Ocean & Coastal Management 156 (2018) 277–289

Contents lists available at ScienceDirect

Ocean & Coastal Management

journal homepage: www.elsevier.com/locate/ocecoaman

Use of ecosystems in coastal erosion management

A. Gracia [a, *], Nelson Rangel-Buitrago [a, b], Judith A. Oakley [c], A.T. Williams [c, d]

[a] Departamento de Biología, Facultad de Ciencias Básicas, Universidad del Atlántico, Km 7 Antigua vía Puerto Colombia, Barranquilla, Atlántico, Colombia
[b] Departamento de Física, Facultad de Ciencias Básicas, Universidad del Atlántico, Km 7 Antigua vía Puerto Colombia, Barranquilla, Atlántico, Colombia
[c] Faculty of Architecture, Computing and Engineering, University of Wales: Trinity Saint David (Swansea), Mount Pleasant, Swansea, Wales, United Kingdom
[d] Interdisciplinary Centre of Social Sciences, (CICS.NOVA.FCSH/UNL), Avenida de Berna, 26 C, 1069-061, Lisboa, Portugal

ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form
29 June 2017
Accepted 12 July 2017
Available online 20 July 2017

Keywords:
Coastal erosion
Adaptation
Protection
Ecosystems
Management
Engineering

ABSTRACT

With a global increase in coastal development, together with increasing storminess and continuing sea level rise, coastal erosion has become a serious problem along a significant percentage of coastlines of many countries. Coastal erosion and shoreline management plans are often implemented on an action-reaction and post-disaster basis, resulting in installation of hard engineering structures, such as, groins, seawalls, revetments, gabions and breakwaters. These hard stabilization structures usually alter the natural environment of the coast, producing negative impacts. They do little to work with nature, and sustainability is a currently a critical issue. Under present and future environmental conditions, the world requires smarter coastal protection strategies that are adaptable, sustainable, multi-functional and economically viable to help solve immediate and predicted coastal erosion problems. An ecosystem-based approach based on the creation and restoration of coastal ecosystems, such as wetlands (e.g. mangroves), biogenic reef structures (e.g. corals, oysters, and mussels), seagrass beds and dune vegetation can offer optimal natural alternatives to help solve coastal erosion. Coastal ecosystems have some capacity for self-repair and recovery, and can provide significant advantages over traditional hard engineering approaches against coastal erosion. Also, they play a vital role in reducing the susceptibility of coastal communities to hazards through their multiple roles in processes, including sediment capture, system roughness and thus attenuation of wave energy. This paper seeks to undertake a general review of adaptation and protection measures against coastal erosion issues, based on incorporation of ecology and ecosystem services into coastal erosion management strategies.

Contents

* Corresponding author.
E-mail address: mariaadrianagracia@mail.uniatlantico.edu.co (A. Gracia).

http://dx.doi.org/10.1016/j.ocecoaman.2017.07.009

1. Introduction

Currently, a high percentage of world coastlines experience issues related to coastal erosion (Zhu, 2010; Pilkey and Cooper, 2014). Under current conditions of a warming climate and rising sea levels, it is expected that coastal erosion processes will shortly reach unmanageable proportions for humanity (Jones and Phillips, 2011; Shi and Kasperson, 2015). The coastal erosion problem becomes much more significant, as coastlines are the ideal place for human concentrations, and the development of different productive activities (Barragan and Andreis, 2015).

The complexity of coastal erosion causes has been addressed worldwide in many studies (Van Rijn, 2011; Pranzini and Williams, 2013), and interrelationships between anthropogenic influences and natural processes have been emphasized (Rangel-Buitrago et al., 2015a,b). In general terms, coastal erosion processes are produced by factors that can be contrasted and include, amongst others: relative sea level rise (RSLR), extreme wave events and alteration in the sediment supply, both natural and human induced.

Most of the world's megacities are situated in the coastal zone where a very particular combination of geographic, economic, and historical conditions are still attracting people and stimulating different migration processes (Brown et al., 2009; Seto et al., 2011; Barragan and Andreis, 2015). Only in the last half century have world coastline populations recorded values close to 3% of the annual average standards for urban growth rate. Under current climate change scenarios, it has been estimated that along low coastlines, almost 30% of residences, if sited within 200 m from the sea, may be severely affected by erosion-related property losses over at least the next 50 years (UN-Habitat, 2009; Leatherman, 2017).

The above, demands urgent sustainable development strategies with implementation of adequate coastal erosion management plans (EU, 2004; Boruff et al., 2005; Pranzini and Williams, 2013). Management plans must become an issue of widespread worldwide concern. Unfortunately, a high percentage of the decision-making within coastal erosion management is strongly conditioned by economic considerations, based on a cost-benefit analysis approach (Cooper and McKenna, 2008) or an action-reaction basis (Rangel-Buitrago et al., 2015a,b, 2017).

Coastal erosion management strategy choice must be a function of a series of variables that include: erosion severity, property rights, funding/legislation, and aesthetics (Williams et al., 2017). Likewise, management strategies must include the techniques, knowledge, equipment, and institutional instruments required to minimize or eliminate coastal erosion related impacts.

Currently, four options can be identified as the main coastal erosion management strategies (see Williams et al., 2017):

- **Protection:** preservation of population centres, economic activities and natural resources (vulnerable areas) using hard structures and/or soft protection measures.
- **Accommodation:** occupying sensitive areas, but acceptance of a greater degree of flooding by changing land use, construction methods and improving preparedness.
- **Planned retreat:** removing structures in developed areas, resettling inhabitants with the requirement that new development is set back from the coast, as appropriate.
- **Sacrifices:** allowing property loss when the suggested protection is non-viable, or the accommodation and retreat option does not exist.

Usually, the protection approach using hard structures is widely perceived as the best coastal erosion management strategy, and in many countries this method is the only alternative (Pranzini, 2017; Rangel-Buitrago et al., 2017). However, hard structures are not necessarily the most adequate solution, and their negative influence has been seen as a critical problem along many coastlines around the world (Griggs, 2005; Charlier et al., 2005; Pranzini and Williams, 2013; Pilkey and Cooper, 2014; Rangel-Buitrago et al., 2017). Hard protection approaches can generate adverse effects such as:

- Accelerated bottom erosion in front of the structure and downdrift scouring.
- Disturbance of sediment supply and beach reduction.
- Alteration of alongshore sediment transport.
- Restricted public access.
- Potential risks for bathers.
- Negative visual effects on the seaside landscape (scenery).

Hard structures are severely challenged in many locations, and are becoming unsustainable due to their costly and continual maintenance requirements, as well as any widening and height increase to keep in step with the increasing coastal erosion risk. Additionally, such structures significantly alter the natural adaptive capacity of any coastline (Temmerman et al., 2013).

Negative experiences prevail over positive ones in the implementation of hard structures as protection measures against coastal erosion due to interfering processes operating at a wide spatial scale (>100 km, Pilkey and Young, 2009; Neal et al., 2017; Rangel-Buitrago et al., 2017; Williams et al., 2017). To avoid such negative experiences, correct application of adequate management policy is required to preserve ecosystems as well as socio-economic activities.

Recently, an ecosystem-based coastal erosion management strategy has been brought into practice as an approach that is more cost-effective, and sustainable, than conventional hard protection approaches (ecosystem-based approach). Management based on habitat diversification can be applied worldwide, particularly in areas that have space between existing urbanization and the coastline to allow for ecosystem development (for example into accommodation and planned retreat strategies). Because ecosystems have the natural ability to reduce extreme wave effects (Shepard et al., 2011), their growth can keep pace with sea-level rise by means of sediment accretion if available (Kirwan et al., 2010), and provide other benefits that go beyond the realm of the coastal protection (e.g. supporting fisheries and tourism, reducing CO_2, amongst others).

This paper reviews adaptation and protection measures against coastal erosion issues based on incorporation of ecosystems. Information presented will be useful to local and national coastal managers and planners who need fresh and innovative approaches, and are a basis for ascertaining facts on which to make sound management decisions that can be implemented into coastal erosion management.

2. Ecosystem management: a necessary step in coastal erosion management

The UNEP (2009) defined Ecosystem Management as "an integrated process to conserve and improve ecosystem health that sustains ecosystem services for human well-being", combining two particular actions:

- Develop and/or maintain ecosystems quality.
- Attempt to ensure in the best way the delivery of different ecosystem services to human well-being.

Under current climate-change conditions, ecosystem management must be incorporated into coastal erosion management strategies because services provided by ecosystems, such as climate regulation, coastal hazards protection and water purification, are necessary for any coastal adaptation and risk reduction scheme (Fig. 1).

Adequate ecosystem management can provide benefits for coastal erosion management and in turn, these benefits include:

Providing a different physical defence from coastal erosion: A healthy ecosystem has the ability to offer to society a high protection from coastal erosion, and, at the same time improve their capacity to cope with the related impacts (Nordstrom, 2005; Borsje et al., 2011).

Increasing co-benefits in the mitigation of climate change responsible for coastal erosion: Climate change increases coastal erosion with sea level rise, and alteration in the intensity and frequency of extreme climate events. Likewise, climate-change impacts usually aggravate problems that coastal areas already face (Masselink and Russell, 2013). Management of the ecosystem can reduce emissions and fix carbon, increasing or maintaining adequate stocks in the different ecosystems (Trumper et al., 2009). Biological carbon sequestration is a useful tool in efforts to mitigate climate change and further related coastal erosion impacts. Also, ecosystems can support achievement of other kinds of economic and social objectives for coastal communities.

