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The Incorporation of Biophysical and Social Components in Coastal Management

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Abstract

Change is inherent in coastal systems, which are amongst the most dynamic ones on Earth. Increasing anthropogenic pressure on coastal zones interferes with natural coastal dynamics and can cause ecosystem imbalances that render the zones less stable. Furthermore, human occupation of coastal zones often requires an uncharacteristic degree of stability for these inherently dynamic coastal systems. Coastal management teams face multifaceted challenges in protecting, rehabilitating and conserving coastal systems. Diverse monitoring schemes and modelling tools have been developed to address these challenges. In this article, we explore various perspectives: the integration of biophysical, ecological and social components; the uncertainties of diverse data sources; and the development of flexible coastal interventions. We propose general criteria and guidance for an Ecosystem-based Management (EbM) to coastal management, which aims primarily at adaptation to global change and uncertainties, and to managing and integrating social aspects and biophysical components based on the flows of energy and matter.

Keywords Coastal processes · Ecosystem-based adaption · Ecosystem-based approach · Green infrastructure · Ecosystem dynamics · Community-based adaptation · Coastal management

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Introduction

Most natural processes in coastal areas are affected by human interference, particularly by the pressures from urban development and agricultural expansion. As the processes and functioning of the ecosystems are altered (Capobianco and Stive 2000) and coasts are transformed, the risks of natural hazards are increased (Silva et al. 2014) and the lives of the people living there are impacted. Coastal ecosystems provide numerous benefits to people, including habitat provision, tourism, scenic beauty, recreation, supporting fishing industries, climate regulation, regulating through carbon storage, filtering of coastal waters, sustaining jobs and ocean economies, reducing risk from flooding and, in some cases, facilitating adaption to a changing climate (Everard et al. 2010; Barbier et al. 2011).

Given the heightened coastal risks and increasing awareness of the relevance of ecosystems in shaping coastal processes and supporting human wellbeing, ecosystem functioning must be included today in planning adaptation strategies at micro- and macro-scales (e.g. land-use policy frameworks, community engagement) (Moosavi 2017). The implementation of measures that mimic the functioning of ecosystems have proven valid in some, but not all, cases (Silva et al. 2017). Normally, structural measures such as submerged breakwaters, are implemented to regulate hydrosedimentary flows (Neckles et al. 2002), while non-structural measures such as sand by-passes across jetties, are intended to maintain naturally dynamic processes and thus restore or maintain hydrosedimentary equilibrium (Cooke et al. 2012; Keshtpoor et al. 2013).

Ecosystem-based Adaptation (EbA) strategies help people adapt to the adverse effects of climate variability and climate change by integrating ecosystem services and socio-econometrics to achieve sustainable exploitation, conservation and restoration of ecosystems (Colls et al. 2009). The services provided by ecosystems can be harnessed to increase local resilience (the capacity of socio-ecological systems to respond to disturbances and retain the essential structures, processes and feedbacks) (Martinez et al. 2017) and enhance the adaptive capacity of society to increasing risks from natural hazards (Jones et al. 2012; Reid 2016). EbA approaches have three main axes. First, it considers ecosystem functioning and continuous adaptation to dynamic ecosystems rather than any fixed solution; second, it aims to produce flexible plans, rather than a blue-print for an end-state; and third, it is based on the continuous acquisition, updating and analysis of information related to ecosystem changes and interventions. Thus, monitoring becomes much more important than in conventional approaches, as the intervention has no cut-off point in time.

The combination of natural or nature-based features with structural elements is used increasingly in coastal management (Borsje et al. 2011; Temmerman et al. 2013), moving away from traditional engineering towards hybrid solutions (e.g. Moosavi 2017; Silva et al. 2017). An example of integrating natural or nature-based features with structural elements is the innovative "Building with Nature" programme, which uses a triangle to depict the relationship between biotic and abiotic environments, man-made infrastructures and societal governance: Nature–Engineering–Society (van Slobbe et al. 2013).

The successful use of green infrastructure (e.g. Firth et al. 2014; Ondiviela et al. 2014) involves maintaining the connectivity and dynamics of ecosystems (Gillis et al. 2014), by mimicking their natural functioning in many cases (e.g. Silva et al. 2017).

EbA will be more effective if it also includes Community-based Adaptation (CbA). CbA has a human rights-based approach to development, targeting the people most affected by the changes and including them in planning, adaptation and implementation (Reid 2016). CbA programmes consider a range of factors, such as disaster risk reduction (DRR), encouraging climate-resilient livelihoods and developing locally adaptive and organisational capacities that address the underlying causes of vulnerability. Decision making which integrates EbA and CbA will provide the best outcomes in coastal management and protection.

Ecosystem-based Management (EbM) is not simply substituting man-made coastal protection infrastructure with ecosystems which have similar functions, it involves a reassessment of the physical, ecological and social factors affecting the area to achieve sustainable coastal management.

This paper explores the state of the art of EbA, EbM and CbA in coastal management and points to some flexible solutions which combine biophysical, ecological and social components. It also provides an understanding of EbM in the context of global changes and uncertainties.

Materials and Methods

Sustainable management of specific coastal and marine systems involves reviewing their past and assessing current and future issues, threats and needs (Gilman 2002). If possible, end-to-end ecosystem models, or coupled models (Heymans et al. 2018), are favoured as they focus on how the physical environment and human interference affect coastal ecosystems and point to possible socio-economic consequences (Serpetti et al. 2017). In the pre-planning stage, physical, ecological and social approaches, which include EbM (EbA and CbA), should produce a concrete diagnosis for the site concerned.

The Physical Component

This refers to the acquisition of the minimal, acceptable and ideal levels of information needed for decision-making, taking into account the relative importance of the effects of wave and wind climates, nearshore currents, temperature and salinity gradients, sediment sources and sinks, sediment transport, geomorphological changes and the effects of changes in relative sea level (Capobianco and Stive 2000). The physical component requires continuous monitoring of the above-mentioned parameters and of their external driving forces, which are susceptible to change as a consequence of human activities.

The physical approach includes exploration of the potential benefits and consequences of coastal disruption (e.g. defence structures, beach nourishment) while focusing on mass/energy fluxes and ecosystem connectivity. Potential interventions may generate windows of opportunity, which foster the establishment of key species, or contribute to the creation of a physical environment that induces appropriate dynamics to mimic specific ecosystem functions (Balke et al. 2014; Martinez et al. 2017).

The Ecological Component

In this approach, the dynamics of the ecosystems must be sufficiently understood to allow predictions to be made concerning their responses to changes in the physical environment. However, this is often complicated by two factors: firstly, the dynamics of an ecosystem may be driven by changes in physical or biological processes in adjacent systems or changes in sediment and nutrient fluxes induced by changes in ecosystem connectivity (Gillis et al. 2014; Guannel et al. 2016). For example, the long-term dynamics of tidal marshes respond to the short-term dynamics and shape of the adjacent tidal flat (Bouma et al. 2016; Cao et al. 2018; Hu et al. 2015). Secondly, ecosystems are inherently complex, with internal positive and negative feedback loops that may cause non-linear responses, delay or bi-stability (Scheffer et al. 2001; van der Heide et al. 2007; van Wesenbeeck et al. 2008). Thus, responses to environmental changes may be masked until sudden collapse is inevitable. Subsequent recovery of such complex systems may be inhibited by the absence of positive feedback loops, despite efforts to restore the previous abiotic conditions (e.g. Heymans and Tomczak 2016; Maxwell et al. 2017; Tomczak et al. 2013).

Monitoring the impact of changes in the physical environment on coastal ecosystems may allow us to identify critical patterns and/or early-warning signals (EWSs) (Rietkerk et al. 2004; Scheffer et al. 2001; van Belzen et al. 2017). Through dynamic systems theory (Scheffer et al. 2009), these EWSs may be detected early enough to allow for measures that mitigate and reverse these changes, and/or allow for adaptation to these changes (Ferrier et al. 2016). However, responding to EWSs may not be sufficient to avert regime shifts. This may be due to the lack of resolution in the monitoring data for systems, which are gradually moving towards a tipping point, to the inherent stochasticity and non-linearity of the processes underlying regime shifts, or to difficulties associated with bio-complexity and knowledge gaps in the field of predictive ecology. Therefore, since there are considerable uncertainties, a precautionary principle should be followed (Southgate et al. 2003; Tedsen and Homann 2013).

