



The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards



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ABSTRACT

Coastal ecosystems, particularly intertidal wetlands and reefs (coral and shellfish), can play a critical role in reducing the vulnerability of coastal communities to rising seas and coastal hazards, through their multiple roles in wave attenuation, sediment capture, vertical accretion, erosion reduction and the mitigation of storm surge and debris movement. There is growing understanding of the array of factors that affect the strength or efficacy of these ecosystem services in different locations, as well as management interventions which may restore or enhance such values. Improved understanding and application of such knowledge will form a critical part of coastal adaptation planning, likely reducing the need for expensive engineering options in some locations, and providing a complementary tool in hybrid engineering design. Irrespective of future climate change, coastal hazards already impact countless communities and the appropriate use of ecosystem-based adaptation strategies offers a valuable and effective tool for present-day management. Maintaining and enhancing coastal systems will also support the continued provision of other coastal services, including the provision of food and maintenance of coastal resource dependent livelihoods.

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1. Background

The effects of climate change are already being felt, especially in many coastal areas. Of particular importance is sea level rise, although its magnitude and rate of change is likely to vary over broad spatial scales and to be hard to predict locally (Cazenave and Llovel, 2010; Han et al., 2010). Many models also predict increases in storm frequency or intensity (Allison et al., 2009; Bender et al., 2010), but even where these remain unchanged it is likely that storm surge and wave impacts will intensify due to rising background sea levels. The result will likely be more devastating coastal storm events, combined with ongoing increased coastal erosion (Douglas et al., 2001) and flooding, gradual inundation of low-lying lands, and, in many areas, the salinization of groundwater (Alpar,

2009; Hossain, 2010). Even under the most optimistic mitigation scenarios, impacts are likely to be considerable and will continue increasing over the next decades.

Climate change adds to the current and growing hazards already faced by coastal communities. However, in spite of these risks, people are drawn to the coasts. The Low Elevation Coastal Zone (LECZ, defined by McGranahan et al. as coastal areas less than 10 m altitude) covers only two per cent of the world's land area, but contains 10 per cent of the world's population (McGranahan et al., 2007). Populations are also growing faster in these regions: in China urban land expansion in the LECZ has been estimated at 13.9% per year compared to 3.9% in western regions (Seto et al., 2011). In the United States coastal counties contributed more than \$6.6 trillion to the gross domestic product in 2011, just under half the nation's total GDP, coming from less than 10% of the land area (NOAA, 2013). Such figures rapidly translate into heavy economic and social vulnerability to coastal hazards and climate change, vulnerability that is growing not only as a result of changing conditions but also because of increasing and often unsustainable coastal development. Concerns are particularly high for many of the world's poorest

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communities, where direct dependence on coastal ecosystems for basic needs such as food and livelihoods is great; alternatives are few; and where capacity to cope with climate change, natural disasters or other disturbance is far less than in wealthier communities (Hale et al., 2009; ISDR, 2009).

Immediate action is necessary, both to reduce emissions and to prepare for inevitable change. For coastal communities, this includes an urgent need to bolster coastal protection to prepare for expected increases in frequency or intensity of storm impacts as well as for longer term impacts such as sea level rise and increased erosion. Where possible such coastal protection needs to be achieved without compromising the significant services and benefits derived from the oceans, including ecosystem services such as the provision of food, tourism and recreation and carbon storage and sequestration. In this regard, the potential role of ecosystems in coastal protection functions may be highly significant.

2. The need for adaptation and coastal protection

The need for action on adaptation has been recognized at local, national and international levels. The outcomes of the Rio+20 Conference also agreed that adaptation is an urgent global priority, and particularly noted that sea level rise and coastal erosion are serious threats for many coastal regions and islands. At their 2010 conference in Cancun, Mexico, Parties to the UN Framework Convention on Climate Change adopted the Cancun Adaptation Framework (CAF), which underlines that adaptation is a challenge faced by all Parties (developing and developed). It particularly aims to reduce vulnerability and build resilience in developing countries, taking into account the urgent needs of those that are particularly vulnerable (UNFCCC, 2011). In addition, local, state and national governments are developing a range of adaptation plans – some address only immediate needs, others lay out a longer-term “climate resilient” development trajectory, but all seek to reduce the vulnerability of people, places and resources. In coastal areas, the focus has been on coastal protection, to mitigate and adapt to sea level rise and coastal hazards (present and future).

To date, efforts at coastal protection have relied heavily on ‘hard’ measures such as seawalls and bulkheads, especially for developed coastal areas with substantial assets facing increased risk (Rosenzweig et al., 2011; Sterr, 2008; Titus et al., 2009). While such approaches can be important and highly effective they can also be costly both to build and to maintain (Anthony and Gratiot, 2012; Bosello et al., 2012). Hard structures can also fail, and there are many examples of such structures exacerbating problems of coastal erosion or damage in adjacent areas (Brown et al., 2011; Saengsupavanich et al., 2009; Stancheva et al., 2011). Increasingly, however, there is recognition that healthy coastal ecosystems play an important role in coastal protection, and in reducing the vulnerability of coastal communities to climate change and coastal hazards. This has led to growing calls for the incorporation of such ecosystems into coastal adaptation planning (Hale et al., 2009; Heath et al., 2009; World Bank, 2009). For example, the Cancun Adaptation Framework recognises the role that healthy ecosystems can play in supporting adaptation and invites Parties to undertake specific actions, including “building resilience of socio-economic and ecological systems, including through economic diversification and sustainable management of natural resources” (UNFCCC, 2011). Recognition of the value of ecosystems services, including coastal protection, also underpins other agreements, notably the new strategic plan and targets of the Convention on Biological Diversity which calls for these values to be “integrated into national and local development and poverty reduction strategies and planning processes” (Aichi Target 2, CBD, 2010). Aichi Target 15 specifically calls on Parties to enhance, by 2020, “ecosystem

resilience and the contribution of biodiversity to carbon stocks, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation”.