Stimulating biodiversity conservation: Ecosystem management can help biodiversity and people in adjusting to changing conditions, and can be used as a tool to safeguard fragile ecosystems and even create new protected areas. This management approach can involve restoration of ecosystems and replication of missing ecosystem processes, such as migration or pollination (Colls et al., 2009). It is important to take into account that an increase of biodiversity, *per se*, does not necessarily contribute to a better functioning system. These functions can be achieved by the use of new approaches, such as Ecological Network Analysis, a management methodology which analyzes within system interactions used to identify holistic properties that are otherwise not evident from direct observations (Fath, 2004).

Strengthening the resilience of natural systems and also human societies to coastal erosion effects: Improving and conserving ecosystem health is paramount for sustaining necessary services in the coastal zone, as well as human well-being. Ecosystems in the right conditions can act as a buffer, increasing resilience of natural and human systems to coastal erosion impacts (Biggs and Smith, 2002). Achieving this requires that ecosystems are viewed as suppliers of a range of intermediate and final services (ES approach - De Jonge et al., 2012) through which human welfare benefits. Sustainable utilisation of this vital resource base is therefore the key notion. It can be argued that assigning monetary values to the benefits provided by 'healthy' ecosystems can supplement scientific and ethical arguments, in favour of environmental protection and biodiversity conservation (Turner et al., 2010). According to De Jonge et al. (2014), there are two complementary ways to achieve this goal:

- Optimisation of the physical habitat-providing conditions.
- Improvement of ecosystem Biome quality.

Inspiring and encouraging community participation in coastal erosion management processes: Optimal ecosystem management tends to provide highly valued and attractive community amenities for coastal communities, for example, scenery exploitation of natural beaches, salt marshes, intertidal areas and small islands for economic purposes (Williams et al., 2016; Rangel-Buitrago et al., 2017).

The need for ecosystem management is recognized worldwide as progressing from the local to the international level. The UN Climate Change Conference, Paris 2015 (COP21) and the more recent UN Biodiversity Conference, Cancun 2016 (COP13) concluded that erosion is a real hazard for many coastal regions, and included ecosystem management in coastal erosion management strategies as a priority. Parties to the UN Framework Convention on Climate Change (developed in 1992) adopted an adaptation framework, which included recommendations that ecosystems can serve as a tool for coastal erosion management. To currently follow these recommendations is a real challenge faced by all Parties involved (developing and developed countries). This challenge mainly aims to reduce coastal erosion vulnerability and build resilience to this hazard in all countries, taking into account the urgent needs of those that are particularly vulnerable (UNFCCC, 2011; Spalding et al., 2014).

Inclusion of ecosystems services into coastal erosion management also strengthen the planning and targets defined in the COP13, which calls for such inclusions in national and local development and planning processes as well as in poverty reduction strategies (CBD, 2010).

All of the above confirm that coastal ecosystems both serve and play significant roles in coastal protection schemes, and minimize the vulnerability of coastal zones. These potential positive results have led to a growing alert for incorporation of ecosystems into coastal management and planning (Heath et al., 2009; World Bank, 2009; Van Slobbe et al., 2013).

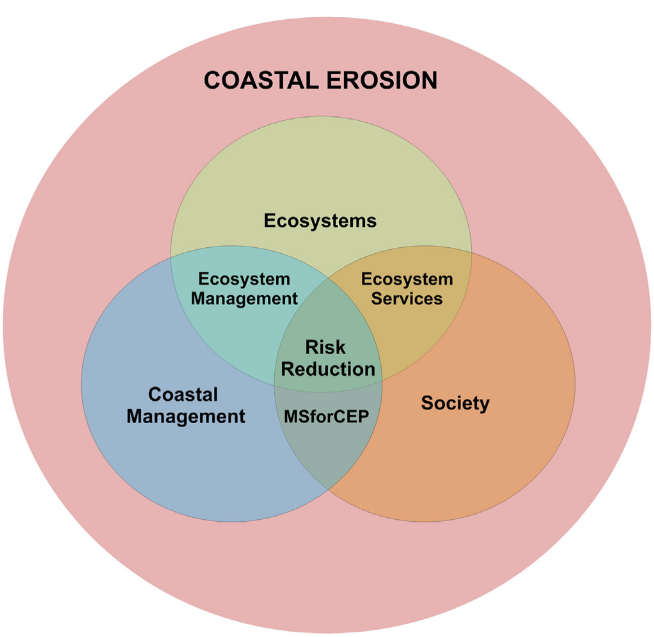

Fig. 1. Risk reduction by means of ecosystems, society and coastal management. MSforCEP: Management Strategies for Coastal Erosion Process.

3. Ecosystems: functions and examples

When applying the ecosystem-based approach, it is necessary to understand key aspects related to coastal protection services of some ecosystems, as well as critical variables that determine their relative effectiveness in coastal erosion management. This can be explained further as follows:

3.1. Coral reefs

Corals are symbiotic organisms whose skeleton consists of calcium carbonate ($CaCO_3$) in the form of aragonite, which has allowed them to become the main builders of reef structures in the tropics (Veron, 2000). Coral reefs are built by scleractinian or hermatypic (stony) coral polyps that require a stable surface on which to settle. They grow in warm, shallow, and nutrient depleted tropical waters and these scleractinian corals are slow growing. Some massive corals may build a skeleton at rates of just a few millimetres per year. Living coral reefs are located mainly in the tropics and sub-tropics between approximately 30°N and 30°S (Done et al., 1996), with diversity diminishing fairly rapidly along latitudinal lines. Coral reefs have more species and co-evolved relationships per unit area than any other marine ecosystem (Done et al., 1996).

Corals have many functions in the coastal erosion management process, but the most important are related to energy dissipation and sediment generation (Fig. 2). Perhaps the most evident are linked to their shape and structure that allows coral reefs to act as a barrier that dissipates wave energy, providing a natural submerged breakwater. The geometry (porosity, surface, tortuosity, roughness and the overall void matrix), water depth above the reef system (depth of flow) and length in the direction of wave propagation are key points in the wave energy dissipation process (Hettiarachchi et al., 2013).

$CaCO_3$ that forms this ecosystem allows construction of skeletons that have a double function: building the ecosystem and generating sediments. Fragmentation and erosion processes (including bio-erosion) transform this compact structure into biogenic, calcareous sands able to feed the coast and maintain its stability.

Corals can also contribute to sedimentation by means of allogenic processes related to mucous secretions. Coral secretions trap suspended particles in the water column, forming aggregates that sink rapidly to the bottom (Wild et al., 2004). Secretions by corals can make it the dominant form of suspended organic matter within and around coral reefs (Marshall, 1968) so particle trapping by mucus may significantly contribute to the sedimentation process.

The importance of coral in coastal erosion management strategies, is well documented, for example, Wielgus et al. (2010) determined that ten years after the disappearance of some species of live corals in the Dominican Republic, erosion rates increased between 65 and 100% along the SE sector of the country, due to substantial sedimentary deficits.

A good example, highlighting the role of corals in coastal erosion management and the importance of the maintenance of ecosystem health, can be found in Sri Lanka. Along the Hikkaduwa coastline, corals are protected in a marine park. During extreme coastal erosion related to the Sumatra tsunami of 26 December 2004, waves were only 2–3 m high, due to energy dissipation benefits provided by the corals, with "damage caused" limited only to a distance of 50 m inland. During the same event, 10 m high waves were generated, causing damage and flooding up to 2 km inland along the Peraliya coastline. This area is located just 3 km from Hikkaduwa, but here the reefs have been extensively affected by bad management practices (Fernando et al., 2005; Liu et al., 2005).

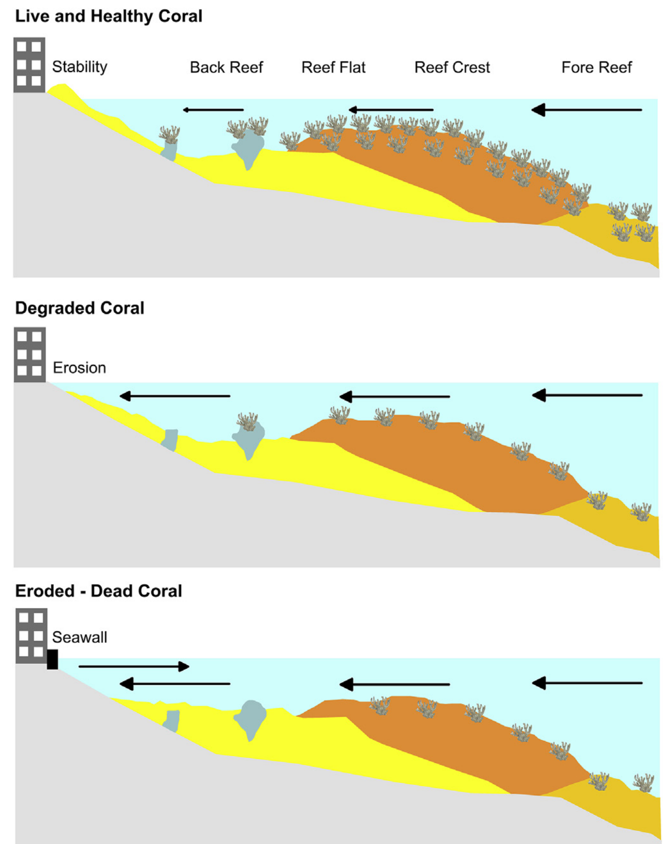

Fig. 2. Wave attenuation and coastal erosion protection given by coral under different management scenarios.