Ecosystems are affected by the physical environment, but they also modify the physical environment. For instance, coastal ecosystems can attenuate waves, slow water flow, secure sediments and reduce storm surge (Feagin et al. 2015; Martinez et al. 2016; Silva et al. 2016a, b), while they are also affected by these conditions. The magnitude and nature of these effects are very context dependent (Ondiviela et al. 2014; Ruckelshaus et al. 2016). Ecosystems with different foundation species, such as coral reefs, saltmarshes, mangroves, dunes and seagrass meadows influence coastal processes differently due to variations in their structure, morphology, species interactions, recruitment rates, longevity and other life history characteristics (reviewed in Arkema et al. 2017a and papers within). The spatial and temporal variations inherent to coastal ecosystems can result in changes such as the rugosity and height of a reef, reef crest width, density and structure of vegetation or/and its protective efficiency against waves and currents. Consequently, gathering site-specific data on these changes during the diagnostic phase will help scientists and managers to better understand and anticipate the role of ecosystems in coastal dynamics.

The additional benefits of EbM, such as the optimal uses of resources and socio-ecological adjustment are included when adaptive management criteria are employed (Mee 2012; Plummer et al. 2012). Ecosystem modifications implemented to enhance coastal protection may induce changes in ecosystem patterns and processes and impact environmental and social conditions (e.g. fisheries, recreation/tourism, carbon storage, water quality).

The Social Component

The dynamic interactions between society and natural ecosystems imply that changing human conditions and activities necessarily drive changes in ecosystems, which in turn, modify human well-being (van Slobbe et al. 2013).

EbM should facilitate social participation in coastal management. But to be adequate and effective, identification of the following points is necessary: the ecosystem services to be used or preserved, the social and economic benefits offered by the services, and the social actors directly involved (Scherer and Asmus 2016). EbM requires social participation and should seek out the actors affected by the specific services/ecosystems and define social groups connected through ecosystem services. This approach should by-pass broader social participation models, which are not necessarily effective in decision-making (Méndez-López et al. 2014).

However, direct participation of the community in planning, monitoring and decision-making is essential: by encouraging stakeholders to implement measures acceptable to the community, serious social or economic conflicts are less likely (Gilman 2002). From the start of a project, the implementation and assessment of alternative strategies, managing expectations and projecting the services considered to the community are vital to promote positive synergies. Including local volunteers in some types of preliminary data collection and post intervention monitoring reduces costs, raises awareness and fosters the spirit of a community sharing in rescue action. Other important issues are the monitoring and quantification of the benefits and costs of each alternative strategy, including social aspects, such as public well-being and safety.

The Diagnosis Process

An ideal coastal diagnosis is based on data of sufficient quality and quantity; unfortunately, this is not always available and, even so, decisions must still be made with the information and knowledge there is, at the time. A simple framework to guide multidisciplinary teams in leveraging the information available and best practices experience is proposed here. First, the team should first prioritise the information groups (ecology, geomorphology, geology, marine climate, socioeconomic and legislation) according to the amount of attention they require (see Fig. 1). The type of activities to be promoted on the coast will determine the priority of the information to be collected. Next, the information available is grouped into the relevance categories: minimum indispensable, acceptable and ideal.

Table 1 shows examples of data for each information group in the three relevance categories. Depending on the problem to be faced, the information necessary will vary in each category, and in some cases, decisions will have to be made with less information, especially when acquiring the data requires long-term monitoring. The examples cited here are intended to serve as a guide for diagnosis and decision-making. Other criteria may be necessary, depending on the nature of a given project.

An EbM approach should consider different sources of information that include current knowledge, ecosystem services, system dynamics and continuous monitoring (Fig. 2).

Considerations for Management

Ecosystem service approaches and models are increasingly used by public authorities and the private sector when seeking to understand how these services influence and are influenced by the biophysical attributes of the coastal zone (Arkema et al. 2015; Reddy et al. 2015).

While there is a tendency towards considering EbA in planning, several challenges hamper their practical implementation. Firstly, there are gaps in the scientific knowledge regarding the protection efficiency of nature-based solutions during extreme events (Möller et al. 2014) and their long-term stability (Ondiviela et al. 2014). From the ecological perspective particularly, there are diverse unknowns that must be addressed in research and development before EbA, rather than the current conventional approach, can be adopted in coastal management. For example, the impact of coastal ecosystem biodiversity (considering community structure and composition) on the provision of ecosystem services still remains largely unknown. In addition, the necessary quantitative long-term and large-scale models, including feedbacks and/or connectivity coastal systems are limited (Gillis et al. 2014; Guannel et al. 2016). Moreover, very few designers and engineers are familiar with such nature-based models. Secondly, there are no standardised methods or tools for the design and safety assessment of ecosystems in a coastal protection scheme nor are there consistent frameworks for legislation or regulation (Restore America's Estuaries 2015). A third challenge is harnessing the support of key stakeholders for the implementation, funding and sustainability of these solutions, as they may be unfamiliar with EbA and its benefits (Olsson et al. 2004; Scyphers et al. 2014; Scyphers et al. 2015). Finally, EbA requires collaboration between governmental agencies, NGOs, private sector enterprises and academic disciplines, which generally work in a rather isolated manner.

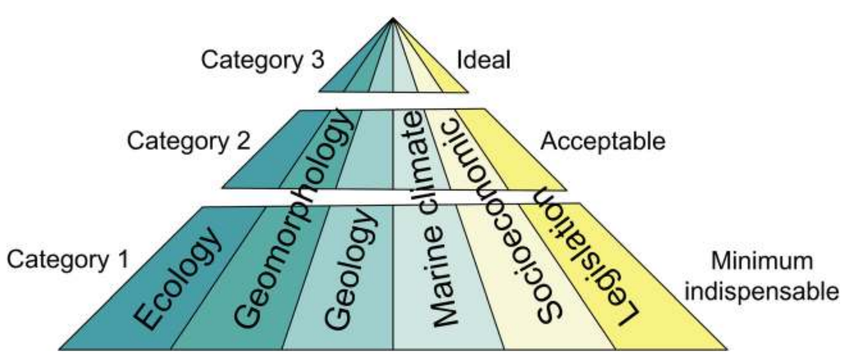

Fig. 1 Information groups and relevance categories to help decision making based on availability of data

Table 1 Examples of coastal data that should be considered in EbM

Information group	Category: 1. Minimum indispensable 2. Acceptable 3. Ideal	Data examples by category
Ecology	1	- Type of coastal ecosystem - Distribution and spatial extent of different ecosystem types - Relevant ecosystem characteristics (e.g., density of trunks or shoots, rooting system, rugosity of reef)
	2	- Degree of ecosystem conservation
	3	- Ecosystem flows (e.g., flows of the founding species, population dynamics of founding and key species, groundwater and surface water quantity and quality; substrate/sediment quality; connectivity)
Geomorphology	1	- Significant geoforms
	2	- Sediment features - Sedimentary balance
	3	- Local morphological evolution - Forecast of coastal response to projected actions
Geology	1	- Origin and main geological characteristics of the site
	2	- Characteristics of sediment mechanics
	3	- Analysis of sediment force and resistance
Marine climate	1	- Main coast shaper - Wave, tide and current regimes - Wind regimes
	2	- Currents induced by waves, tidal currents, long. and cross shore currents, bed shear stress - Air temperature, humidity, atmospheric pressure
	3	- Hydro-meteorological risk assessment - Prediction of the consequences of extreme and extraordinary events
Socioeconomic	1	- Population data - Main economic activities - Land data (e.g., property values, land farmed communally, land use permits) - Historical or cultural value of the area
	2	- Population growth rate
	3	- Historical records of vector diseases in the population - Causes of mortality of flora, fauna and humans
Legislation	1	- Federal maritime terrestrial zone - Protected natural areas
	2	- Protection measures - Local territorial planning
	3	- Federal, state and local normativity for ecological, land use and specific activity

Evaluation of ecosystem services is also useful in understanding the trade-offs amongst adaptation options and strategies. Four generic strategies in coastal management are considered: (1) *Protect*: preserve vulnerable areas, especially centres of population, economic activities or natural resources, by using hard structures and/or soft protection measures; (2) *Accommodate or Adapt*: if the occupation of sensitive areas is to persist, a greater degree of flooding caused by changes in land use should be accepted, construction methods adapted and preparedness improved; (3) *Planned retreat*: remove

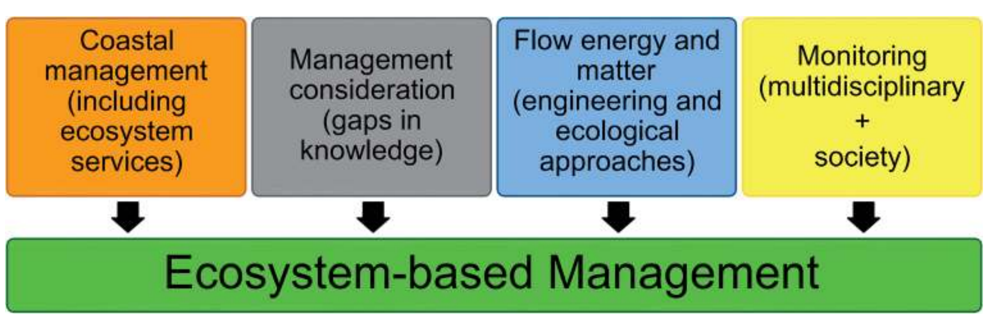

Fig. 2 Aspects to be considered in Ecosystem-based Management (EbM)

structures in areas which are currently developed, resettling inhabitants and legislating for new development to be set at an appropriate distance from the coast; and (4) *Do nothing*: no action is planned because it is believed that nothing will work, or because the solutions offered do not warrant the required investment (Dronkers et al. 1990). EbA approaches consider the strategies of protect, accommodate and planned retreat.

