan, K.M., Shaw, M.R., Cameron, D.R., Underwood, E.C., Daily, G.C., 2006. Conservation planning for ecosystem services. PLoS Biol. 4, e379.

Chapman, M.G., Blockley, D.J., 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. Oecologia 161, 625-635.

Chapman, M.G., 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.

Chapman, P.M., Smith, M., 2012. Assessing, managing and monitoring contaminated aquatic sediments. Mar. Pollut. Bull. 64, 2000-2004.

Chappell, J., Eliot, I., Bradshaw, M., Lonsdale, E., 1979. Experimental control of beach face dynamics by watertable pumping. Eng. Geol. 14, 29-41.

Ciavola, P., Vicinanza, D., Fontana, E., 2008. Beach drainage as a form of shoreline stabilization: case studies in Italy, 31st International Conference on Coastal Engineering. World Scientific, pp. 2646-2658.

CNOOC, 2013. Annual Report. China National Offshore Oil Corporation Limited.

COA, 2012. Offshore Oil and Gas Resources Sector Security Inquiry, Office of the Inspector of Transport Security, Department of Infrastructure and Transport. Commonwealth of Australia, Canberra.

Cooke, B.C., Jones, A.R., Goodwin, I.D., Bishop, M.J., 2012. Nourishment practices on Australian sandy beaches: A review. J. Environ. Manage. 113, 319-327.

Coombes, M.A., Naylor, L.A., Viles, H.A., Thompson, R.C., 2013. Bioprotection and disturbance: Seaweed, microclimatic stability and conditions for mechanical weathering in the intertidal zone. Geomorphology 202, 4-14.

Cooper, J.A.G., McKenna, J., 2008. Working with natural processes: the challenge for coastal protection strategies. Geogr. J. 174, 315-331.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. Nature 387, 253-260.

Creese, R.G., Glasby, T.M., West, G., Gallen, C., 2009. Mapping the habitats of NSW estuaries. I&I NSW Fisheries No. 113. Report to the Hunter Central Rivers Catchment Management Authority, p. 95.

CSIRO, 2009. Water in northern Australia. Summary of reports to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO, Australia, p. 12pp.

Dafforn, K.A., Glasby, T.M., Airoldi, L., Rivero, N.K., Mayer-Pinto, M., Johnston, E.L., 2015. Marine urbanisation: an ecological framework for designing multifunctional artificial structures. Front. Ecol. Environ. 13, 82-90.

Dafforn, K.A., Glasby, T.M., Johnston, E.L., 2008. Differential effects of tributyltin and copper anti-foulants on recruitment of non-indigenous species. Biofouling 24, 23-33.

Dafforn, K.A., Glasby, T.M., Johnston, E.L., 2009. Links between estuarine condition and spatial distributions of marine invaders. Divers. Distrib. 15, 807-821.

Davis, J.L., Takacs, R.L., Schnabel, R., 2006. Evaluating ecological impacts of living shorelines and shoreline habitat elements: an example from the upper western Chesapeake Bay. Management, Policy, Science, and Engineering of Nonstructural Erosion Control in the Chesapeake Bay, 55.