3.2. Mangroves

Mangroves are assemblages of salt-tolerant trees and shrubs found in intertidal zones and estuarine margins, on shallow and muddy ground, with calm waters (estuaries, bays, coves, coastal lagoons, etc.). The vegetation has adapted to live in salt water, either continuously or during high tides. Mangroves grow in harsh environmental settings, such as, high salinity, high temperature, high sedimentation, extreme tides, and anaerobic soils (Giri et al., 2011). The trees have adaptations in their roots, leaves, and trunk, allowing them to grow in unstable terrain, without oxygen and flooded with sea water. The roots of the mangroves are crucial because they allow the plant to catch O_2 and have structures in the stems and leaves that help to expel excess salt absorbed from the root. Mangrove forests can be found in both tropical and subtropical areas of the world between approximately 30° N and 30° S. In 2000, the global mangrove forest total surface area was estimated to be 137,760 km^2 in 118 countries and territories and about 75% of this area is concentrated in 15 countries (Dayton et al., 2005; Giri et al., 2011).

Mangroves are termed "ecosystem engineers" because the conjunction of their intrinsic properties (width, structure, tree size), their link with other ecosystems and also underpinning factors can be useful in the reduction of coastal erosion (Fig. 3). This ecosystem has the ability to significantly reduce the energy of any kind of fluid that is moving through them. The energy lost when wind and waves pass through mangrove roots and branches can range between 15 and 65%, minimizing seabed scour and further sediment movement (Spalding et al., 2014). At the same time, their structure can reduce winds across the surface of the water, reducing the re-formation or propagation of waves.

Mangrove forest structure is a key point in determining possible protection during extreme erosive wave events and tsunamis. For example, narrower belts can reduce impacts of high wind speeds and large waves occurring during major storms, while extensive areas can reduce severe storm surge floods and tsunami waves. Of course, this capacity also depends on the size and forward speed of the storm, tsunami characteristics and coast setting. However, it has been determined that mangroves are more efficient at reducing surge levels, if the event passes over relatively quickly (McKee and

Faulkner, 2000).

The dynamics of sedimentation in mangroves are complex (Furukawa et al., 1997; Gutierrez et al., 2011). Mangrove roots help generate and bind new sediments and soils. The above-ground roots slow down the water-flow process, stimulate sediment deposition, and reduce erosion. Sedimentation rates correlate with root density and between 70 and 80% of suspended sediment brought in from coastal waters may be trapped in mangroves (Young and Harvey, 1996; Furukawa et al., 1997). However, extreme drainage and conversion of areas to other uses generate a rapid breakdown of organic matter as oxygen becomes available in the soil, which entails a subsidence process as a final result (McIvor et al., 2013).

Case studies highlight the importance of mangroves in coastal erosion processes and their management strategies can be found mainly in tropical areas. For example, along some coastal areas of Guyana where mangroves forests have been destroyed to give way to aquaculture or agriculture, coastal erosion has increased significantly, reaching rates of up to −3 m per year (Gratiot et al., 2011).

On the other hand, the Indonesian government and partners recently developed a programme of mangrove restoration near the city of Semarang, northern Java island. This initiative aims to enhance coastal resilience for almost 80,000 people located in Central Java by mitigating coastal flooding and erosion. Simultaneously they want to provide the people with a long-term perspective for sustainable development through revitalization of aquaculture areas for crab and shrimp farming.

If mangroves are integrated appropriately, they can contribute to coastal erosion reduction in almost every coastal setting. It is important to take into account that they do not always provide a stand-alone solution and most of the time need to be combined with other measures to achieve a desired level of protection.

3.3. Seagrass

Seagrasses are the only representative group of marine angiosperms that have evolved from land to sea and have adapted to the marine environment. They are permanently submerged and attached to the sediment. Towards the tropics, species such as *Thalassia testudinum* and *Syringodium filiforme* cover extensive areas; whilst in estuaries and other coastal areas of higher latitudes, eelgrass (*Zostera* spp.) form dense meadows (Deegan et al., 2001). Seagrasses serve as habitat, shelter, and food for marine species (juvenile and adult stages of molluscs, crustaceans, and fish of commercial and ecological interest).

Seagrasses are able to significantly influence the hydrodynamic environment by reducing current velocity, dissipating wave energy and stabilizing sediment (Fig. 4). This ecosystem can alter the bottom roughness (Nepf and Vivoni, 2000) and the vertical flow profile (Granata et al., 2001), especially when canopy heights represent more than 15% of the height of the water column (Dayton

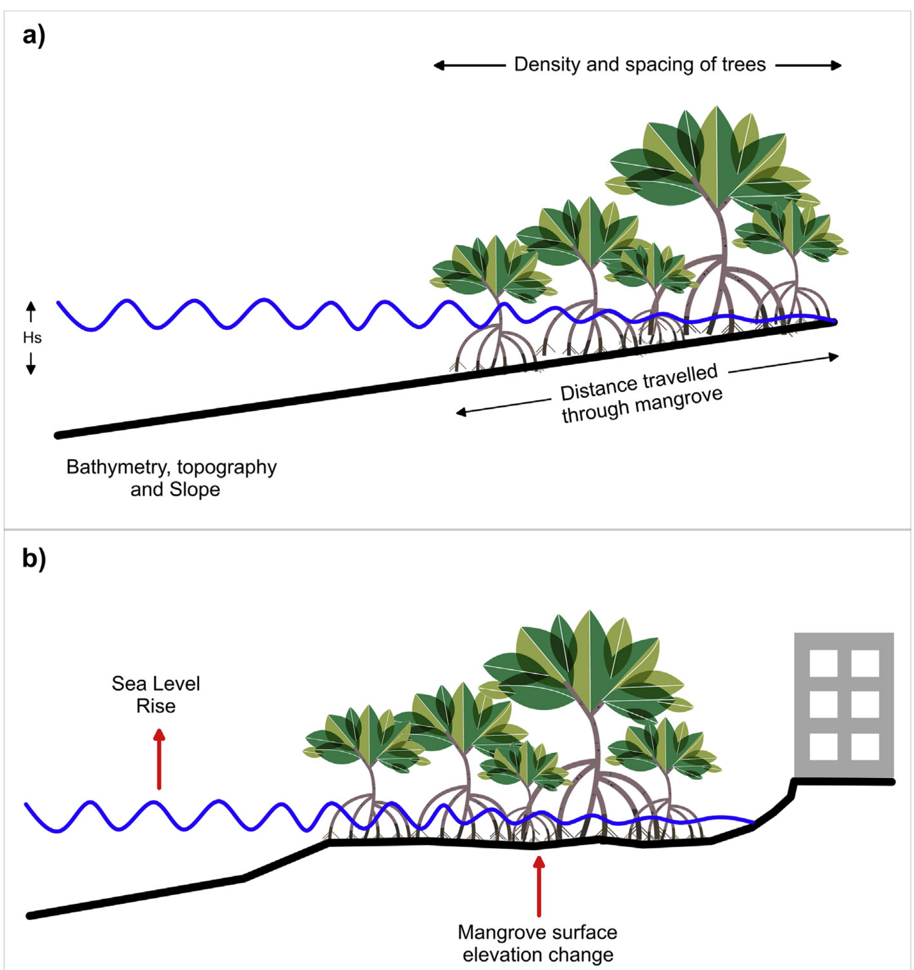

Fig. 3. a) factors affecting wave attenuation and coastal erosion in mangroves. b) example of how mangrove's soil surfaces rises and potentially allowed keep pace with sea-level rise.

et al., 2005). When a wave reaches the ecosystem, a negligible energy reflection and weak wave attenuation by friction is produced. This situation is opposite to what happens to most hard structures, e.g. seawalls and breakwaters, where this same process gives rise to higher energy reflection and wave attenuation by breaking and friction with further loss of sediment (Dayton et al., 2005; Ondiviela et al., 2014).

Additionally, they have the capacity to stabilize and maintain sediments in shallow areas. Due to their ability to dampen waves and currents, seagrass canopies can increase sediment deposition, decrease re-suspension (Lopez and Garcia, 1998) and even directly intercept suspended sediment (Gutierrez et al., 2011). Also, exopolymeric substances secreted by epiphytes can bind sediment particles to seagrass leaves (Agawin and Duarte, 2002). Similarly, they can influence the original seafloor topography through the accretion of rhizomes and roots in the sediments, thus exerting new forces over hydrodynamics and sedimentation.

The efficiency of this ecosystem is primarily and strongly based on the density, standing biomass, plant stiffness and incident energy flux (Orth et al., 2006; González-Ortiz et al., 2016). Optimal conditions for enhancing coastal erosion defence provided by seagrasses can be reached at shallow waters, and low wave energy environments, where a high interaction between water flow and leaves in both, vertical and horizontal dimensions dominates (Ondiviela et al., 2014).

A successful case study related to the use of this ecosystem was developed on the Albany coast, Western Australia. The comparison between waves heights in dense and patchy seagrass meadows of *Posidonia coriacea* (currently accepted name: *P. ostenfeldii*) with areas that had no vegetation, concluded that waves were 10–30% smaller in dense seagrass areas, compared to a bare seafloor. In regions with patchy seagrasses, wave height was reduced by approximately 10%. *Posidonia coriacea*, commonly found along this coast, has become an important coastal management strategy in a decades-long battle against erosion (Buckley et al., 2013).

Another example can be found at Ifaty, situated 25 km north of Toliara in south-west Madagascar. This is a calm, protected shallow area characterized by the development of sporadic extreme wave events able to generate coastal erosion. With the aim of reducing impacts of this processes the community with the support of international institutions, developed an adaptation plan that consists in the planting of seven different seagrass species along intertidal zones (*Syringodium. isoetifolium, Thalassia hemprichii, Thalassodendron ciliatum, Cymodocea rotundata, C. serrulata, Halodule whrightii* and *H. uninervis*). After the programme implementation, a decrease in wave heights during extreme events was evident (Gullström et al., 2002).