Each of these strategies have consequences for the expectations of the people and the value of the coastal systems, such as access to open space, recreational opportunities, productive fisheries, cultural and aesthetic enjoyment and the tourism industry. Assessing the costs and benefits (both monetary and non-monetary) of alternative ecosystem-based approaches in combination with community engagement is essential for aligning project outcomes and community values and expectations (Schultz 2011; Austen et al. 2019).

Flow of Energy and Matter Through Ecosystems as an Engineering Tool

Until recently, engineers and ecologists have treated coastal management from their exclusive perspectives: coastal engineers focusing on the protection of human goods and services; on ensuring the physical environment is safe for humans and restricting its dynamics to socially acceptable changes; and ecologists focusing on the conservation and restoration of coastal ecosystems. With non-integrated approaches to coastal management, traditional engineering interventions, such as rigid constructions or beach nourishment, commonly disturb natural ecosystem flows, which may cause undesirable changes in biogeochemical cycles as well as in the distribution and abundance of foundation and/or key species. On the other hand, environmental regulations may be too rigid, inhibiting the implementation of transitional actions. Such regulations often do not consider the adaptation of ecosystems to changing conditions or to extreme events. For example, a well-defined area or a landmark organism may be highly protected, whereas the quality, quantity and variability of matter and energy are not guaranteed (e.g. Christianen et al. 2014). This is often the case when sources or sinks (of sediments, nutrients, pollutants or energy) are located far away (Gillis et al. 2014; Gillis et al. 2017) and are not taken into consideration in local studies.

The acknowledgement of these limitations should bring changes in the mindset of decision makers and in their approach to coastal management. Where possible, engineering projects should aim to allow for the establishment of ecosystems which provide different ecosystem services (Balke et al. 2011; Balke et al. 2014; Hu et al. 2015) by constructing wave-attenuating and sediment-accreting hard structures and/or through the implementation of soft solutions which allow natural cycles to be restored. Conversely, in cases where flows of energy and matter cannot be restored, it is often possible to make permanent changes in the physical environment by constructing structures or implementing actions that mimic the non-functioning part of the ecosystem. Both approaches seek to guarantee the inter- and trans-connectivity within and between ecosystems, allowing restoration of the dynamic balance of mass, energy and species flows, with their respective cycles for calm and stormy periods.

Monitoring

In an integrated approach, monitoring involves multidisciplinary teams of stakeholders, coastal engineers, coastal ecologists and social scientists, each with their specific vision. Challenges regarding communication amongst the teams from different disciplines and monitoring activities must be overcome to effectively transfer the information to coastal stakeholders.

Group sessions and workshops for the stakeholders and experts are essential to set preliminary parameters based on their importance and interest. Several methodologies for participatory work and prioritisation are available, such as the matrix of impacts and efforts (Kneebone et al. 2017), optimisation techniques (Rustagi 1994) or any multivariate analysis (Bartholomew et al. 2008). Calibration is also necessary, given the necessity of building knowledge with variables from different disciplines (Botero et al. 2015).

The monitoring data should be recorded using predetermined temporal (per second, hourly, daily, monthly or seasonally) and spatial scales (from centimetres, to metres or kilometres), specific to each variable and each location. Specific, case by case, protocols must be designed and implemented to understand the structure and dynamics of the biophysical elements and to make accurate predictions on sustainability and the impact of climatic events on society and the ecosystems (Borsje et al. 2011). These protocols depend on the availability of historical data and technical and economic resources, which are highly variable.

Quantitative physical (hydrodynamics, morphology, geology, climatic, meteorology etc.), ecological (species, abundance, diversity, communities, available resources, nutrients etc.) and socio-economic (stakeholders, activities, well-being etc.) parameters should be measured, supplemented with desk, and possibly also laboratory, analysis.

Arguably, providing useful monitoring information to decision makers is a major difficulty. It is necessary to compile the technical-scientific data into a user friendly frame, such as standardised data sheets (Botero et al. 2015). An interesting approach is the CoastView project, which combines video monitoring and in situ measurements (Huntley and Stive 2007). This project recognised the need to turn research outcomes into products of value for managers, and made a concerted effort to bridge communication gaps between researchers and managers. Emerging technologies, such as Unmanned Aerial Vehicles (UAV) or satellite images are now more accessible, enabling off-shore measurements, coupled with sensitive field measurements. Traditional in-situ measurements can be complemented by more recent remote sensing technology. The new technologies demand a reconfiguration of the roles and responsibilities of the actors involved in research, management, data collection and control.

Another technique to help in coastal decision-making, is Decision Support Systems (DSS), which is an exploratory tool that assesses the condition of a system under a variety of adaptation and mitigation scenarios (Zanuttigh et al. 2014). Several kinds of DSS exist, depending on the type of coast, the activities taking place, or the status of ecological conservation. DSS are mainly computer based tools with different ranges of information: from ecological to physical and from economic to human development data. These systems can deal with three main groups of coastal needs: (1) evaluation of the consequences of diverse coastal threats, (2) estimation of risks related to climate change, and (3) prediction of management scenarios and cost-benefit rates for the optimal use of coastal resources (Zanuttigh et al. 2014). Examples of DSS available in the literature include STELLA (Tan et al. 2018), RISC-KIT (Van Dongeren et al. 2018), DESYCO (Torresan et al. 2016), THESEUS (Zanuttigh et al. 2014), CLIMSAVE (Harrison et al. 2013) and InVEST (Sharp et al. 2018). DSS are envisaged as an effective means of clarifying the language of scientists and decision makers and making alternative options understandable for laypeople whose participation in the project should always be encouraged. Such clear communication is indispensable for integral, multidisciplinary monitoring.

In the following section, three examples of coastal management interventions that combine these aspects are described.

Examples of an Ecosystem-Based Approach

Case study 1: Implementing structural measures to restore fluxes and connectivity, as occurred in Puerto Morelos (Mexico). Puerto Morelos is the oldest port on the Mexican Caribbean, located at coordinates 20° 51′ 13″ North, 86° 52′ 31″ West, between two of the most important tourist resorts in Mexico; Cancun and Playa del Carmen. Until 1950, there were only 80 inhabitants, but expansion of tourism nearby produced a sharp increase in population, which has grown at a rate of 19% for the last 10 years, reaching more than 37,500 (INEGI 2015). From the 1960s onwards, several constructions have modified the hydrosedimentary balance, triggering sand accumulation in some areas and erosion in adjacent beaches. Additionally, coral bleaching and diseases have reduced rugosity and altered the protection and biogenic sediment production services provided by the reefs, which are 300–1200 m from the shoreline, causing more beach erosion. Many of the constructions that triggered the beach erosion cannot be removed for economic or legal reasons (e.g. containment walls are required for insurance), so the problem continues to grow.

In 2007, extreme waves and currents generated by Hurricane Dean (Mancera et al. 2009; Silva-Casarin et al. 2009) severely eroded the beach in front of the Now Jade Hotel (located in Puerto Morelos). A long-term beach restoration programme began in 2008. The measures employed addressed the hydrosedimentary imbalance caused by the construction of a nearby marina. The programme involved the construction of two modular, artificial reefs (phases 1 and 2; Fig. 3) and the restoration of a coastal sand dune on the beach, in front of the hotel (phase 3).

Phase 1 started in 2008 with a monitoring programme, technical study and environmental impact assessment to contain the problem of erosion by building an artificial reef in 2010. The artificial reef consisted of an ecologically enhanced hard infrastructure, 150 m from the shoreline.