DECC, 2013. Oil and gas: field data, Department of Energy & Climate Change UK.
Dennison, W.C., 2008. Environmental problem solving in coastal ecosystems: A paradigm shift to sustainability. Estuar. Coast. Shelf Sci. 77, 185-196.
Dickie, I., McAleese, L., Pearce, B., Treweek, J., 2013. Marine Biodiversity Offsetting - UK Scoping Study. Report to the Crown Estate, London, UK.
Dugan, J.E., Airoldi, L., Chapman, M.G., Walker, S.J., Schlacher, T., 2011. 8.02 - Estuarine and coastal structures: Environmental effects, a focus on shore and nearshore structures, in: Wolanski, E., McLusky, D. (Eds.), Treatise on Estuarine and Coastal Science. Academic Press, Waltham, pp. 17-41.
Dupont, J.M., 2008. Artificial reefs as restoration tools: a case study on the West Florida Shelf. Coast. Manage. 36, 495-507.
EC, 2010. Oil and Gas Exploration and Production: Questions and Answers. European Commission, Brussels.
EC, 2013. Building a green infrastructure for Europe. European Commission, Belgium.
Esteves, L.S., 2013. Is managed realignment a sustainable long-term coastal management approach? J. Coast. Res. 65, 933-938.
EWEA, 2014. European offshore wind industry - key trends and statistics 1st half 2014, European Wind Energy Association.
Fabi, G., Spagnolo, A., Bellan-Santini, D., Charbonnel, E., Çiçek, B.A., García, J.J.G., Jensen, A.C., Kallianiotis, A., Santos, M.N.d., 2011. Overview on artificial reefs in Europe. Braz. J. Oceanogr. 59, 155-166.
Ferentinos, J., 2013. Global offshore oil and gas outlook. Infield Systems, London.
Firth, L.B., Thompson, R.C., Abbiati, M., Airoldi, L., Bohn, K., Bouma, T.J., Bozzeda, F., Ceccherelli, V.U., Colangelo, M.A., Evans, A., Ferrario, F., Hanley, M.E., Hinz, H., Hoggart, S.P., Jackson, J., Moore, P., Morgan, E.H., Perkol-Finkel, S., Skov, M.W., Strain, E.M., Belzen, J.v., Hawkins, S.J., 2014. Between a rock and a hard place: environmental and engineering considerations when designing coastal defence structures. Coast. Eng. 87, 122-135.
Floerl, O., Inglis, G.J., 2003. Boat harbour design can exacerbate hull fouling. Austral Ecol. 28, 116-127.
Foster, N.M., Hudson, M.D., Bray, S., Nicholls, R.J., 2013. Intertidal mudflat and saltmarsh conservation and sustainable use in the UK: A review. J. Environ. Manage. 126, 96-104.
Freckman, D.W., Blackburn, T.H., Brussaard, L., Hutchings, P., Palmer, M.A., Snelgrove, P.V.R., 1997. Linking Biodiversity and Ecosystem Functioning of Soils and Sediments. Ambio 26, 556-562.
French, P.W., 2006. Managed realignment – The developing story of a comparatively new approach to soft engineering. Estuar. Coast. Shelf Sci. 67, 409-423.
Garbutt, R., Reading, C., Wolters, M., Gray, A., Rothery, P., 2006. Monitoring the development of intertidal habitats on former agricultural land after the managed realignment of coastal defences at Tollesbury, Essex, UK. Mar. Pollut. Bull. 53, 155-164.
GBRMPA, 2013. Great Barrier Reef Biodiversity Conservation Strategy 2013. Great Barrier Reef Marine Park Authority, Townsville.
Gedan, K., Kirwan, M., Wolanski, E., Barbier, E., Silliman, B., 2011. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. Clim. Change 106, 7-29.
Goff, M., 2010. Evaluating Habitat Enhancements of an Urban Intertidal Seawall: Ecological Responses and Management Implications. University of Washington, Washington, USA.
Gordon, A., Langford, W.T., Todd, J.A., White, M.D., Mullerworth, D.W., Bekessy, S.A., 2011. Assessing the impacts of biodiversity offset policies. Environ. Model. Software 26, 1481-1488.
Grayson, J., Chapman, M., Underwood, A., 1999. The assessment of restoration of habitat in urban wetlands. Landscape Urban Plann. 43, 227-236.
Grech, A., Bos, M., Brodie, J., Coles, R., Dale, A., Gilbert, R., Hamann, M., Marsh, H., Neil, K., Pressey, R., 2013. Guiding principles for the improved governance of port and shipping impacts in the Great Barrier Reef. Mar. Pollut. Bull. 75, 8-20.