3.4. Shellfish reefs

Several hard-ground-building bivalve species occur in estuarine and temperate marine environments. These bivalves can build spatially and topographically complex habitats that foster unique assemblages of organisms. Such biogenic reef, bank, and shell-bed ecosystems add hard substrates to soft, unstable, and often relatively flat bottoms within sedimentary systems (Fig. 5). These surfaces can be topographically rough, with fractal complexity capable of reducing wave energy and erosion (Commito and Rusignuolo, 2000; Kochmann et al., 2008). These structures can act as barriers that generate dams, to hold pools of water, and increase immersion time above the shoreward bank margin, facilitating sediment deposition. Extensive shellfish banks and beds have the ability to minimize the impacts of direct water flow, extreme waves, storm surges, and can stabilize the shoreline (Coen et al., 2007; Palumbi et al., 2009).

Some species form reefs by interactive shell fusion, or a combination of gregarious clustering and the weaving of sticky byssus thread (Goldberg, 2013). Under low to moderate wave and tidal current action, increased deposition on beds and reefs causes sediment to build up to form banks that can be higher than the ambient substrate (Meadows et al., 1998). Two groups, oysters and byssus-bearing bivalves, are the most representative. Oysters (e.g. *Crassostrea gigas* and *C. virginica*) are sessile bivalve molluscs generally found between latitudes 64° N and 44° S. They inhabit coastal waters, where large aggregations can sometimes cover extensive areas of the bottom in estuarine areas. These shell beds also can exist above the substrate, attached to various objects, e.g. stones, pilings, shipwrecks, and even discarded bottles. Oyster reefs and beds may be intertidal or subtidal biogenic structures, formed by oysters living at high densities and building a habitat with significant surface complexity (Baggett et al., 2014). Oyster reefs can increase the biodiversity of the intertidal zone by forming a new hard substrate for other species in soft sediment environments. Another fundamental property of oysters is filtration capacity (Vader, 2014). They filter the water and reduce turbidity by extracting phytoplankton and organic and inorganic particles from the water column (NOAA, 2017). The reefs formed by oysters accumulate carbon in the calcium carbonate of their shells that help reduce the concentration of greenhouse gasses (Goldberg, 2013).

Bivalves with a byssus secretory gland include the blue mussel *Mytilus edulis*, horse mussel *Modiolus modiolus* and other members of the family Mytilidae, as well as giant clams (family Tridacnidae), and oysters of the genus *Pinctada* (Pteriidae). Specifically to Mytilidae, several groups of mussels form large, dense reef-like assemblages on hard substrata from subtidal and the low intertidal areas to depths of 10 m or more in many temperate areas around

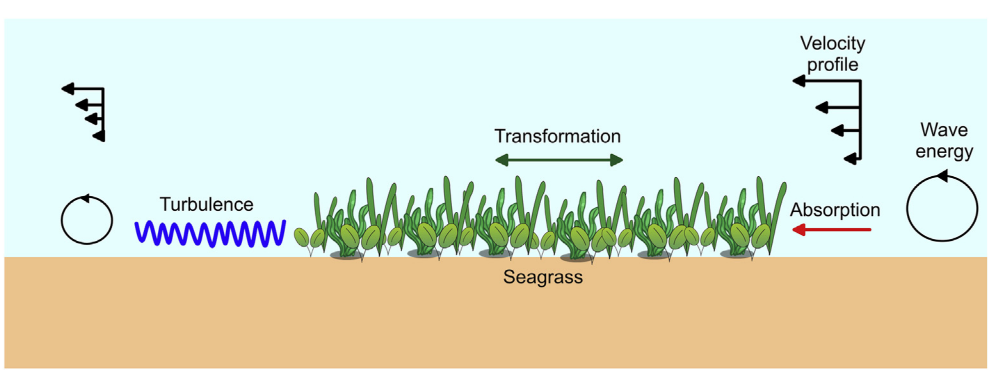

Fig. 4. Physical processes related to influence of seagrasses into wave attenuation and coastal erosion reduction.

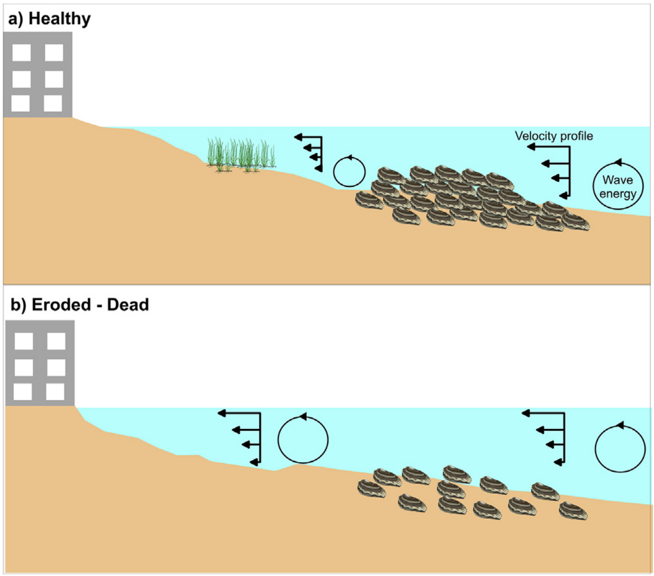

Fig. 5. Wave attenuation and coastal erosion protection given by shellfish reefs under two different scenarios.

the world. The shell and byssus may often provide the only three-dimensionally complex and stable environments available. These structures may be necessary for forming a food source and refuge, as well as a suitable substrate for the settlement of other sessile organisms (Goldberg, 2013). Individual mussels and the edges of small mussel patches reduce critical erosion velocity and this produces local scour.

In Bangladesh, oyster farming is used as a management strategy to combat coastal erosion. The ECOBAS project tested the oyster potential as a way to increase sedimentation, thereby helping to protect vulnerable sectors of coastline against erosion, and to determine their capacity as a sustainable aquatic food source for consumption and trade. The project has demonstrated that oyster reefs can induce accretion of sediment on the lee side of the reef. As a result of this accumulation process, salt marsh and mangrove development have been enhanced.

3.5. Dune vegetation

Dune vulnerability - a reduced ability to adapt to change, is of serious concern not only in Western Europe but on a world wide scale (Williams et al., 2001). Coastal vegetated dunes ecosystem has the capacity to dramatically modify and stabilize the physical environment (Gutierrez et al., 2011). Vegetation (e.g. marram grass *Ammophila arenaria*) stimulates dune growth by trapping and stabilizing wind-moving sand (Fig. 6). Small plants located on the face of eroded dunes can enhance the natural development above the limit of direct wind or wave attack. Additionally, grasses can be transplanted to encourage growth of new foredunes along the toe of existing dunes, as long as these species are tolerant to occasional seawater inundation. Planting grasses from seed can be undertaken, but will not usually be successful along the dynamic foredune environment.

Sand deposition in dunes occurs by means of three clear mechanisms (Pethick, 1984):

- Wind energy is dissipated due to a boundary layer formed by the vegetation.
- Sand hits the surface of the plant and is trapped in the same dune.
- Plus the dense subsoil mat formed by the grass rootlet system tends to bind and stabilize trapped sediment.

Different interrelated factors influence dune formation and shape, including dune plant species, morphology and density, sand supply, wind speed, and wave action during extreme events (Hesp, 1989).

Vegetation sowing and transplanting *per se* will not construct new dunes or completely prevent erosion. Plants encourage natural recovery creating a reservoir of sand within the dunes that better enables their ability to withstand erosion. Fencing, thatching and beach recycling are often necessary to help in sand accretion. Additionally, these works can provide extra protection from waves and will reduce damage due to trampling. Once vegetation is well established, dunes may become self-sustaining, although any erosion damage will need to be rapidly repaired.

A good example of dune vegetation as a coastal erosion management strategy is located at Papamoa, a coastal township located on the Bay of Plenty, New Zealand (Jenks and Brake, 2001). In the early 1990's, storms severely eroded dunes within a few metres of some property boundaries. In 1994, following concern from local residents, a management programme was initiated to improve dune ecosystems. The work focused on restoration of a good cover of sand binding species on the seaward face of the dune, with plantings of several thousand shoots of *Spinifex squarrosus* and *Ficinia spiralis* and fertilizer application to existing stands of these species to assist in their recovery and spread. Dune access walk-overs were installed in high use areas to protect sensitive vegetation from human trampling. This management strategy has successfully reached a complete dune restoration, resulting in a seaward dune advance of 10–25 m, providing a much wider dune with a more gentle, vegetated and resilient front slope to help buffer current and future erosion.

4. Strengths and limitations

Under current global climate change and growing coastal erosion vulnerability, coastal-erosion management by means of hard structures has grown to a point of no return where significant economic losses and much greater impacts are generated (Stancheva et al., 2011; Pranzini and Williams, 2013; Pilkey and Cooper, 2014). Coastal erosion management using ecosystems can provide a better and more cost-effective, sustainable, and ecologically sound alternative to conventional coastal engineering. Currently, many existing coastal ecosystems already provide some degree of protection with no installation cost (Barbier et al., 2013; Spalding et al., 2013).

Coastal erosion management is part of the total service value of the ecosystem (Grabowski et al., 2012), and this approach has multiple additional benefits compared with conventional engineering methods. These benefits include nature conservation, the creation of recreational spaces, carbon sequestration, improvement of water quality, production of fisheries, etc. For example, in the Maldives, a study by The Atoll Ecosystem Conservation Project (TAECP) (Hunnam and Moosa, 2008) looked at the value of the protection services provided by ecosystems. TAECP is an initiative of the Government of the Maldives, United Nations Development Program and the Global Environment Facility (GEF), designed to establish an efficient conservation system as a pilot on Baa Atoll, one of the 25 major coral atolls that make up the Maldives in the central Indian Ocean. This study found that the total cost of constructing hard protection structures to substitute the barriers currently provided by ecosystems (i.e. coral reefs) would be between USD 1.6–2.7 billion. The associated expenses of the damages

Fig. 6. Example of dune stabilization by the use of planting, fencing and thatching at a) Netherlands, b) Portugal, c) Spain.

that would be caused to infrastructure, should the protection afforded by ecosystems be degraded or lost, would be even higher than these values (IUCN, 2009).