The structure was designed and constructed in limited time and using available data. Subsequent, permanent monitoring verified that the erosion had been controlled and that the beach was partially regenerating, without transferring the erosion problem to adjacent beaches. Phase 2 started in 2011, with the design and construction, in 2012, of a second artificial reef, 80 m long, to stabilise the northern part of the beach. The artificial reefs mimic the protection services of a natural reef, dissipating part of the wave energy through friction and turbulence. They also serve as a habitat, providing a substrate for animals and plants, including coral larvae. This project was possible thanks to the information gathered previously in long-term monitoring of the maritime climate, beach morphodynamics and marine ecosystems (Mancera et al. 2009; Silva-Casarin et al. 2009; Ruiz et al. 2010; Cerdeira-Estrada et al. 2012; Martell-Dubois et al. 2012; Torres-Freyermuth et al. 2012; Alcerreca et al. 2013). In phases 1 and 2, the cost of the artificial reefs was relatively small, compared with the cost of traditional coastal protection engineering work: phase 1 cost US$253,000 and phase 2 cost US$164,000, including the technical studies, the environmental impact assessment and the permanent monitoring programme (Pablo Lucena, Now Jade Hotel, personal communication 2018). In contrast, employing traditional coastal protection infrastructure would have cost around US$2 million.

After 8 years, the beach is stable and the artificial reefs host coral species, such as sea fan (*Gorgonia flabellum*), white encrusting zoanthid (*Palythoa caribaeorum*) and brain coral (*Diploria labyrinthiformis*). The connectivity of the system

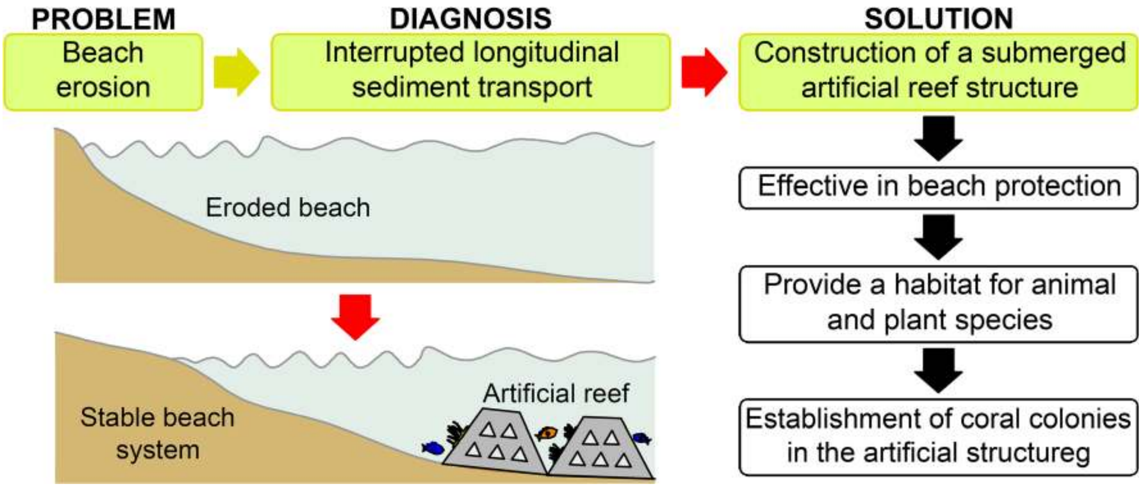

Fig. 3 Use of an artificial reef to improve coastal protection in the EbA example (schematic)

has allowed other species to colonise the reef and nearby seagrass has regenerated naturally. Thus, the beach and the sea in front of it have recovered their natural dynamics (Silva et al. 2016b, 2017). The artificial reefs have proved to be resilient to perturbations and recovered after the massive *Sargassum* influxes of 2015 and 2016 (see van Tussenbroek et al. 2017). The solution was flexible and adaptive, mimicking ecosystem services provided by the coral reefs and maintaining the connectivity of the ecosystems in the system. The monitoring was carried out by the hotel staff and with local resources, making it both technically and economically viable.

Finally, a third phase of the project at Now Jade was initiated in 2016, to provide resilience to the beach by restoring the coastal sand dunes. This phase was designed as a result of observations on the evolution of the coastal system through monitoring. Phase 3 is on-going, with a total budget of US$50,000 (Pablo Lucena, Now Jade Hotel, personal communication, 2018). Although the result of this example was positive, the implementation of artificial reefs is intrusive and therefore requires extensive studies of the ecosystem, coastal dynamics and sediment transport and should be part of an integrated coastal management plan. Without such studies and plans, implementation may have undesirable effects, such as changing sedimentary regimes in nearby areas or the destruction of other ecosystems, such as seagrass meadows, that also provide coastal protection services. The presence of the reefs is now an attraction for the hotel guests. This case study shows that monitoring can be used as an engineering tool to optimise economic resources and reduce uncertainty.

> Case study 2: Over the last 80 years, the city of La Plata, on the coastal plain of Río de la Plata, Argentina, has extracted groundwater from a semi-confined aquifer to supply freshwater for the city and agriculture. The demand for water increased as the urban area expanded and the number of greenhouses increased, resulting in soil sealing and reduced groundwater recharge to the unconfined aquifer. In 1940, the surface of the developed area was approximately 26 km^2, whereas by 2013, it was approximately 98 km^2 (Kruse et al. 2013). Because of the hydraulic connections between the unconfined and semi-confined aquifers, both systems suffered from dewatering, causing changes in flow patterns and increasing the saltwater intrusion from the paleo-seawater deposits into the freshwater zones. Although the unconfined aquifer is still an important source of freshwater for the semi-confined aquifer, an increase in the water pumped upward from both the higher areas and the coastal plains was observed (Kruse et al. 2013). The coastal plain is a large wetland on the margin of the Río de la Plata estuary. Groundwater discharge, from local flows in the unconfined aquifer and from regional flows in the underlying semi-confined aquifer, is one of the main hydrological components that sustains it. Salinisation of the semi-confined aquifer in the coastal plain also changed the physical environment in the unconfined aquifer, due to the ascending groundwater flows, producing a new biological environment (Kruse et al. 2013). It was, therefore, essential to define guidelines and restrictions for groundwater extraction, which allowed the multiple uses of water, for urban, agricultural and ecosystem needs, to continue, while protecting the long-term availability of the water bodies.

The result of the EbM was the creation of protection zones in the recharge areas. The protected wetlands helped to increase the freshwater inflow to the aquifer and boosted the natural freshwater outflow from the ecosystem (Temmerman et al. 2013). The design and implementation of this solution involved decision makers and the local population at all stages (Fig. 4).

The adoption of an EbM approach for the La Plata coastal zone was possible since it was supported by: (1) Ecology data, such as ecosystem type and spatial distribution, ecosystem

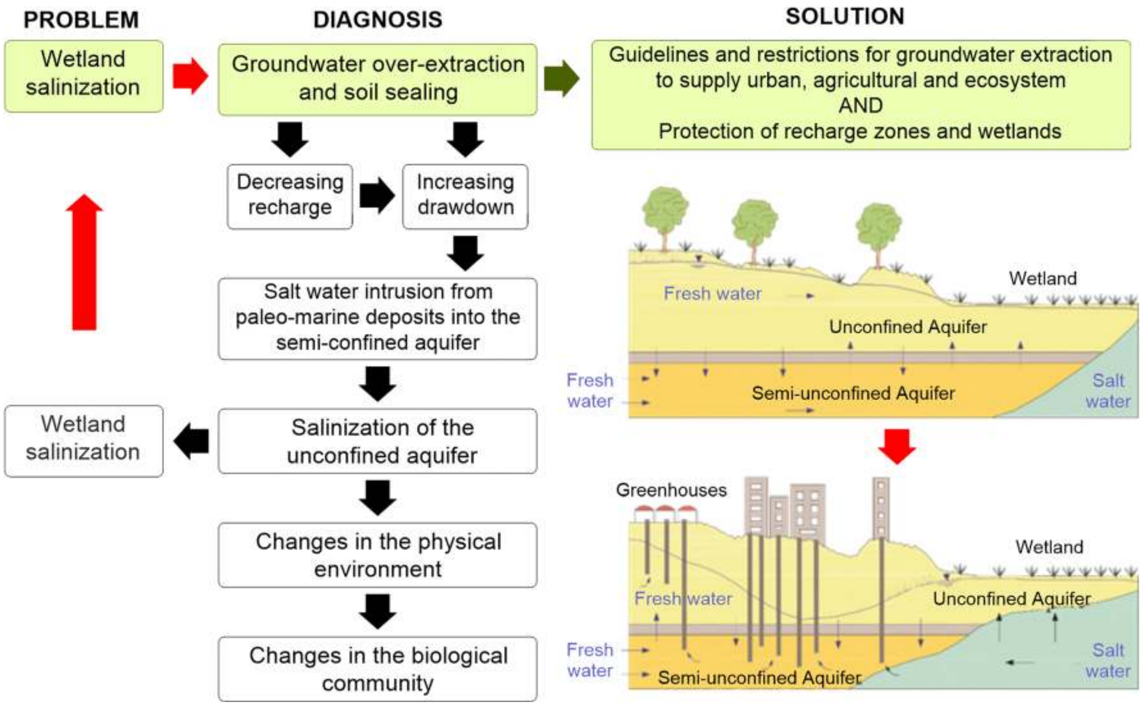

Fig. 4 Salt-water intrusion from paleo-marine deposits increasing salinity discharge into a groundwater-dependent wetland in a coastal plain, near La Plata, Argentina (schematic)

flows (groundwater quantity and quality, surface water distribution) and groundwater monitoring data (Kruse et al. 2013; Carol et al. 2013; Santucci et al. 2016a); (2) coastal geology and geomorphology data, such as local and regional geology, morphological coastal evolution and the dynamics of the deposition of ancient sediment (Auge 2005; Santucci et al. 2016b); (3) Hydro-meteorological and water balance data (Kruse et al. 2004; Kruse et al. 2013); and (4) population data,