Hamm, L., Capobianco, M., Dette, H., Lechuga, A., Spanhoff, R., Stive, M., 2002. A summary of European experience with shore nourishment. Coast. Eng. 47, 237-264.
Hanson, H., Brampton, A., Capobianco, M., Dette, H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. Beach nourishment projects, practices, and objectives—a European overview. Coast. Eng. 47, 81-111.
Hashim, R., Kamali, B., Tamin, N.M., Zakaria, R., 2010. An integrated approach to coastal rehabilitation: Mangrove restoration in Sungai Haji Dorani, Malaysia. Estuar. Coast. Shelf Sci. 86, 118-124.
Hoang Tri, N., Adger, W.N., Kelly, P.M., 1998. Natural resource management in mitigating climate impacts: the example of mangrove restoration in Vietnam. Global Environ. Change 8, 49-61.
Hoggart, S.P.G., Hanley, M.E., Parker, D.J., Simmonds, D.J., Bilton, D.T., Filipova-Marinova, M., Franklin, E.L., Kotsev, I., Penning-Rowsell, E.C., Rundle, S.D., Trifonova, E., Vergiev, S., White, A.C., Thompson, R.C., 2014. The consequences of doing nothing: The effects of seawater flooding on coastal zones. Coast. Eng. 87, 169-182.
Holmes, J., Clark, R., 2008. Enhancing the use of science in environmental policy-making and regulation. Environ. Sci. Policy 11, 702-711.
JAPEX, 2015. Domestic Oil and Gas Fields. Japan Petroleum Exploration Co. Ltd.
Kaiser, M.J., 2006a. The Louisiana artificial reef program. Mar. Policy 30, 605-623.
Kaiser, M.J., 2006b. The Texas Artificial Reef Program. Mar. Technol. Soc. J. 40, 62-72.
Kamali, B., Hashim, R., Akib, S., 2010. Efficiency of an integrated habitat stabilisation approach to coastal erosion management. Int. J. Phys. Sci 5, 1401-1405.
Kingsley-Smith, P.R., Joyce, R.E., Arnott, S.A., Roumillat, W.A., McDonough, C.J., Reichert, M.J., 2012. Habitat use of intertidal eastern oyster (Crassostrea virginica) reefs by nekton in South Carolina estuaries. J. Shellfish Res. 31, 1009-1021.
Koike, K., 1996. The countermeasures against coastal hazards in Japan. GeoJournal 38, 301-312.
Kousky, C., 2014. Managing shoreline retreat: a US perspective. Clim. Change 124, 9-20.
Laaksonen, T., 2012. A Market Analysis on the Global Boating Industry. Tampere University of Applied Sciences, Tampere.
Langhamer, O., Wilhelmsson, D., 2009. Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes–a field experiment. Mar. Environ. Res. 68, 151-157.
Lee, S.Y., Dunn, R.J.K., Young, R.A., Connolly, R.M., Dale, P.E.R., Dehayr, R., Lemckert, C.J., McKinnon, S., Powell, B., Teasdale, P.R., Welsh, D.T., 2006. Impact of urbanization on coastal wetland structure and function. Austral Ecol. 31, 149-163.
Leonard, D., Kullmann, H.G., 2010. Design of marine habitat mitigation structure, in: Ward, T., Ostbo, B.I. (Eds.), Ports 2010: Building on the Past, Respecting the Future. American Society of Civil Engineers, Jacksonville, Florida, United States.
Lewis III, R.R., 2005. Ecological engineering for successful management and restoration of mangrove forests. Ecol. Eng. 24, 403-418.
Lozano-Minguez, E., Kolios, A.J., Brennan, F.P., 2011. Multi-criteria assessment of offshore wind turbine support structures. Renew. Energ. 36, 2831-2837.
Macreadie, P.I., Fowler, A.M., Booth, D.J., 2011. Rigs-to-reefs: will the deep sea benefit from artificial habitat? Front. Ecol. Environ. 9, 455-461.
McKenney, B.A., Kiesecker, J.M., 2010. Policy development for biodiversity offsets: a review of offset frameworks. Environ. Manage. 45, 165-176.
MIAA, 2010. Size and Characteristics of the Australian Marina Sector. Marina Industries Associtaion of Australia.
Morang, A., Waters, J.P., Stauble, D.K., 2014. Performance of Submerged Prefabricated Structures to Improve Sand Retention at Beach Nourishment Projects. J. Coast. Res. 30, 1140-1156.
Nagelkerken, I., Sheaves, M., Baker, R., Connolly, R.M., 2013. The seascape nursery: a novel spatial approach to identify and manage nurseries for coastal marine fauna. Fish Fish., n/a-n/a.
Naidoo, R., Ricketts, T.H., 2006. Mapping the economic costs and benefits of conservation. PLoS Biol. 4, e360.