Narayan et al. (2016), analysed costs and benefits of fifty-two coastal erosion management ecosystem-based projects around the world, and found that mangroves and salt marshes can be up to five times cheaper than a breakwater, and could even become more economic than a series of groynes (Table 1). The above highlights that a coastal erosion management strategies based on ecosystems is strongly linked to competitiveness. An optimal valuation of ecosystem benefits is paramount in coastal management and planning, because the loss of profits that may occur with the implementation of an inadequate coastal erosion management strategy may be considerable.

Despite the advantages, it is important to take into account limitations in the implementation of ecosystem-based coastal erosion management. Perhaps the key point is the "area of application" because ecosystems demand space to flourish, and sometimes require more space than conventional hard structures. For example, along urbanized coastlines (e.g. Manila, Tokyo), space availability is minimum or sometimes non-existent due to the need for other coastal erosion management strategies. Usually, the more space that is available between urbanized areas at risk and the sea, the higher the efficiency of the ecosystem solution (Temmerman et al., 2013).

Development of the ecosystem and its functionality depends on the coastal setting, hydrodynamics, structure, and habitat dimensions, together with the severity of coastal erosion. Human factors also can play a fundamental role in this process. Human-related degradation is a significant driver of ecosystem functionality by means of direct modification of core ecosystem mechanisms and the impacts on the main species (Silliman et al., 2009; Altieri et al., 2012).

Knowledge of ecosystem resilience thresholds and the external forcing that generates coastal erosion is necessary. These factors must be assessed, particularly given an understanding that no linearity exists inside coastal erosion processes (Koch et al., 2009; Pilkey and Pilkey-Jarvis, 2007). This is confirmed by Kench and Brander (2006) who determined that wave attenuation by coral reefs can be diminished with increasing water depth over a reef structure, but during extreme storm surges, the role of this ecosystem in wave attenuation may be much reduced.

Ecosystems usually have a recovery capacity, but this recovery is not immediate. In some cases, recovery can be very slow and can even become lost due to external factors. Extreme events can lead to loss of living cover in mangroves, reefs, and other ecosystems. However, frequency and sequentiality of these extreme events, now modified by climatic change conditions, can alter recovery processes and eliminate the ecosystem completely (Rangel-Buitrago and Anfuso, 2013). For example, extreme wave events are a natural occurrence and can help in the maintenance of wetlands, mangroves, and dunes, but can also lead to more extreme changes in elevation and the replacement of ecosystems (Howes et al., 2010; Rangel-Buitrago and Anfuso, 2011; Thomas et al., 2015). The recovery capacity and hence ecosystem resilience may also be affected by poor ecosystem health (Hughes, 1994). However, optimal recovery rates may be obtained using anthropogenic interventions such as reforestation (González-Ortiz et al., 2014; Villazán et al., 2016).

Currently, knowledge of coastal erosion management by means of ecosystems is, in part, little known and less applied and very few studies exist. In this study a step-wise implementation approach is recommended as a good means of enhancing the success of this approach which consists of:

- Maintain and protect existing ecosystems.
- Restore such damaged or lost systems.

Table 1
Costs and benefits derived from coastal protection and restorations projects (Narayan et al., 2016). n = total no. of projects for each habitat type. CI = confidence interval; ^: Project costs not scaled; areas for which costs are reported vary across studies; *: Replacement cost ratio = submerged breakwater cost/nature-based defence cost; #: High exposure regions defined as regions with >10 J/m^2 average annual wave energy based on global deep-water wave climate; ✞: Coastal protection benefit types = ER–savings in erosion damage costs; FL–savings in damages costs from storms; ST–savings in costs of adjacent coastal structures; BC–project benefit/cost ratio >1.

Ecosystem	Reported restoration project costs^ as US $ Per m^2: median (Range)	Estimated replacement cost ratios*: average (95% CI)	% of projects implemented for coastal protection	% of projects in high exposure regions #	% of projects reporting coastal protection benefits✞
Coral Reefs	115.62 (2–7490)	NA	5	80	ER– 5; FL– 5
Oyster Reefs	135.63 (107–316)	NA	75	50	NA
Mangroves	0.1 (0.05–6.43)	5 (3.1–6.9)	76	35	FL– 50; ST– 34; BC–41

- If the coastal erosion managment is based on ecosystems, establish adequate ecosystems where environments are compatible.
- Start with small-scale pilot projects.
- Utilise interdisciplinary intensive monitoring.
- Expand these pilot projects to large-scale projects with a suitably adjusted design and application to reality.

A 100% success rate in coastal erosion management by ecosystems cannot be guaranteed, but this high percentage of success is difficult to achieve, even for conventional hard structures that are currently being utilised. It is important to take into account that inaccurate public perceptions may severely hinder coastal erosion management, especially ecosystem-based management strategies, thus the need for education.

5. How to include ecosystems into coastal erosion management

The above reveals the definitive role that ecosystems can play in coastal erosion management, disaster risk and climate change adaptation, and highlights the necessity of ecosystem inclusion in the global environmental and political agenda. However, while the science is clear, the corresponding integration is more difficult, and needs to be enhanced for everyone's benefit. Currently, national policies and local actions taking an integrated and holistic approach to address the downward spiral of increased coastal erosion impacts, ecosystem degradation, and more frequent climate-related disasters, are mostly lacking (UNEP, 2009; Jones and Phillips, 2011).

Prioritizing the role of ecosystems across all coastal countries is urgent. The current conditions of climate change trigger a broad shift towards a global civilization that could be sustainable if *Homo sapiens* seizes the opportunities and starts acting intelligently. World coastal countries, especially the most vulnerable countries, must try to manage coastal erosion with fresh and innovative approaches, especially ecosystem-based initiatives, and at the same time try to replace old and less effective management processes.

De Jonge et al. (2012) suggest a series of tools, to generate accurate management information and thus guide adequate management actions. These tools integrating ecological, economic and social aspects, include:

- **Conceptual assessment design of the ecosystem:** because this is of prime importance, a precise definition of the ecosystem properties, problems and goals for achievement is necessary (for example how corals can be used for coastal erosion management).
- **Use of indicators:** this step can be developed by means of biological indicators, determining habitats and ecological characterization, modeling and integrating Ecological Network Analysis (ENA).
- **Integration of indicators and tools:** Data from very diverse fields, such as, ecological, economic and social spheres are required for a framework to guide the integration. One approach could be use of the 'integral system' as starting point to fill the gaps in information and data. Berkes and Folke (1998) suggested 'The social-ecological system's connection' (SES), which assumes that a series of concepts, such as, resilience, complexity or sustainability, are inherent to this kind of analysis.
- **Development of social and economic analysis of a decision support system**: where meaningful, it might be necessary to place monetary values on the benefits provided by 'healthy' ecosystems.
- **Use of Driver-Pressure-State change-Impact-Response (DPSIR) as a framework for further tool development:** The DPSIR approach was developed by OECD and soon followed by further applications (Turner et al., 1998; De Jonge et al., 2014). DPSIR can be defined as an operational framework identifying 'drivers' of change which lead to individual 'pressures' causing a different system 'state' which consequently result in 'impacts' on human welfare, which then require a policy/management 'response'.
- **Developing the integration among ecological, economic and social aspects.**

An Integrated Coastal Zone Management (ICZM) framework is the ideal space to develop integration. This framework stimulates complete incorporation of different coastal activities by coordinating government and the private sector (Olsen et al., 1997). Combining erosion management with ecosystems usage and ICZM is an excellent opportunity to strengthen several integrative efforts. Cheong et al. (2013) highlighted that weak coastal governance, bad political practices, small financial commitments and the nature of public participation can hinder the formation of ICZM regulations, and made it a challenge to incorporate coastal erosion management into unstable ICZM regimes.

Adequate coastal management and conservation requires that the present use of coastal resources must meet the needs of the population as well as the environment, without endangering the ability of future generations to respond to their needs. Any coastal erosion management strategy requires implementation of effective and efficient solutions based on knowledge of magnitudes, trends and causes, and includes coastal users' priorities and preferences identifying, maintaining and, where possible, enhancing the value of beaches to the economic, environmental and social well-being of local communities (Komar and McDougal, 1988). A short-term perspective conditioned by economic considerations manifested in an action-reaction basis or a cost-benefit analysis approach does not work under this framework. Clearly coastal erosion management must be focused on identifying the problems together with implementation of strategies from a regional and long-term perspective.

Management is a complicated process that requires a holistic view to finding practical solutions that many times go beyond a national issue (Bush et al., 1996; Williams and Micallef, 2009; Cooper and Pilkey, 2012). Currently, coastal erosion management is a worldwide imperative because for every day that passes, the problem becomes more intricate and the solution by means of investment of large amounts of money is not always the best answer.

As world coastal population increases and climate change impacts become more severe, increasing pressure is applied to government at all levels to resolve the coastal erosion problem. Unfortunately, from a governance viewpoint, many coastal erosion management strategies fail due to a weak institutional framework, accompanied by diluted and compromised coastal erosion management regulations.