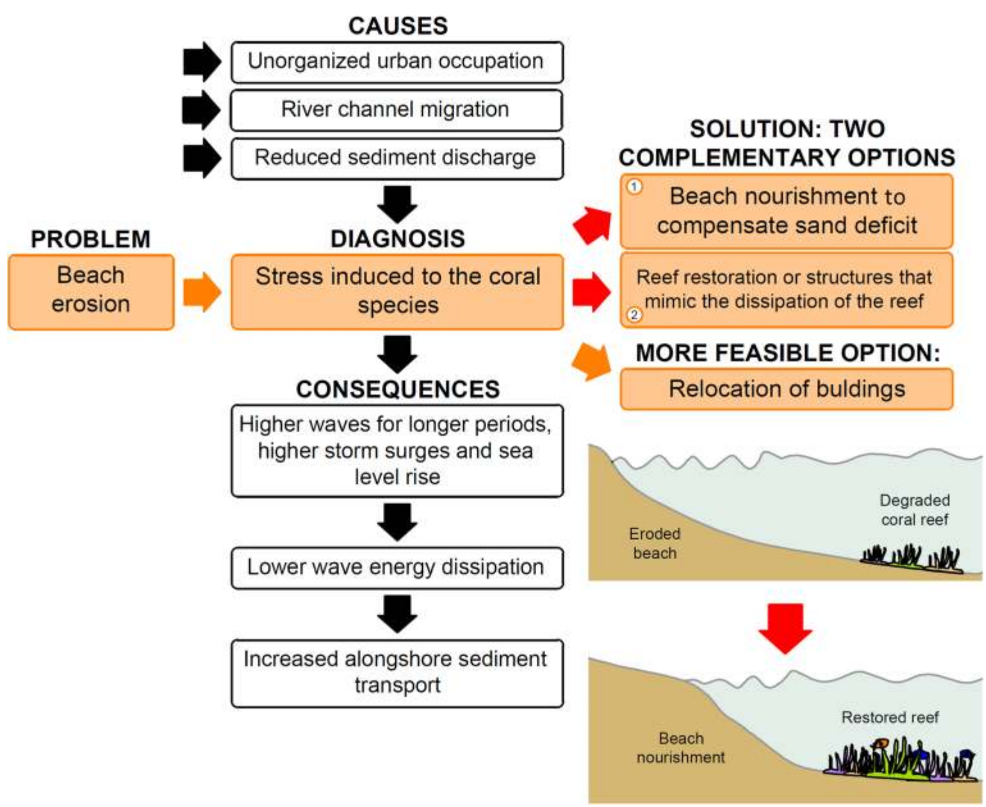

Fig. 5 Restoration of coastal processes in Carne de Vaca, Brazil (squematic)

such as population growth (INDEC 2010), major economic activities and land use data, including the development of economic sectors and urban expansion, as well as the water needs for the multiple uses (Delgado et al. 2018; Auge 2005; Carol et al. 2013).

> Case study 3: The beach of Carne de Vaca, on the northeast coast of Brazil, suffers from chronic erosion. Situated on the south bank of the Tracunhaém River, in the state of Pernambuco, this small fishing village is a summer bathing resort, surrounded by coconut tree plantations. The beach is protected by two reefs that dissipate 80% of incoming energy. In 1915, after the expansion of Recife harbour, the northerly alongshore sediment transport was blocked by the jetty. Erosion was worsened after uncontrolled urban development, reef degradation, river channel migration and a reduction in the sediment discharged by the river (Albers et al. 2013).

When erosion began to cause damage to private properties near Carne de Vaca, "homemade" protection alternatives were implemented in the area without any proper technical knowledge. Thirty groins were deployed on the beach, of which five were made of coconut timber from the local plantations, in the hope of reducing the erosion using cheap, locally available materials. For the first 5 years, the coconut timber structures worked quite well, retaining sediments and reducing the rate of local shoreline retreat. However, they later began to disintegrate, allowing the sediment to bypass the structures.

This first action was a temporal solution to contain the problem. Subsequent monitoring showed that a second phase was needed to stabilise the system and provide further resilience. This next step should include enhancement of the sediment supply, beach nourishment and reef restoration or the construction of structures that mimic the hydrodynamic functioning of the reef. Due to the magnitude of the problem and the costs involved in resolving it, the relocation of some buildings is also needed (Silva et al. 2017) (Fig. 5). For a successful outcome, the involvement of the community is vital.

Conclusions

The effects of extreme natural events, such as storms, are hazardous to property, infrastructure and agricultural areas and present risks to human life. However, these extreme events are also important for the dynamic equilibrium of coastal ecosystems, bringing temporary connectivity of ecosystems, or isolation of them, generating the natural renewal of species and flushing out the system (e.g. Whelan III et al. 2011). For this reason, when designing and implementing restoration or protection projects, the natural dynamics of the ecosystems and the species affected by these projects must be considered. Monitoring of biophysical, ecological, and social components is fundamental to determine the effectiveness and potential consequences of any action implemented for coastal protection and management. In general, when considering an EbA, it is important to bear in mind that:

1. In the long term, ecosystem-based solutions are generally less costly and require less maintenance than traditional engineering designs. However, EbA solutions usually require more time to implement and the effects are slower, compared with conventional solutions. For EbA solutions, it is necessary to ensure sufficient space and time for the natural ecosystem processes to take place, allowing the natural responses to occur over long periods of calm and sudden extreme conditions.
2. The development of new, innovative coastal management strategies that include the integration of ecosystem functioning and fluxes of matter and energy in pre-planning stages, will provide disaster risk reduction, as the coast becomes more resilient, effectively protecting human infrastructure, as shown in the Puerto Morelos case study.
3. Soft solutions must be evaluated with the same rigour as other engineering solution, as they may cause similar secondary effects. For example, the dredging activities necessary for artificial nourishment of a beach may damage benthic communities, and modify the habitats of a keystone foundation or key species. Equally, the quality of the sand transferred in an EbA-based beach-nourishment project may affect the habitat of coastal species, such as the marine turtle (Rumbold et al. 2001; Temmerman et al. 2013).
4. In spite of the acknowledged benefits of an EbA, in some cases, the use of rigid or hybrid infrastructure may be most suitable, for example to contain hazardous waste or to create a substrate that facilitates the colonisation and establishment of specific species. Traditional engineering interventions often face stressors individually, while EbM usually addresses multiple stressors integrally. However, incomplete knowledge of the ecological impacts of traditional engineering will generally undermine predictions that would be required for life-cycle design, so that monitoring and adaptation become crucial.
5. To reduce the risk of failure, any coastal intervention (whether green infrastructure or a conventional approach) must first start with a complete and accurate diagnosis. The strategies that can be implemented range from the restoration of flows of matter and energy to those that mimic changes in ecosystem connectivity and their diverse effects. Frequently the temporarily creation of windows of opportunity for foundation or key species increases the possibility of a successful intervention.
6. Since every ecosystem and society has respectively different environmental and socio-economic conditions, it is

not advisable to simply copy EbM from one situation to another. Specific schemes must be developed for each particular case, based on appropriate diagnosis and monitoring programmes.

Taking these points into consideration, coastal interventions needs a more adaptive and flexible approaches which must include: (a) *Biophysical research* to generate new knowledge and thus achieve a robust ecosystem service science, with improved/new concepts, modelling tools and techniques for EbA implementation. This may affect policies for coastal protection in a world facing increasingly greater uncertainties, (b) *Practical EbM implementation*, which is impossible without interaction amongst social scientists, engineers and ecologists, in collaboration with stakeholders and policy-makers, to co-produce feasible solutions.