Naylor, L.A., Coombes, M.A., Venn, O., Roast, S.D., Thompson, R.C., 2012. Facilitating ecological enhancement of coastal infrastructure: The role of policy, people and planning. Environ. Sci. Policy 22, 36-46.

Nelson, E., Mendoza, G., Regetz, J., Polasky, S., Tallis, H., Cameron, D., Chan, K.M.A., Daily, G.C., Goldstein, J., Kareiva, P.M., Lonsdorf, E., Naidoo, R., Ricketts, T.H., Shaw, M., 2009. Modeling multiple ecosystem services, biodiversity conservation, commodity production, and tradeoffs at landscape scales. Front. Ecol. Environ. 7, 4-11.

Nelson, E., Polasky, S., Lewis, D.J., Plantinga, A.J., Lonsdorf, E., White, D., Bael, D., Lawler, J.J., 2008. Efficiency of incentives to jointly increase carbon sequestration and species conservation on a landscape. Proc. Natl. Acad. Sci. USA 105, 9471-9476.

NSWDECC, 2009. Environmentally Friendly Seawalls: A Guide to Improving the Environmental Value of Seawalls and Seawall-lined Foreshores in Estuaries. NSW Department of Environment and Climate Change, Sydney, Australia.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., KÖHler, M., Liu, K.K.Y., Rowe, B., 2007. Green roofs as urban ecosystems: ecological structures, functions, and services. Bioscience 57, 823-833.

OffshoreWind.net, 2012. North American Offshore Wind Project Information. OffshoreWind.

Orth, R.J., Carruthers, T.J.B., Dennison, W.C., Duarte, C.M., Fourqurean, J.W., Heck, K.L., Hughes, A.R., Kendrick, G.A., Kenworthy, W.J., Olyarnik, S., Short, F.T., Waycott, M., Williams, S.L., 2006. A global crisis for seagrass ecosystems. Bioscience 56, 987-996.

Owens, S., Petts, J., Bulkeley, H., 2006. Boundary work: knowledge, policy, and the urban environment. Environ. Plann. 24, 633.

Papadopoulou-Vrynioti, K., Alexakis, D., Bathrellos, G.D., Skilodimou, H.D., Vryniotis, D., Vassiliades, E., Gamvroula, D., 2013. Distribution of trace elements in stream sediments of Arta plain (western Hellas): the influence of geomorphological parameters. Journal of Geochemical Exploration 134, 17-26.

Pérez-Alberti, A., Pires, A., Freitas, L., Chaminé, H., 2013. Shoreline change mapping along the coast of Galicia, Spain, Proceedings of the ICE - Maritime Engineering, pp. 125-144.

Pérez-Alberti, A., Trenhaile, A., Pires, A., López-Bedoya, J., Chaminé, H., Gomes, A., 2012. The effect of boulders on shore platform development and morphology in Galicia, north west Spain. Cont. Shelf Res. 48, 122-137.

Perkol-Finkel, S., Ferrario, F., Nicotera, V., Airoldi, L., 2012. Conservation challenges in urban seascapes: promoting the growth of threatened species on coastal infrastructures. J. Appl. Ecol. 49, 1457-1466.

Peterson, C.H., Bishop, M.J., 2005. Assessing the environmental impacts of beach nourishment. Bioscience 55, 887-896.

Piazza, B.P., Banks, P.D., La Peyre, M.K., 2005. The potential for created oyster shell reefs as a sustainable shoreline protection strategy in Louisiana. Restor. Ecol. 13, 499-506.

Piola, R.F., 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., Johnston, E.L., 2009. Comparing differential tolerance of native and non-indigenous marine species to metal pollution using novel assay techniques. Environ. Pollut. 157, 2853-2864.

Pires, A., Chaminé, H.I., Piqueiro, F., Rocha, F., 2013. Coastal Geo-Engineering Techniques for the Assessment of Rock Armour Structures. Marine Georesources & Geotechnology 32, 155-178.

Pires, A.C., Gomes, A., Chaminé, H.I., 2009. Dynamics of coastal systems using GIS analysis and geomaterials evaluation for groins. Environmental & Engineering Geoscience 15, 245-260.