Under current climate change conditions, coastal erosion management plans that include ecosystems are required. The integrated coastal management policy cycle formulated by Olsen et al. (1997) is a good starting point to achieve this purpose. This cycle includes:

- Identification and understanding of coastal erosion processes.
- Preparation and planning of strategies.
- Managing and evaluation.

In the last two stages, ecosystems can be incorporated using the Spalding et al. (2014) approach that outlines the follow steps:

- Quantify ecosystem services in addition to coastal protection.
- Consider ecosystems in vulnerability assessments of coastal communities.
- Develop scenarios and tools that model compound coastal erosion risks.
- Build decision support systems to help communities visualize impacts and possible solutions.
- Engage stakeholders.
- Enact policies to ensure environmental integrity.
- Incorporate proven management interventions.
- Strengthen the capacity for implementation.

The above can be included in policies supporting strategies and above all, must be constructed with enough robust scientific research for decision makers to make rational decisions. For example, due to the increasing importance of ecosystem management in adapting and responding to climate change impacts and associated coastal erosion risks, a political commitment at the highest level is urgently needed. Political support is also required that helps integration of ecosystems into coastal erosion management strategies, coastal disaster risk reduction and climate change adaptation policy frameworks and practices (UNEP - WCMC, 2011). The UN Biodiversity Conference, (COP13-2016) recommended that adequate financial, knowledge and technological resources be allocated respectively for integrating ecosystem management in climate change and coastal disaster risk reduction portfolios. This must be included in national policy-setting and raising awareness, planning, practices and capacity building.

Several key features of coastal erosion management by an ecosystem approach make this a competitive strategy in a wide range of settings:

Economy: Implementation can avoid high capital investments derived from an expensive infrastructure, e.g. rock armouring. Ecosystems can have lower long-term maintenance costs, and some can take less time to implement. Savings derived from natural infrastructure can be quite significant.

Extra Benefits: Implementation of this strategy also improves water quality, supports recreation, provides new habitats, delivers economic and other societal benefits.

Multiplicity: These projects can be developed successfully in a wide range of habitats and coastal types. Knowledge of coastal systems may guide implementation of the strategy.

High Community Value: This strategy can be very familiar with local communities, and can be critical in raising new project funds and building political support.

Flexibility: Under the right conditions ecosystems have the capacity to adapt by themselves.

Complementary Support: Can enhance existing restoration and conservation projects.

A considerable level of cooperation is required from all stakeholders to take action on the coastal erosion issue and ecosystem degradation. This will help foster and narrow existing links between ecosystem and coastal erosion management, disaster risk reduction and climate change adaptation, as well as between science and policy.

6. Future considerations

Ecosystems are not static, so continuous and iterative research, evaluation, and monitoring are essential for active application of this coastal erosion management strategy. Also, to understand and monitor the state of the ecosystem, evaluation of management performance is an immediate task to determine if implemented management strategies are efficient and profitable (Douvere and Ehler, 2011).

In this point a question arises: How to improve efforts of knowledge utilization that are typically employed during the decision-making processes that deal with environmental complexity in the coastal erosion management by mean of ecosystems? De Jonge and Giebels (2015) suggest two simple steps to reach this:

- **Enhancing environmental knowledge utilization:** by means of using the diversity in factors, reducing uncertainty by combining techniques, reducing uncertainty by contra expertise.
- **Redesigning the decision-making process**: When focussing on the uncertainties that demand resolution, analogies can be found between the problems related to the technical tools and the process of decision-making itself.

Success of the applied strategy will depend on the determination of realistic operational objectives and indicators, all included into ICZM contexts. Likewise, any approach must include local communities and other stakeholders. Uncertainties in forecasts of coastal erosion and climate can significantly harm any kind of management strategy and planning. Understanding climate effects and human reactions in the past can improve predictions for future impacts, and lead to better application of coastal erosion management strategies. Information gaps must be filled and more evidence is needed on the role of ecosystems in reducing the erosional vulnerability. From a societal point of view, the necessities are to communicate the real cost savings and benefits of conserving ecosystems in the context of reducing coastal erosion to make this strategy more appealing and competitive with alternative approaches.

Solving the coastal erosion problem needs application of adequate coastal management strategies. In some cases, there is no 'one and only' solution that may solve the problem, and implementation of a range of different strategies is required. It is necessary to facilitate application of all existing approaches, and to encourage quantification, monitoring, and development of new technologies based on ecosystems. As an improved sense of what approaches work is developed in different locations and under different scenarios, there is a better possibility in responding to the big question: **How can we solve the coastal erosion issue?**

7. Conclusions

Worldwide, coastal erosion affects millions of people, infrastructure, tourism, and trade, causing significant human suffering and losses. In past years, related insured losses reached an all-time high, and impacts are predicted to reach large magnitudes if population growth rates and climate change continue to increase.

Management strategies for coastal erosion must include knowledge and the necessary institutional instruments required to minimize or eliminate coastal erosion related impacts. Their use must generate an optimal benefit to reducing society's vulnerability due to coastal erosion hazards.

Unfortunately, most of the time, decision-making in coastal erosion management is conditioned by economic considerations or a cost-benefit analysis approach.

Coastal erosion management is a policy and implementation process, involving general decision-making and optimal technology application, and most successful management is integrated within the activities of all planning departments, rather than acted upon in an isolationist way.

Recent history indicates that the most used coastal management strategy developed to control and mitigate coastal erosion issues has been protection based on construction of hard defence structures. Most of the time this approach is based principally on an action-reaction, or post-disaster basis, entailing that initiatives are usually triggered by emergencies, not by prevention.

The world urgently requires smart management strategies to help solve the coastal erosion problem. Coastal erosion management can benefit substantially with the use of ecosystems because these can improve the physical environment, generating positive changes in biotic or abiotic materials by their structures or activities, have some capacity for self-repair and recovery, and have multiple roles in processes that includes sediment capture and energy attenuation.

Although the use of ecosystems by itself cannot guarantee a 100% success rate, combination with other strategies seems a promising way forward towards a more sustainable coastal erosion management plan. Therefore, ecosystems must be included and not overlooked in any coastal planning schemes.

Within the last few years, the ecosystem-based approach has received much attention but there are still many needs in research, education, and practice that must be covered. As climate change raises the risk and incidence of coastal hazards, it is imperative that the scientific community continues to examine the role of ecosystems in coastal erosion management.

Acknowledgements

This work is a contribution to research groups: “Geology, Geophysics and Marine - Coastal Process”, Universidad del Atlántico (Barranquilla, Colombia) and “Coastal and Marine Research Group”, University of Wales Trinity Saint David (Swansea, Wales, UK). Thanks to all reviewers that contributed in the improvement of manuscript.