The points discussed above highlight the need for EbM to anticipate trade-offs and potential impacts on target resources, encouraging the development of a common language or means of communication, through which diverse stakeholders can define shared goals, and support the development of performance standards that capture social, as well as ecological and physical, outcomes (Arkema et al. 2017b; Olander et al. 2015).

By understanding and disseminating the importance of ecosystems in the well-being of people, it is hoped the commitment of society to restore and preserve natural ecosystems will be reinforced.

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References

Albers, T., B. Bakermans, F. Habets, J. Jacobs and J. Keij. 2013. Coastal zone of Bairro Novo and Carne de Vaca-Pernambuco, Northeast Brazil. Master Master, TU Delft.

Alcerreca, J.C., R. Silva, and E. Mendoza. 2013. Simple settling velocity formula for calcareous sand. *Journal of Hydraulic Research* 51 (2): 215–219.

Arkema, K.K., G.M. Verutes, S.A. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthal, M. Ruckelshaus, G. Guannel, and J. Toft. 2015. Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. *Proceedings of the National Academy of Sciences* 112 (24): 7390–7395.

Arkema, K.K., R. Griffin, S. Maldonado, J. Silver, J. Suckale, and A.D. Guerry. 2017a. Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities. *Annals of the New York Academy of Sciences* 1399 (1): 5–26.

Arkema, K.K., S.B. Scyphers, and C. Shepard. 2017b. Living shorelines for people and nature. In *The science and management of nature-based coastal protection*, 11–30. Boca Raton: CRC Press, Taylor & Francis Group.

Auge, M. P. 2005. Hidrogeología de La Plata, Provincia de Buenos Aires. In Relatorio del XVI Congreso Geológico Argentino, 293–311. Asociación Geológica Argentina, La Plata, Buenos Aires

Austen M., Anderson P., Armstrong C., Döring R., Hynes S., Levrel H., Oinonen S., Ressurreição A. (2019) Valuing marine ecosystems—taking into account the value of ecosystem benefits in the blue economy, Coopman, J., Heymans, J.J., Kellett, P., Muñiz Piniella, A., French, V. [Eds.] *Future Science Brief 5 of the European Marine Board, Ostend, Belgium*. 40pp. ISBN: 9789 ISSN: 4920-43696.

Balke, T., T.J. Bouma, E.M. Horstman, E.L. Webb, P.L. Erftemeijer, and P.M. Herman. 2011. Windows of opportunity: thresholds to mangrove seedling establishment on tidal flats. *Marine Ecology Progress Series* 440: 1–9.

Balke, T., P.M. Herman, and T.J. Bouma. 2014. Critical transitions in disturbance-driven ecosystems: Identifying windows of opportunity for recovery. *Journal of Ecology* 102 (3): 700–708.

Barbier, E.B., S.D. Hacker, C. Kennedy, E.W. Koch, A.C. Stier, and B.R. Silliman. 2011. The value of estuarine and coastal ecosystem services. *Ecological Monographs* 81 (2): 169–193.

Bartholomew, D.J., F. Steele, J. Galbraith, and I. Moustaki. 2008. *Analysis of multivariate social science data*: Chapman and Hall/CRC.

Borsje, B.W., B.K. van Wesenbeeck, F. Dekker, P. Paalvast, T.J. Bouma, M.M. van Katwijk, and M.B. de Vries. 2011. How ecological engineering can serve in coastal protection. *Ecological Engineering* 37 (2): 113–122.

Botero, C., C. Pereira, M. Tosic, and G. Manjarrez. 2015. Design of an index for monitoring the environmental quality of tourist beaches from a holistic approach. *Ocean & Coastal Management* 108: 65–73.

Bouma, T., J. Van Belzen, T. Balke, J. Van Dalen, P. Klaassen, A. Hartog, D. Callaghan, Z. Hu, M. Stive, and S. Temmerman. 2016. Short-term mudflat dynamics drive long-term cyclic salt marsh dynamics. *Limnology and Oceanography* 61 (6): 2261–2275.

Cao, H., Z. Zhu, T. Balke, L. Zhang, and T.J. Bouma. 2018. Effects of sediment disturbance regimes on Spartina seedling establishment: Implications for salt marsh creation and restoration. *Limnology and Oceanography* 63 (2): 647–659.

Capobianco, M., and M.J.F. Stive. 2000. Soft intervention technology as a tool for integrated coastal zone management. *Journal of Coastal Conservation* 6 (1): 33–40.

Carol, E., E. Kruse, M. Mancuso, and M. Melo. 2013. Local and regional water flow quantification in groundwater-dependent wetlands. *Water Resource Management.* 34: 26–32.

Cerdeira-Estrada, S., T. Heege, M. Kolb, S. Ohlendorf, A. Uribe, A. Muller, R. Garza, R. Ressl, R. Aguirre, and I. Mariño. 2012. Benthic habitat and bathymetry mapping of shallow waters in Puerto Morelos reefs using remote sensing with a physics based data processing. In: Geoscience and Remote Sensing Symposium (IGARSS), 2012 IEEE International, 4383–4386: IEEE.

Christianen, M.J., P.M. Herman, T.J. Bouma, L.P. Lamers, M.M. van Katwijk, T. van der Heide, P.J. Mumby, B.R. Silliman, S.L. Engelhard, and M. van de Kerk. 2014. Habitat collapse due to overgrazing threatens turtle conservation in marine protected areas. *Proceedings of the Royal Society of London B: Biological Sciences* 281 (1777): 20132890.

Colls, A., N. Ash, and N. Ikkala. 2009. *Ecosystem-based adaptation: A natural response to climate change*: IUCN Gland.

Cooke, B.C., A.R. Jones, I.D. Goodwin, and M.J. Bishop. 2012. Nourishment practices on Australian sandy beaches: A review. *Journal of Environmental Management* 113: 319–327.

Delgado, I., E. Carol, A. Casco, and M. Mac Donagh. 2018. The peri-urban interface: Hydrological effects of anthropogenic pressure. *Pollution Research* 37: 83–91.

Dronkers, J., J. Gilbert, L. Butler, J.J. Carey, J. Campbell, E. James, C. McKenzie, R. Misdorp, N. Quin, and K. Ries. 1990. Strategies for adaptation to sea level rise. Report of the IPCC Coastal Zone Management Subgroup: Intergovernmental Panel on Climate Change, Geneva.

Everard, M., L. Jones, and B. Watts. 2010. Have we neglected the societal importance of sand dunes? An ecosystem services perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems* 20 (4): 476–487.

Feagin, R.A., J. Figlus, J.C. Zinnert, J. Sigren, M.L. Martínez, R. Silva, W.K. Smith, D. Cox, D.R. Young, and G. Carter. 2015. Going with the flow or against the grain? The promise of vegetation for protecting beaches, dunes, and barrier islands from erosion. *Frontiers in Ecology and the Environment* 13 (4): 203–210.

Ferrier, S., K. Ninan, P. Leadley, R. Alkemade, L. Acosta, H. Akçakaya, L. Brotons, W. Cheung, V. Christensen, and K. Harhash. 2016. The methodological assessment report on scenarios and models of biodiversity and ecosystem services. Secretariat of the Intergovernmental Platform for Biodiversity and Ecosystem Services, Bonn, Germany.

Firth, L., R. Thompson, K. Bohn, M. Abbiati, L. Airoldi, T. Bouma, F. Bozzeda, V. Ceccherelli, M. Colangelo, and A. Evans. 2014. Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures. *Coastal Engineering* 87: 122–135.

Gillis, L., T. Bouma, C. Jones, M. Van Katwijk, I. Nagelkerken, C. Jeuken, P. Herman, and A. Ziegler. 2014. Potential for landscape-scale positive interactions among tropical marine ecosystems. *Marine Ecology Progress Series* 503: 289–303.

Gillis, L.G., C.G. Jones, A.D. Ziegler, D. van der Wal, A. Breckwoldt, and T.J. Bouma. 2017. Opportunities for protecting and restoring tropical coastal ecosystems by utilizing a physical connectivity approach. *Frontiers in Marine Science* 4: 374.

Gilman, E. 2002. Guidelines for coastal and marine site-planning and examples of planning and management intervention tools. *Ocean & Coastal Management* 45 (6-7): 377–404.

Guannel, G., K. Arkema, P. Ruggiero, and G. Verutes. 2016. The power of three: Coral reefs, seagrasses and mangroves protect coastal regions and increase their resilience. *PLoS One* 11 (7): e0158094.