Regnery, B., Kerbiriou, C., Julliard, R., Vandevelde, J., Le Viol, I., Burylo, M., Couvet, D., 2013. Sustain common species and ecosystem functions through biodiversity offsets: Response to Pilgrim et al. Conserv. Lett 6, 385-386.

Rogers, K., Saintilan, N., Copeland, C., 2014. Managed retreat of saline coastal wetlands: challenges and opportunities identified from the Hunter River Estuary, Australia. Estuaries and Coasts 37, 67-78.

Ryan, A., Gorddard, R., Abel, N., Leitch, A., Alexander, K., Wise, R., 2011. Perceptions of Sea-Level Rise Risk and the Assessment of Managed Retreat Policy: Results from an Exploratory Community Survey in Australia. CSIRO: Climate Adaptation National Research Flagship, Australia, p. 54pp.

Schiff, K., Brown, J., Diehl, D., Greenstein, D., 2007. Extent and magnitude of copper contamination in marinas of the San Diego region, California, USA. Mar. Pollut. Bull. 54, 322-328.

Seaman, W., 2007. Artificial habitats and the restoration of degraded marine ecosystems and fisheries. Hydrobiologia 580, 143-155.

SER, 2002. The SER Primer on Ecological Restoration, in: Restoration, S.f.E. (Ed.), SER International Science and Policy Working Group.

Skilodimou, H., Th Stefouli, M., Bathrellos, G., 2002. Spatio-temporal analysis of the coastline of Faliro Bay, Attica, Greece. Estudios Geológicos 58, 87-93.

Smith, 2006. Intregrating habitat and shoreline dynamics into living shoreline applications, in: Erdle, S.Y., Davis, J.L.D., Sellner, K.G. (Eds.), Management, policy, science, and engineering of nonstructural erosion control in the Chesapeake Bay, Proceedings of the 2006 Living Shoreline Summit, Chesapeake Bay.

Society, G., 2001. The Earth in our hands. 7 - Coastal erosion, in: London, T.G.S.o. (Ed.), London.

SPUR, 2012. Ocean beach master plan. San Francisco Planning and Urban Research Association, San Francisco.

Strauss, B.H., Ziemlinski, R., Weiss, J.L., Overpeck, J.T., 2012. Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States. Environmental Research Letters 7, 014033.

Suding, K.N., 2011. Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42, 465.

Suding, K.N., Gross, K.L., Houseman, G.R., 2004. Alternative states and positive feedbacks in restoration ecology. Trends Ecol. Evol. 19, 46-53.

Thomas, C.D., 2011. Translocation of species, climate change, and the end of trying to recreate past ecological communities. Trends Ecol. Evol. 26, 216-221.

Troell, M., Joyce, A., Chopin, T., Neori, A., Buschmann, A.H., Fang, J.-G., 2009. Ecological engineering in aquaculture — Potential for integrated multi-trophic aquaculture (IMTA) in marine offshore systems. Aquaculture 297, 1-9.

Turner, I.L., Leatherman, S.P., 1997. Beach dewatering as a'soft'engineering solution to coastal erosion: a history and critical review. J. Coast. Res., 1050-1063.

Vicinanza, D., Guida, A., Ferrante, V., Ciavola, P., 2010. Performance of a Beach Dewatering System-Chiaiolella Beach, Procida Island, Italy. J. Coast. Res., 753-761.

Waltham, N.J., Connolly, R.M., 2011. Global extent and distribution of artificial, residential waterways in estuaries. Estuar. Coast. Shelf Sci. 94, 192-197.

Waltham, N.J., Sheaves, M., 2015. Expanding coastal urban and industrial seascape in the Great Barrier Reef World Heritage Area: Critical need for coordinated planning and policy. Mar. Policy 57, 78-84.

Waltham, N.J., Teasdale, P.R., Connolly, R.M., 2011. Contaminants in water, sediment and fish biomonitor species from natural and artificial estuarine habitats along the urbanized Gold Coast, Queensland. J. Environ. Monit.

Widmer, W., Underwood, A., Chapman, M., 2002. Recreational boating on Sydney Harbour. Public perception of potential environmental impacts. Natural Resource Management 5, 22-27.