References

Agawin, N.S.R., Duarte, G.M., 2002. Evidence of direct particle trapping by a tropical seagrass meadow. Estuaries 25, 1205–1209.
Altieri, M., Funes-Monzote, F., Petersen, P., 2012. Agroecologically efficient agricultural systems for smallholder farmers: contributions to food sovereignty. Agron. Sustain. Dev. 32, 1–13.
Baggett, L.P., Powers, S.P., Brumbaugh, R., Coen, L.D., DeAngelis, B., Greene, J., Hancock, B., Morlock, S., 2014. Oyster Habitat Restoration Monitoring and Assessment Handbook. The Nature Conservancy, Arlington.
Bank, World, 2009. The World Bank Annual Report 2009-Year in Review. The World Bank, Washington.
Barbier, E.B., Georgiou, I.Y., Enchelmeyer, B., Reed, D.J., 2013. The value of wetlands in protecting Southeast Louisiana from hurricane storm surges. PLoS ONE 8, e58715.
Barragan, J.M., Andreis, M., 2015. Analysis and trends of the world's coastal cities and agglomerations. Ocean Coast. Manage 114, 11–20.
Berkes, F., Folke, C., 1998. Linking Social and Ecological Systems. Management Practices and Social Mechanisms for Building Resilience. Cambridge University Press, Cambridge.
Biggs, B.J.F., Smith, R., 2002. Taxonomic richness of stream benthic algae: effects of flood disturbance and nutrients. Limnol. Oceanogr. 47, 1175–1186.
Borsje, B.W., van Wesenbeeck, B.K., Dekker, F., Paalvast, P., Bouma, T.J., van Katwijk, M.M., de Vries, M.B., 2011. How ecological engineering can serve in coastal protection. Ecol. Eng. 37, 113–122.
Boruff, B.J., Emrich, C., Cutter, S., 2005. Erosion hazard vulnerability of US coastal counties. J. Coast. Res. 5, 932–942.
Brown, R.R., Keath, N., Wong, T.H.F., 2009. Urban water management in cities: historical, current and future regimes. Water. Sci. Technol. 59, 847–855.
Buckley, G.L., Whitmer, A., Grove, J.M., 2013. Parks, trees, and environmental justice: field notes from Washington, DC. Appl. Environ. Educ. Commun. 12, 148–162.
Bush, D.M., Pilkey, O.H., Neal, W.J., 1996. Living by the Rules of the Sea. Duke University Press, Durham.
CBD, 2010. Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. CBD, Montreal.
Charlier, R.H., Chaineux, M.C.P., Morcos, S., 2005. Panorama of the history of coastal protection. J. Coast. Res. 21 (1), 79–111.
Cheong, S.M., Silliman, B., Wong, P.P., van Wesenbeeck, B., Kim, C.K., Guannel, G., 2013. Coastal adaptation with ecological engineering. Nat. Clim. Chang. 3, 787–791.
Coen, L.D., Brumbaugh, R.D., Bushek, D., Grizzle, R., Luckenbach, M.W., Posey, M.H., Powers, S.P., Tolley, S.G., 2007. Ecosystem services related to oyster restoration. Mar. Ecol. Prog. Ser. 341, 303–307.
Colls, A., Ash, N., Ikkala, N., 2009. Ecosystem-based Adaptation: a Natural Response to Climate Change. IUCN, Gland.
Commito, J.A., Rusignuolo, B.R., 2000. Structural complexity in mussel beds: the fractal geometry of surface topography. J. Exp. Mar. Biol. Ecol. 225, 133–152.
Cooper, J.A.G., McKenna, J., 2008. Social justice in coastal erosion management: the temporal and spatial dimensions. Geoforum 39, 294–306.
Cooper, J.A.G., Pilkey, O.H., 2012. Pitfalls of Shoreline Stabilization: Selected Case Studies. Springer, London.
Dayton, P., Curran, S., Kitchingman, A., Wilson, M., Catenazzi, A., Restrepo, J., Birkeland, C., Blaber, S., Saifullah, S., Branch, G., Boersma, D., Nixon, S., Dugan, P., Davidson, N., Vorosmarty, C., 2005. An assessment of ecosystems services. In: Hassan, R., Scholes, R., Ash, N. (Eds.), Ecosystems and Human Well-being: Current State and Trends. Island press, Washington, pp. 165–455.
De Jonge, V.N., Giebels, D., 2015. Handling the ‘environmental knowledge paradox’ in estuarine and coastal policy making. Ocean. Coast. Manage. 108, 3–12.
De Jonge, V.N., Pinto, R., Turner, R.K., 2012. Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' ‘ecosystem approach’. Ocean. Coast. Manag. 68, 169–188.
De Jonge, V.N., Schuttelaars, H.M., van Beusekom, J.E.E., Talke, S.A., deSwart, H.E., 2014. The influence of channel deepening on estuarine turbidity levels and dynamics, as exemplified by the Ems estuary. Estuar. Coast. Shelf Sci. 139, 46–59.
Deegan, L.A., Bowen, J.L., Drake, D., Fleeger, J.W.C., Friedrichs, T., Galvan, K.A., Hobbie, J.E., Hopkinson, C., Johnson, J.M., Johnson, D.S., Lemay, D.E., Miller, E., Peterson, B.J., Picard, C., Sheldon, S., Vallino, J., Warren, R.S., 2001. Susceptibility of salt marshes to nutrient enrichment and predator removal. Ecol. Appl. 17, S42–S63.
Done, T.J., Ogden, J.C., Wiebe, W.J., Rosen, B.R., 1996. Biodiversity and ecosystem function of coral reef. In: Mooney, H.A., Cushman, J.H., Medina, E., Sala, O.E., Schulze, E.D. (Eds.), Functional Roles of Biodiversity: a Global Perspective. Wiley, New York, pp. 475–484.
Douvere, F., Ehler, C., 2011. The importance of monitoring and evaluation in adaptive maritime spatial planning. J. Coast. Conserv. 15 (2), 305–311.
EU, 2004. Living with Coastal Erosion in Europe – Sediment and Space for Sustainability. Office for Official Publications of the European Communities, Luxembourg.
Fath, B.D., 2004. Network analysis in perspective: comments on “WAND: an ecological network analysis user-friendly tool”. Environ. Model. Softw. 19, 341–343.
Fernando, H.J.S., Mendis, S.G., McCulley, J.L., Perera, K., 2005. Coral poaching worsens tsunami destruction in Sri Lanka. Eos Trans. AGU 86, 301–304.
Furukawa, K., Wolanski, E., Mueller, H., 1997. Currents and sediment transport in mangrove forests. Estuar. Coast. Shelf. Sci. 44, 301–310.
Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20, 154–159.
Goldberg, W.M., 2013. The Biology of Reefs and Reef Organisms. University of Chicago Press, Chicago.
González-Ortiz, V., Egea, L.G., Jiménez-Ramos, R., Moreno-Marín, F., Pérez-Lloréns, J.L., Bouma, T.J., Brun, F.G., 2014. Interactions between seagrass complexity, hydrodynamic flow and biomixing alter food availability for associated filter-feeding organisms. PLos ONE. 9 (8), e104949.
González-Ortiz, V., Egea, L.G., Jiménez-Ramos, R., Moreno-Marín, F., Pérez-

Lloréns, J.L., Bouma, T.J., Brun, F.G., 2016. Submerged vegetation complexity modifies benthic infauna communities: the hidden role of the belowground system. Mar. Ecol. 37 (3), 543–552.

Grabowski, J., Brumbaugh, R., Conrad, R., Keeler, A., Opaluch, J., Peterson, C.H., Piehler, M.F., Smyth, A.R., 2012. Economic valuation of ecosystem services provided by oyster reefs. BioScience 62, 900–909.

Granata, T.C., Serra, T., Colomer, J., Casamitjana, X., Duarte, C.M., Gacia, E., 2001. Flow and particle distributions in a nearshore seagrass meadow before and after a storm. Mar. Ecol. Prog. Ser. 218, 95–106.

Gratiot, N., Gardel, A., Anthony, E.J., 2011. Trade-wind waves and mud dynamics on the French Guiana coast, South America: input from ERA-40 wave data and field investigations. Mar. Geol. 236 (1–2), 15–26.

Griggs, G.B., 2005. The impacts of coastal armoring: shore and beach, 73 (1), 13–22.

Gullström, M., de la Torre-Castro, M., Bandeira, S.O., Björk, M., 2002. Seagrass ecosystems in the western indian ocean. Ambio 31, 588–596.

Gutierrez, M.H., Pantoja, S., Tejos, E., Quiñones, R.A., 2011. The role of fungi in processing marine organic matter in the upwelling ecosystem off Chile. Mar. Biol. 158, 205–219.

Heath, M., Phillips, J., Munroe, R., Langley, N., 2009. How Healthy Ecosystems Are Helping the World's Most Vulnerable Adapt to Climate Change. Birdlife International, Cambridge.

Hesp, P.A., 1989. A review of biological and geomorphological processes involved in the initiation and development of incipient foredunes. Proc. R. Soc. Edinb. Biol. 96B, 181–201.

Hettiarachchi, S., Samarawickrama, H., Fernando, H.J.S., 2013. Investigating the performance of coastal ecosystems for hazard mitigation. In: Estrella, M., Renaud, F., Sudmeier-Rieux, K. (Eds.), The Role of Ecosystems in Disaster Risk Reduction. United Nations University Press, Geneva, pp. 57–81.

Howes, N.C., FitzGerald, D.M., Hughes, Z.J., 2010. Hurricane-induced failure of low salinity wetlands. Proc. Natl. Acad. Sci. 107, 14014–14019.

Hughes, T.P., 1994. Catastrophes, phase-shifts, and large-scale degradation of a Caribbean coral reef. Science 265, 1547–1551.

Hunnam, P., Moosa, L., 2008. Atoll Ecosystem Conservation Project Baa Atoll. UNESCO, Malé.

IUCN, 2009. Ecosystem-based Adaptation: a Natural Response to Climate Change. IUCN, Gland.

Jenks, G.K., Brake, L.A., 2001. Enhancing dune function and landscape integrity. J. Coast. Res. 34, 528–534.

Jones, A., Phillips, M., 2011. Disappearing Destinations: Climate Change and the Future Challenges for Coastal Tourism. Cabi, London.

Kench, P.S., Brander, R.W., 2006. Wave processes on coral reef flats: implications for reef geomorphology using Australian case studies. J. Coast. Res. 209–223.

Kirwan, M., Glenn, L., Guntenspergen, R., D'Alpaos, A., Morris, J.T., Mudd, S., Temmerman, S., 2010. Limits on the adaptability of coastal marshes to rising sea level. Geophys. Res. Lett. 37 (23), L23401.

Koch, E.W., Barbier, E.B., Silliman, B.R., Reed, D.J., Perillo, G.M.E., Hacker, S.D., Granek, E.F., Primavera, J.H., Muthiga, N., Polasky, S., Halpern, B.S., Kennedy, C.J., Kappel, C.V., Wolanski, E., 2009. Non-linearity in ecosystem services: temporal and spatial variability in coastal protection. Front. Ecol. Environ. 7, 29–37.

Kochmann, J., Buschbaum, C., Volkenborn, N., Reise, K., 2008. Shift from native mussels to alien oysters: differential effects of ecosystem engineers. J. Exp. Mar. Biol. Ecol. 364, 1–10.

Komar, P.D., McDougal, W.G., 1988. Coastal erosion and engineering structures: the Oregon experience. J. Coast. Res. 4, 77–92.

Leatherman, S., 2017. Coastal erosion and the United States national flood insurance Program. Ocean. Coast. Manage. http://dx.doi.org/10.1016/j.ocecoaman.2017.04.004.

Liu, X., Miller, G.Y., McNamara, P.E., 2005. Do antibiotics reduce production risk for U.S. pork producers? J. Agric. Appl. Econ. 37, 565–575.

Lopez, F., Garcia, M., 1998. Open-channel flow through simulated vegetation: suspended sediment transport modelling. Water. Resour. Res. 34, 2341–2352.

Marshall, M., 1968. Observations on organic aggregates in the vicinity of coral reefs. Mar. Biol. 2, 50–55.

Masselink, G., Russell, P., 2013. Impacts of climate change on coastal erosion. Sci. Rev. 13, 71–86.

McIvor, A.L., Spencer, T., Möller, I., Spalding, M., 2013. The Response of Mangrove Soil Surface Elevation to Sea Level Rise. The Nature Conservancy. University of Cambridge, and Wetlands International, Cambridge.

McKee, K.L., Faulkner, P.L., 2000. Restoration of biogeochemical function in mangrove forests. Restor. Ecol. 8, 247–259.