Harrison, P.A., I.P. Holman, G. Cojocaru, K. Kok, A. Kontogianni, M.J. Metzger, and M. Gramberger. 2013. Combining qualitative and quantitative understanding for exploring cross-sectoral climate change impacts, adaptation and vulnerability in Europe. *Regional Environmental Change* 13 (4): 761–780.

Heymans, J.J., and M.T. Tomczak. 2016. Regime shifts in the northern Benguela ecosystem: Challenges for management. *Ecological Modelling* 331: 151–159.

Heymans JJ, Skogen M, Schrum C, Solidoro C. 2018. Enhancing Europe's capability in marine ecosystem modelling for societal benefit. Larkin KE, Coopman J, Muñiz Piniella A, Kellett P, Simon C, Rundt C, Viegas C, Heymans JJ. [Eds.] *Future science brief 4 of the European Marine Board, Ostend, Belgium*. 32 pp. ISBN: 9789492043580; ISSN: 2593-5232.

Hu, Z., J. Belzen, D. Wal, T. Balke, Z.B. Wang, M. Stive, and T.J. Bouma. 2015. Windows of opportunity for salt marsh vegetation establishment on bare tidal flats: The importance of temporal and spatial variability in hydrodynamic forcing. *Journal of Geophysical Research: Biogeosciences* 120 (7): 1450–1469.

Huntley, D., and M. Stive. 2007. CoastView special issue foreword. *Coastal Engineering* 6: 461–462.

INEGI 2015. Cuéntame, información por entidad del conteo intercensal 2015 (http://cuentame.inegi.org.mx/monografias/informacion/qroo/territorio/div_municipal.aspx?tema=me&e=23): Instituto Nacional de Estadística, Geografía e Informática.

Instituto Nacional de Estadística y Censos (INDEC). 2010. Encuesta de hogares, Buenos Aires. Argentina.

Jones, H.P., D.G. Hole, and E.S. Zavaleta. 2012. Harnessing nature to help people adapt to climate change. *Nature Climate Change* 2 (7): 504–509.

Keshtpoor, M., J.A. Puleo, J. Gebert, and N.G. Plant. 2013. Beach response to a fixed sand bypassing system. *Coastal Engineering* 73: 28–42.

Kneebone, S., L. Smith, and K. Fielding. 2017. The impact-likelihood matrix: A policy tool for behaviour prioritisation. *Environmental Science & Policy* 70: 9–20.

Kruse, E., L. Varela, P. Laurencena, M. Deluchi, A. Rojo, and E. Carol. 2004. Modificaciones del ciclo Hidrológico en un Area del Noreste de la Provincia de Buenos Aires, Argentina. Serie Hidrogeología y Aguas Subterráneas: 11: 131–139. Instituto Geológico Minero de España. ISBN 84-7840-539-9. Madrid.

Kruse, E., E. Carol, M. Mancuso, P. Laurencena, M. Deluchi, and A. Rojo. 2013. Recharge assessment in an urban area: A case study of La Plata, Argentina. *Hydrogeology Journal* 21 (5): 1091–1100.

Mancera, E.E., R.S. Casarín, E.M. Baldwin, I.M. Tapia, and F.R. Rentería. 2009. Análisis de la variación del nivel del mar y de las corrientes marinas inducidas por el huracán Wilma frente a Puerto Morelos, Quintana Roo, México. *Tecnología y Ciencias del Agua* 24: 111–126.

Martell-Dubois, R., E. Mendoza-Baldwin, I. Mariño-Tapia, R. Silva-Casarín, and E. Escalante-Mancera. 2012. Impactos de corto plazo del huracán Dean sobre la morfología de la playa de Cancún, México. *Tecnología y ciencias del agua* 3: 89–111.

Martinez, M.L., R. Silva, E. Mendoza, I. Odériz, and O. Pérez-Maqueo. 2016. Coastal dunes and plants: An ecosystem-based alternative to reduce dune face erosion. *Journal of Coastal Research* 75 (sp1): 303–307.

Martinez, M.L., A. Taramelli, and R. Silva. 2017. Resistance and resilience: Facing the multidimensional challenges in coastal areas. *Journal of Coastal Research* 77: 1–6.

Maxwell, P.S., J.S. Eklöf, M.M. van Katwijk, K.R. O'Brien, M. de la Torre-Castro, C. Boström, T.J. Bouma, D. Krause-Jensen, R.K.F. Unsworth, B.I. van Tussenbroek, and T. van der Heide. 2017. The fundamental role of ecological feedback mechanisms for the adaptive management of seagrass ecosystems—A review. *Biological Reviews* 92 (3): 1521–1538.

Mee, L. 2012. Between the devil and the deep Blue Sea: The coastal zone in an Era of globalisation. *Estuarine, Coastal and Shelf Science* 96: 1–8.

Méndez-López, M.E., E. García-Frapolli, D.J. Pritchard, M.C.S. González, I. Ruiz-Mallén, L. Porter-Bolland, and V. Reyes-Garcia. 2014. Local participation in biodiversity conservation initiatives: A comparative analysis of different models in South East Mexico. *Journal of Environmental Management* 145: 321–329.

Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. Van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, and M. Miranda-Lange. 2014. Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience* 7 (10): 727–731.

Moosavi, S. 2017. Ecological coastal protection: Pathways to living shorelines. *Procedia Engineering* 196: 930–938.

Neckles, H.A., M. Dionne, D.M. Burdick, C.T. Roman, R. Buchsbaum, and E. Hutchins. 2002. A monitoring protocol to assess tidal restoration of salt marshes on local and regional scales. *Restoration Ecology* 10 (3): 556–563.

Olander, L., R. Johnston, and H. Tallis. 2015. Best practices for integrating ecosystem services into decision making: Nicholas Institute Working Paper. https://nicholasinstitute.duke.edu/sites/default/files/publications/es_best_practices_fullpdf_0. Pdf.

Olsson, P., C. Folke, and T. Hahn. 2004. Social-ecological transformation for ecosystem management: The development of adaptive co-management of a wetland landscape in southern Sweden. *Ecology and Society* 9, 4.

Ondiviela, B., I.J. Losada, J.L. Lara, M. Maza, C. Galván, T.J. Bouma, and J. van Belzen. 2014. The role of seagrasses in coastal protection in a changing climate. *Coastal Engineering* 87: 158–168.

Plummer, R., B. Crona, D.R. Armitage, P. Olsson, M. Tengö, and O. Yudina. 2012. Adaptive Comanagement: A systematic review and analysis. *Ecology and Society* 17, 3.

Reddy, S.M., R.I. McDonald, A.S. Maas, A. Rogers, E.H. Girvetz, J. North, J. Molnar, T. Finley, G. Leathers, and J.L. DiMuro. 2015. Finding solutions to water scarcity: Incorporating ecosystem service values into business planning at the Dow Chemical Company's Freeport, TX facility. *Ecosystem Services* 12: 94–107.

Reid, H. 2016. Ecosystem- and community-based adaptation: Learning from community-based natural resource management. *Climate and Development* 8 (1): 4–9.

Restore America's Estuaries. 2015. Living shorelines: from barriers to opportunities: Restore America's Estuaries Arlington, Virginia. https://www.estuaries.org/images/stories/RAEReports/RAE_LS_Barriers_report_final.pdf.

Rietkerk, M., S.C. Dekker, P.C. De Ruiter, and J. van de Koppel. 2004. Self-organized patchiness and catastrophic shifts in ecosystems. *Science* 305 (5692): 1926–1929.

Ruckelshaus, M.H., G. Guannel, K. Arkema, G. Verutes, R. Griffin, A. Guerry, J. Silver, J. Faries, J. Brenner, and A. Rosenthal. 2016. Evaluating the benefits of green infrastructure for coastal areas: Location, location, location. *Coastal Management* 44 (5): 504–516.

Ruiz, G., E. Mendoza, R. Silva, G. Posada, and I. Mariño. 2010. La geomorfología como herramienta para el análisis de las formaciones costeras y sus alteraciones de largo plazo. Aplicación a la Península de Yucatán. Cambio Climático En México: 125.

Rumbold, D., P. Davis, and C. Perretta. 2001. Estimating the effect of beach nourishment on Caretta caretta (loggerhead sea turtle) nesting. *Restoration Ecology* 9 (3): 304–310.

Rustagi, J.S. 1994. Optimization techniques in statistics. In *Statistical modeling and decision science, optimization techniques in statistics*, ed. J.S. Rustagi, 269-296: Academic Press.

Santucci, L., E. Carol, and E. Kruse. 2016. Identification of palaeo-seawater intrusion in groundwater using minor ions in a semi-confined aquifer of the Río de la Plata littoral (Argentina). *Science of the Total Environment* 566–567: 1640–1648.