Wilson, J.C., Elliott, M., Cutts, N.D., Mander, L., Mendão, V., Perez-Dominguez, R., Phelps, A., 2010. Coastal and offshore wind energy generation: Is it environmentally benign? Energies 3, 1383-1422.

List of Figures

Figure 1. Conceptual diagram of the key marine spatial planning challenges and opportunities in the coastal zone. (a) unmanaged coastal zone has widespread loss of natural wetland features and habitat; system is operating under reduced capacity, and deteriorating water quality health. Opportunities to repair and restore exist, though require stakeholder consideration and marine spatial planning approaches. (b) managed coastal area under a program of spatial planning, that achieves a balance for users and services essential for ecosystems.

Figure 2. Examples of unplanned (A-D) and managed (E-H) coastal and offshore scenarios. A. Unmodified homogenous seawalls for coastal defence lack a diverse natural assemblage (Photo: R. Morris), B. Operational offshore platform supports resource extraction (Photo: N. Rivero), C. Groynes trap sediment to reduce longshore drift with negative consequences further down the coast (Photo: © ricul), D. Untreated stormwater enters the catchment (Photo: K. Dafforn), E. Eco-engineering of structures to enhance biodiversity (e.g. "flowerpots") (Photo: R. Morris), F. Decommissioned offshore platform supports tourism and recreational activities (Photo: © beusbeus), G. Managed retreat enhances coastal defence and provides recreational (e.g. pocket beaches) (Photo: K. Dafforn), H. Oyster reef restoration e.g. "oyster castles" provides natural protection and a contaminant trap (Photo: K. Dafforn).

Table 1 – The extent of current marine infrastructure		
Infrastructure	**Extent**	**Refs.**
Recreational infrastructure	Australia: 356 marinas and approx. 800,000 registered recreational boats	(MIAA, 2010)
	United Kingdom: 545 marinas/yacht harbours, 541,560 recreational boats	(Laaksonen, 2012)
	Europe: 2700 Germany, >1500 Sweden, 1135 Netherlands, 1293 Poland, 1770 Finland, 421 Italy, 358 Spain, 250 Denmark, 156 Croatia, 22 Greece, 22 Ireland, 15 Czech Rep marinas/yacht harbours; 881,000 Sweden, 737,000 Finland, 617,638 Italy, 523,000 Netherlands, 506,000 France, 503,795 Germany, 219,998 Spain, 151,331 Greece, 58,585 Poland, 55,000 Denmark, 27,000 Ireland, 16,283 Czech Rep recreational boats	(Laaksonen, 2012)
	United States: ~11,000 marinas/yacht harbours, ~16.6 million recreational boats	(Laaksonen, 2012)
	Asia: 570 marinas/yacht harbours, ~224,000 recreational boats in Japan	(Laaksonen, 2012)
Coastal and foreshore defence infrastructure	Australia: 32 – 49% of foreshore modified with seawalls in some Sydney estuaries	(Creese et al., 2009)

	United Kingdom: 44% of coastline in England and Wales defended with hard engineering	(Society, 2001)
	Europe: 22 000 km2 of coastal zone armoured	(Airoldi and Beck, 2007)
	United States: > 50 % of some estuaries and bays modified and ca. 5 – 30% coastlines armoured	(Dugan et al., 2011)
	Asia: ca. 27 % of 34 500 km of Japan's coastline hardened with coastal defence structures	(Koike, 1996)
Offshore energy resources	Australia: Wind: no current proposals Oil & Gas: > 17 oil & gas fields, largest in Bass Strait comprises 23 platforms	 (Amin, 2014) (COA, 2012)
	United Kingdom: Wind: 18 wind farms, >700 individual turbines Oil & Gas: 170 operational oil fields, 132 operational gas fields	 (Amin, 2014) (DECC, 2013)
	Europe: Wind: 73 wind farms, 2304 individual turbines Oil & Gas: 181 Netherlands, 6 Ireland, 123 Italy, 4 Spain, 2 Greece, 7 Romania, 1 Bulgaria, 3 Poland	 (EWEA, 2014) (EC, 2010)