Meadows, P.S., Meadows, A., West, F.J.C., Shand, P.S., Shaikh, M.A., 1998. Mussels and mussels beds (*Mytilus edulis*) as stabilizers of sedimentary environments in the intertidal zone. In: Blacj, K.S., Paterson, D.M., Cramp, A. (Eds.), Sedimentary Processes in the Intertidal Zone. Geological Society, London, pp. 331–347.

Narayan, S., Beck, M.W., Reguero, B.G., Losada, I.J., van Wesenbeeck, B., Pontee, N., 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS ONE 11 (5), e0154735.

Neal, W.J., Pilkey, O.H., Cooper, A.J.G., Longo, N., 2017. Why coastal regulations fail. Ocean. Coast. Manage. http://dx.doi.org/10.1016/j.ocecoaman.2017.05.003.

Nepf, H.M., Vivoni, E.R., 2000. Flow structure in depth-limited, vegetated flow. J. Geophys. Res. Biogeosci. 105, 28547–28557.

NOAA. 2017. http://www.habitat.noaa.gov/pdf/ecology_of_oysters.pdf.

Nordstrom, K.F., 2005. Beach nourishment and coastal habitats: research needs for improving compatibility. Restor. Ecol. 13, 215–222.

Olsen, S., Tobey, J., Kerr, M., 1997. A common framework for learning from ICM Experience. Ocean. Manage. 37 (2), 155–174.

Ondiviela, B., Losada, I.J., Lara, J.L., Maza, M., Galvan, C., Bouma, T.J., van Belzen, J., 2014. The role of seagrasses in coastal protection in a changing climate. Coast. Eng. 87, 158–168.

Orth, R.J., Luckenbach, M.L., Marion, S.R., Moore, K.A., Wilcox, D.J., 2006. Seagrass recovery of in the Delmarva coastal bays, USA. Aquat. Bot. 84, 26–36.

Palumbi, S.R., Sandifer, P.A., Allan, J.D., Beck, M.W., Fautin, D.G., Fogarty, M.J., Halpern, B.S., Incze, L.S., Leong, J.-A., Norse, E., Stachowicz, J.J., Wall, D.H., 2009. Managing for ocean biodiversity to sustain marine ecosystem services. Front. Ecol. Environ. 7, 204–211.

Pethick, J., 1984. An Introduction to Coastal Geomorphology. Routledge, New York.

Pilkey, O.H., Cooper, A., 2014. The Last Beach. Duke University press, Durham.

Pilkey, O.H., Pilkey-Jarvis, L., 2007. Useless Arithmetic: Why Environmental Scientists Can't Predict the Future. Columbia University Press, New York.

Pilkey, O.H., Young, R., 2009. The Rising Sea. Island Press, Washington.

Pranzini, E., 2017. Shore protection in Italy: from hard to soft engineering … and back. Ocean. Coast. Manage. http://dx.doi.org/10.1016/j.ocecoaman.2017.04.018.

Pranzini, E., Williams, A.T., 2013. Coastal Erosion and Protection in Europe. Routledge - Earthscan, London.

Rangel-Buitrago, N., Anfuso, G., 2011. An application of Dolan and Davis (1992) classification to coastal storms in SW Spanish littoral. J. Coast. Res. SI 64, 1891–1895.

Rangel-Buitrago, N., Anfuso, G., 2013. Winter wave climate, storms and regional cycles: the SW Spanish Atlantic coast. Int. J. Clim. 33, 2142–2156.

Rangel-Buitrago, N., Anfuso, G., Ergin, A., Williams, A.T., 2015a. Assessing and Managing the Coastal Scenery. Blue Solutions from Latin America and the Wider Caribbean. GTZ, Berlin.

Rangel-Buitrago, N., Anfuso, G., Williams, A.T., 2015b. Coastal erosion along the Caribbean coast of Colombia: magnitudes, causes and management. Ocean. Coast. Manage. 114, 129–144.

Rangel-Buitrago, N., Williams, A.T., Anfuso, G., 2017. Hard protection structures as a principal coastal erosion management strategy along the Caribbean coast of Colombia. A chronicle of pitfalls. Ocean. Coast. Manage. http://dx.doi.org/10.1016/j.ocecoaman.2017.04.006.

Seto, K.C., Fragkias, M., Güneralp, B., Reilly, M.K., 2011. A meta-analysis of global urban land expansion. PLoS ONE 6, e23777.

Shepard, C.C., Crain, C.M., Beck, M.W., 2011. The protective role of coastal marshes: a systematic review and meta-analysis. PLoS ONE 6, e27374.

Shi, P., Kasperson, R., 2015. World Atlas of Natural Disaster Risk. Springer-Verlag, Berlin.

Silliman, B.R., Grosholz, E.D., Bertness, M.D., 2009. Human Impacts on Salt Marshes: a Global Perspective. University of California Press, Berkeley.

Spalding, M.D., Meliane, I., Milam, A., Fitzgerald, C., Hale, L.Z., 2013. Protecting marine spaces: global targets and changing approaches. Ocean. Yearb. 27, 213–248.

Spalding, M.D., Ruffo, S., Lacambra, C., Meliane, I., Hale, L.Z., Shepard, C.C., Beck, M.W., 2014. The role of ecosystems in coastal protection: adapting to climate change and coastal hazards. Ocean. Coast. Manage. 90, 50–57.

Stancheva, M., Rangel-Buitrago, N., Anfuso, G., Palazov, A., Stanchev, H., Correa, I., 2011. Expanding level of coastal armouring: case studies from different countries. J. Coast. Res. SI 64, 1815–1819.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nat 504, 79–83.

Thomas, T., Phillips, M.R., Lock, G., 2015. An analysis of subaerial beach rotation and influences of environmental forcing adjacent to the proposed Swansea Bay Tidal Lagoon. Appl. Geogr. 62, 276–293.

Trumper, K., Bertzky, M., Dickson, B., van der Heijden, G., Jenkins, M., Manning, P., 2009. The Natural Fix? the Role of Ecosystems in Climate Mitigation. A UNEP Rapid Response Assessment. United Nations Environment Programme, Cambridge.

Turner, R.K., Lorenzoni, I., Beaumont, N., Bateman, I.J., Langford, I.H., McDonald, A.L., 1998. Coastal management for sustainable development: analysing environmental and socio-economic changes on the UK coast. Geogr. J. 164, 269–281.

Turner, R.K., Hadley, D., Luisetti, T., Lam, V., Cheung, W., 2010. An Introduction to Socio-economic Assessment within a Marine Strategy Framework. DEFRA, London.

UN-Habitat, 2009. UN-habitat Annual Report 2009. United Nations, New York.

UNEP - WCMC, 2011. The Climate Relevance of Ecosystems beyond Forests and Peatlands – a Review of Current Knowledge and Recommendations for Action. German Federal Agency for Nature Conservation, Bonn.

UNEP, 2009. The Role of Ecosystem Management in Climate Change Adaptation and Disaster Risk Reduction. UNEP, Copenhagen.

UNFCCC, 2011. Report of the conference of the Parties on its sixteenth session, held in Cancun from 29 november to 10 december 2010. In: Part Two: Action Taken by the Conference of the Parties at its Sixteenth Session (FCCC/CP/2010/7/Add.1). UNFCCC, Cancun.

Vader, P., 2014. Oyster Reefs and Coastal Protection. Delatares. The Hague.

Van Rijn, L., 2011. Coastal erosion and control. Ocean. Coast. Manage. 54 (12), 867–887.

Van Slobbe, E., de Vriend, H.J., Aarninkhof, S., Lulofs, K., de Vries, M., Dircke, P., 2013. Building with Nature: in search of resilient storm surge protection strategies. Nat. Hazards 66, 1461–1480.

Veron, J.E.N., 2000. Corals of the World. Australian Institute of Marine Science, Townsville.

Villazán, B., Brun, F.G., González-Ortiz, V., Vergara, J.J., 2016. Flow velocity and light level drive non-linear response of seagrass Zosteranoltei to ammonium enrichment. Mar. Ecol. Prog. Ser. 545, 109–121.
Wielgus, J., Balmford, A., Lewis, T.B., Mora, C., Gerber, L.R., 2010. Coral reef quality and recreation fees in marine protected areas. Conserv. Lett. 3, 38–44.
Wild, C., Rasheed, M.Y., Werner, U., Franke, U., Johnstone, R., Huettel, M., 2004. Degradation and mineralization of coral mucus in reef environments. Mar. Ecol. Prog. Ser. 267, 159–171.
Williams, A.T., Micallef, A., 2009. Beach management Principles and Practice. Earthscan, London.
Williams, A.T., Alveirinho-Dias, J., Garcia Novo, F., Curr, R., Garcia-Mora, Pereira, A., 2001. Integrated dune management: checklists. Cont. Shelf. Res. 21, 1937–1960.
Williams, A.T., Pranzini, E., Giardino, A., 2016. Canons of coastal engineering in the United Kingdom: seawalls/groynes, a century of change? J. Coast. Res. 32 (5), 1196–1211.
Williams, A.T., Rangel-Buitrago, N., Pranzini, E., Anfuso, G., 2017. The management of coastal erosion. Ocean. Coast. Manage. http://dx.doi.org/10.1016/j.ocecoaman.2017.03.022.
Young, B.M., Harvey, L.E., 1996. A spatial analysis of the relationship between mangrove (*Avicennia marina* var. *australasica*) physiognomy and sediment accretion in the Hauraki Plains, New Zealand. Estuar. Coast. Shelf. Sci. 42, 231–246.
Zhu, X., 2010. Technologies for Climate Change Adaptation – Coastal Erosion and Flooding. UNEP Risø Centre on Energy, Climate and Sustainable Development, Roskilde.