Santucci, L., E. Carol, G. Borzi, and G. Garcia. 2017a. Hydrogeochemical and isotopic signature of surface and groundwater in a highly industrialized sector of the Rio de la Plata coastal plain (Argentina). *Marine Pollution Bulletin* 120 (1-2): 387–395.

Santucci, L., E. Carol, and E. Kruse. 2017b. Quaternary marine ingressions as indicated by hydrogeochemical evidence in the semi-confined aquifer of the littoral of the Río de la Plata, Argentina. *Quaternary Research* 88: 160–167.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. *Nature* 413 (6856): 591–596.

Scheffer, M., J. Bascompte, W.A. Brock, V. Brovkin, S.R. Carpenter, V. Dakos, H. Held, E.H. Van Nes, M. Rietkerk, and G. Sugihara. 2009. Early-warning signals for critical transitions. *Nature* 461 (7260): 53–59.

Scherer, M.E., and M.L. Asmus. 2016. Ecosystem-based knowledge and management as a tool for integrated coastal and ocean management: A Brazilian initiative. *Journal of Coastal Research* 75 (sp1): 690–694.

Schultz, P.W. 2011. Conservation means behavior. *Conservation Biology* 25 (6): 1080–1083.

Scyphers, S.B., J.S. Picou, R.D. Brumbaugh, and S.P. Powers. 2014. Integrating societal perspectives and values for improved stewardship of a coastal ecosystem engineer. *Ecology and Society* 19.

Scyphers, S.B., J.S. Picou, and S.P. Powers. 2015. Participatory conservation of coastal habitats: The importance of understanding homeowner decision making to mitigate cascading shoreline degradation. *Conservation Letters* 8 (1): 41–49.

Serpetti, N., A. Baudron, M. Burrows, B. Payne, P. Helaouët, P. Fernandes, and J. Heymans. 2017. Impact of ocean warming on sustainable fisheries management informs the ecosystem approach to fisheries. *Scientific Reports* 7 (1): 13438.

Sharp, R., H.T. Tallis, T. Ricketts, A.D. Guerry, S.A. Wood, R. Chaplin-Kramer, E. Nelson, D. Ennaanay, S. Wolny, N. Olwero, K. Vigerstol, D. Pennington, G. Mendoza, J. Aukema, J. Foster, J. Forrest, D. Cameron, K. Arkema, E. Lonsdorf, C. Kennedy, G. Verutes, C.K. Kim, G. Guannel, M. Papenfus, J. Toft, M. Marsik, J. Bernhardt, R. Griffin, K. Glowinski, N. Chaumont, A. Perelman, M.M. Lacayo, L. Mandle, P. Hamel, A.L. Vogl, L. Rogers, W. Bierbower, D. Denu, and J. Douglass. 2018. InVEST user's guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Silva, R., M.L. Martínez, P.A. Hesp, P. Catalan, A.F. Osorio, R. Martell, M. Fossati, G. Miot da Silva, I. Mariño-Tapia, P. Pereira, R. Cienguegos, A. Klein, and G. Govaere. 2014. Present and future challenges of coastal erosion in Latin America. *Journal of Coastal Research* 71: 1–16.

Silva, R., M. Martínez, I. Odériz, E. Mendoza, and R. Feagin. 2016a. Response of vegetated dune–beach systems to storm conditions. *Coastal Engineering* 109: 53–62.

Silva, R., E. Mendoza, I. Mariño-Tapia, M.L. Martínez, and E. Escalante. 2016b. An artificial reef improves coastal protection and provides a base for coral recovery. *Journal of Coastal Research* 75 (sp1): 467–471.

Silva, R., D. Lithgow, L.S. Esteves, M.L. Martínez, P. Moreno-Casasola, R. Martell, P. Pereira, E. Mendoza, A. Campos-Cascaredo, P. Winckler Grez, A.F. Osorio, J.D. Osorio-Cano, and G.D. Rivillas. 2017. Coastal risk mitigation by green infrastructure in Latin America. *Proceedings of the Institution of Civil Engineers-Maritime Engineering* 170 (2): 39–54.

Silva-Casarin, R., E. Mendoza-Baldwin, E. Escalante-Mancera, I. Marino-Tapia, and F. Ruiz-Renteria. 2009. Wind waves induced by hurricane Wilma in Puerto Morelos, Quintana Roo, Mexico. *Ingeniería hidráulica en México* 24: 93–109.

Southgate, H.N., K.M. Wijnberg, M. Larson, M. Capobianco, and H. Jansen. 2003. Analysis of field data of coastal morphological evolution over yearly and decadal timescales. Part 2: Non-linear techniques. *Journal of Coastal Research*: 776-789.

Tan, W.-J., C.-F. Yang, P.-A. Château, M.-T. Lee, and Y.-C. Chang. 2018. Integrated coastal-zone management for sustainable tourism using a decision support system based on system dynamics: A case study of Cijin, Kaohsiung, Taiwan. *Ocean & Coastal Management* 153: 131–139.

Tedsen, E., and G. Homann. 2013. Implementing the precautionary principle for climate engineering. *Carbon & Climate Law Review* 7 (2): 90–100.

Temmerman, S., P. Meire, T.J. Bouma, P.M. Herman, T. Ysebaert, and H.J. De Vriend. 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504 (7478): 79–83.

Tomczak, M.T., J.J. Heymans, J. Yletyinen, S. Niiranen, S.A. Otto, and T. Blenckner. 2013. Ecological network indicators of ecosystem status and change in the Baltic Sea. *PLoS One* 8 (10): e75439.

Torresan, S., A. Critto, J. Rizzi, A. Zabeo, E. Furlan, and A. Marcomini. 2016. DESYCO: A decision support system for the regional risk assessment of climate change impacts in coastal zones. *Ocean & Coastal Management* 120: 49–63.

Torres-Freyermuth, A., I. Mariño-Tapia, C. Coronado, P. Salles, G. Medellín, A. Pedrozo-Acuña, R. Silva, J. Candela, and R. Iglesias-Prieto. 2012. Wave-induced extreme water levels in the Puerto Morelos fringing reef lagoon. *Natural Hazards and Earth System Sciences* 12 (12): 3765–3773.

van Belzen, J., J. van De Koppel, M.L. Kirwan, D. Van Der Wal, P.M. Herman, V. Dakos, S. Kéfi, M. Scheffer, G.R. Guntenspergen, and T.J. Bouma. 2017. Vegetation recovery in tidal marshes reveals critical slowing down under increased inundation. *Nature Communications* 8: ncomms15811.

van der Heide, T., E. van Nes, G. Geerling, A. Smolders, T. Bouma, and M. van Katwijk. 2007. Positive feedbacks in seagrass ecosystems—Theoretical and management implications. *Ecosystems* 10 (8): 1311–1322.

Van Dongeren, A., P. Ciavola, G. Martinez, C. Viavattene, T. Bogaard, O. Ferreira, R. Higgins, and R. McCall. 2018. Introduction to RISC-KIT: Resilience-increasing strategies for coasts. *Coastal Engineering* 134: 2–9.

van Slobbe, E., H.J. de Vriend, S. Aarninkhof, K. Lulofs, M. de Vries, and P. Dircke. 2013. Building with nature: In search of resilient storm surge protection strategies. *Natural Hazards* 66 (3): 1461–1480.

van Tussenbroek, B.I., H.A.H. Arana, R.E. Rodríguez-Martínez, J. Espinoza-Avalos, H.M. Canizales-Flores, C.E. González-Godoy, M.G. Barba-Santos, A. Vega-Zepeda, and L. Collado-Vides. 2017. Severe impacts of brown tides caused by Sargassum spp. on near-shore Caribbean seagrass communities. *Marine Pollution Bulletin* 122 (1–2): 272–281.

van Wesenbeeck, B.K., J. van de Koppel, P.M. Herman, M.D. Bertness, D. van der Wal, J.P. Bakker, and T.J. Bouma. 2008. Potential for sudden shifts in transient systems: Distinguishing between local and landscape-scale processes. *Ecosystems* 11 (7): 1133–1141.

Whelan, T., III, B. Van Tussenbroek, and M.B. Santos. 2011. Changes in trace metals in Thalassia testudinum after hurricane impacts. *Marine Pollution Bulletin* 62 (12): 2797–2802.

Zanuttigh, B., D. Simcic, S. Bagli, F. Bozzeda, L. Pietrantoni, F. Zagonari, S. Hoggart, and R.J. Nicholls. 2014. THESEUS decision support system for coastal risk management. *Coastal Engineering* 87: 218–239.