	United States: Wind: 5 active projects Oil & Gas: 2634 Gulf of Mexico, 23 Pacific installations	 (OffshoreWind.net, 2012) (BSEE, 2013)
	Asia: Wind: 5 wind farms, 70 individual turbines (China); 1 wind farm, 1 individual turbine (South Korea), 3 wind farms, 17 individual turbines (Japan) Oil & Gas: China > 20 oil fields, 257,292 km2 exploration areas, China > 5 gas fields, Japan 1 oil & gas field	 (Amin, 2014) (CNOOC, 2013; JAPEX, 2015)
	South America: Oil & Gas: Brazil > 20 oil fields	 www.petrobras.com.br
Artificial reefs	Australia: 2 Western Australia, 19 South Australia, 6 Queensland, 1 New South Wales	
	United Kingdom: 6 reefs	(Fabi et al., 2011)

	Europe: 103 Spain, 70 Italy, 30 France (total 246)	(Fabi et al., 2011)
	United States: 83 reefs from 120 decommissioned oil and gas platforms Louisiana, >35 reefs from 70 decommissioned oil and gas platforms Texas, 448 artificial reef sites covering ~664 nm2 (~300 active) concrete materials dominate (38%) followed by concrete modules (30%), steel vessels and barges (11%), bridge materials (9%), military equipment- mainly armored combat tanks (4%), steel materials (4%), limestone (3%) and miscellaneous materials (0.8%) Florida, Delaware - 14 reefs; Maryland - 20 artificial reef sites of Chesapeake Bay and 10 permitted reef sites on the oceanside/coastal bays; 8 fishing reefs in the ocean; one research reef in the ocean and one small reef in the bay behind Ocean City.	(Kaiser, 2006a), EPA, USA (website, accessed 19-01-2015)(Kaiser, 2006b)
	Asia: 44 throughout Asia	(Baine, 2001)
	South America: Brazil: At least 2 sets of 16 artificial reefs made by concrete and tire on the North coast of Rio de Janeiro	Zalmon
Artificial residential waterways	Australia & New Zealand: 93 canals and lakes, 381 km long, 35 km2	(Waltham and Connolly, 2011)

	Europe: 27 canals and lakes, 279 km long, 9 km2	(Waltham and Connolly, 2011)
	North America: 150 canals and lakes, 2960 km long, 171 km2	(Waltham and Connolly, 2011)
	Asia: 29 canals and lakes, 300 km long, 43 km2	(Waltham and Connolly, 2011)

977

Table 2 – Coastal infrastructure management strategies from engineering and ecosystem perspectives

Management strategy	Definition and examples	Refs.
Hard engineering	Hard structures engineered to prevent land-sea interactions e.g. offshore breakwaters e.g. seawalls e.g. groynes e.g. dykes	(Cooper and McKenna, 2008)
Eco-engineering	Combines hard engineering principles with ecological processes e.g. artificial crevices e.g. artificial rock pools e.g. “Bioblocks” e.g. “Flowerpots”	(Chapman and Underwood, 2011)
Soft engineering	Human controls on natural processes but without hard structures e.g. beach nourishment e.g. artificial dune construction e.g. saltmarsh creation e.g. managed retreat	(Cooper and McKenna, 2008)

Habitat restoration	The process of assisting the recovery of an habitat that has been degraded, damaged or destroyed e.g. mangrove restoration e.g. saltmarsh restoration e.g. dune restoration e.g. oyster reef restoration	(SER, 2002)

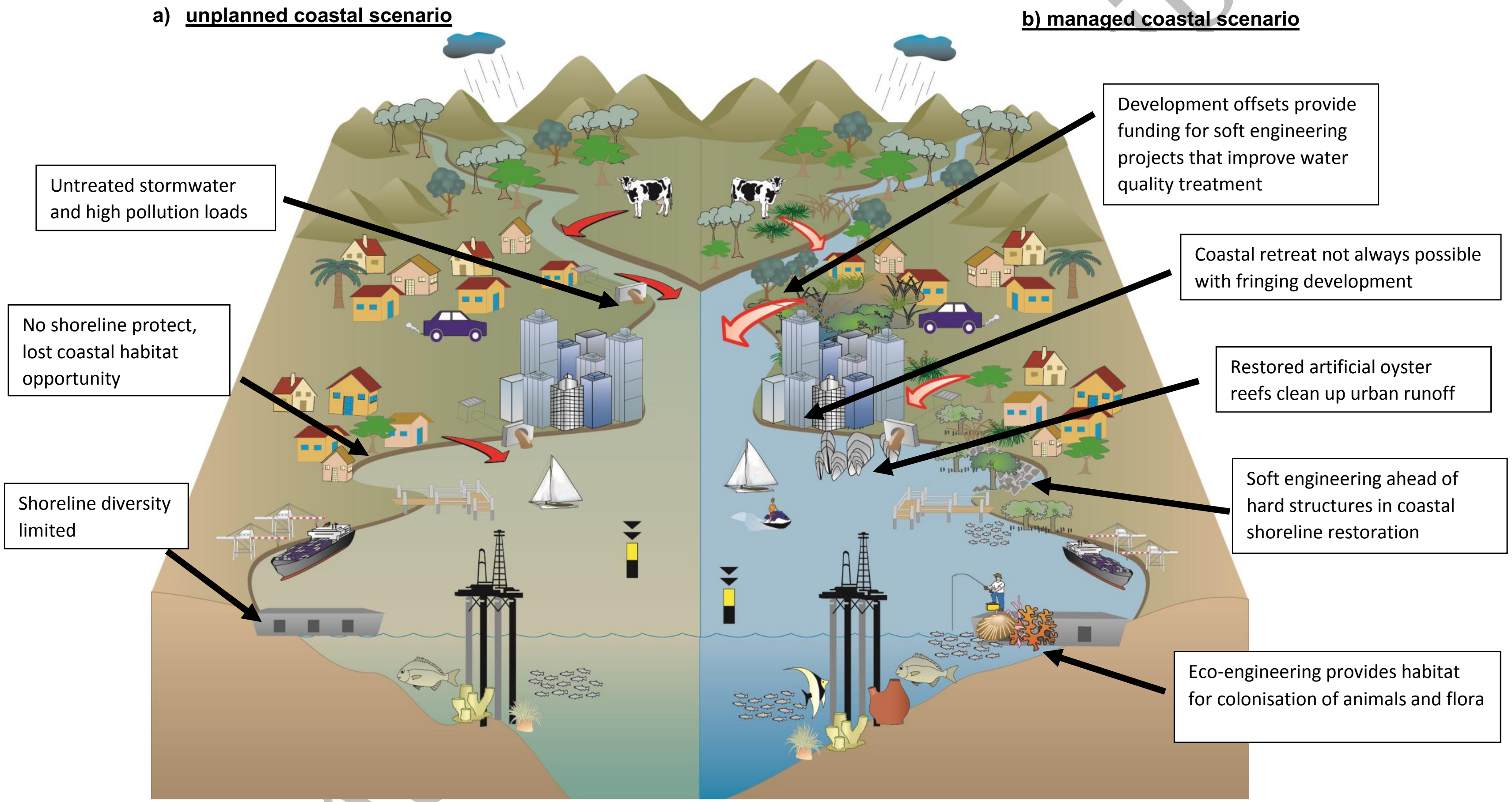
a) unplanned coastal scenario
b) managed coastal scenario
Untreated stormwater and high pollution loads
No shoreline protect, lost coastal habitat opportunity
Shoreline diversity limited
Development offsets provide funding for soft engineering projects that improve water quality treatment
Coastal retreat not always possible with fringing development
Restored artificial oyster reefs clean up urban runoff
Soft engineering ahead of hard structures in coastal shoreline restoration
Eco-engineering provides habitat for colonisation of animals and flora

Fig 1.

988


A - Unmodified homogenous seawalls for coastal defence lack a diverse natural assemblage
E - Eco-engineering of structures to enhance biodiversity (e.g. "flowerpots")
B – Operational offshore platform supports resource extraction
F – Decommissioned offshore platform supports tourism and recreational activities
C – Groynes trap sediment to reduce longshore drift with negative consequences further down the coast
G – Managed retreat enhances coastal defence and provides recreational (e.g. pocket beaches)
D – Untreated stormwater enters the catchment
H – Oyster reef restoration e.g. "oyster castles" provides natural protection and a contaminant trap

Fig. 2