3. The role of ecosystems in coastal protection

This paper reviews the coastal protection functions of ecosystems, as well as variables that may determine their relative effectiveness among locations. It should be noted that in many places, two or more ecosystems may lie in close proximity and provide additive benefits in terms of coastal protection. Further, coastal protection benefits typically represent only part of a range of ecosystem services, ranging from food security to recreation, and that the combined value of multiple ecosystems can be very great indeed. We conclude with recommendations for the increased and appropriate utilisation of natural coastal protection as a central component of strategies to reduce human vulnerability and adapt to climate change.

3.1. The role of coastal wetlands: salt marshes and mangroves

Salt marshes and mangroves contribute to coastal protection by reducing wave energy, increasing sedimentation, and/or reducing erosion and movement of sediments (see reviews in Gedan et al., 2011; Shepard et al., 2011). Dense vegetation cover reduces water flow velocities, turbulent flows and shear stress over the sea bed, promoting sediment deposition, which can create accretion. In some cases deposition stimulates below ground root production (McKee and Cherry, 2009), and these roots further improve soil cohesion and tensile strength, slowing rates of erosion at marsh edges. The roots themselves can also present a physical barrier between the water and soil, particularly in places where root systems extend below low tide levels (Gedan et al., 2011). In terms of wave attenuation, short-period wind and swell waves can be dramatically altered as they pass over or through coastal vegetation. Wave heights can be reduced by between 13% and 66% over 100 m of mangroves (reviewed in McIvor et al., 2012a). In one UK study, salt marshes reduced wave height by almost 61%, and total wave energy by an average of 82% (Möller et al., 1999).

The protective role of mangroves during extreme events has also been documented. Storm surges can be slowed by wide mangrove tracts: rates of surge height reduction have been recorded at between 4 and 48 cm per kilometre of passage through mangrove, so it may take several kilometres of mangrove to have a major impact on any large storm (Krauss et al., 2009; McIvor et al., 2012b; Zhang et al., 2012). This attenuation of long-period storm surges acts in concert with a continuing role in short-period wave attenuation and reducing wave generation through the reduction of wind-speeds across the water surface (Day et al., 2007; McIvor et al., 2012b). For tsunamis the role of mangroves is less well quantified, although there have been a considerable number of publications following the 2004 Indian Ocean Tsunami (Braatz et al., 2006; Dahdouh-Guebas et al., 2005; Danielsen et al., 2005; Kathiresan and Rajendran, 2005; Tanaka et al., 2007). These studies have been hindered by a lack of pre-impact data or experimental controls and some appear to have exaggerated the role that mangroves may have played in coastal protection (Baird and Kerr, 2008; Kerr et al., 2006). However, there is a growing consensus that mangroves do attenuate wave action and reduce debris movement during major natural hazards (Alongi, 2008; Wolanski, 2007). While in the most extreme tsunamis, which can involve 10–15 m or higher waves, both natural and engineered sea defenses may be of limited effectiveness, under more “routine” scenarios, it is clear mangroves provide significant protection.

The role of salt marshes in extreme events is less well documented, although coastal wetlands have been directly linked to the mitigation of coastal damage in large areas of the southern United States (Costanza et al., 2008; Day et al., 2007). Feagin et al. (2009) suggested that salt marshes may be less effective in reducing erosion during extreme events, but achieve benefits through the longer term modification of sediment dynamics.

Coastal habitats such as salt marshes and mangroves may have an advantage over engineered coastal defenses if they increase in elevation and grow with sea level rise. Evidence as to whether they actually can “keep up” with sea level rise is inconclusive and highly site specific. In many mangrove and salt marsh communities the existence of very deep peats clearly indicates vertical accretion over time (McIvor et al., 2013; McKee et al., 2007). Kirwan and Temmerman (2009) suggest that salt marsh accretion rates will accelerate in line with sea level rise at rates of up to 5 mm per year, although others suggest that in northern areas, short growing seasons would result in considerably lower accretion rates (Ashton et al., 2008). Surface accretion may be a poor measure of elevation change, and recent studies have shown that sub-surface processes can also greatly influence elevation through root growth (positive influence), subsidence, decomposition, dessication and other processes. A number of studies have begun to take into account these complex processes and are enabling the measurement of true surface elevation change. These appear to build a complex picture – elevation increases of up to 6 mm per year have been recorded in some mangrove areas, but a few locations have shown net elevation loss (reviewed in McIvor et al., 2013).

Studies of peat accretion over millennial time-frames show apparently more dramatic rates of change, with sediments building up at up to 10 mm/yr in some locations (Ellison, 2009; Woodroffe and Mulrennan, 1993). Even these studies, however, also record of places where mangrove soils have become submerged, possibly linked to periods of rapid sea level rise (McIvor et al., 2013). Rates of

elevation change are also likely to be highly influenced by sediment supply, as well as by position in estuary (salinity regime) (Craft et al., 2009).

While it has long been known that the coastal protection services provided by both mangroves and salt marshes are highly variable from site to site, recent reviews have begun to elucidate some of the key drivers of variance (Table 1). In addition, the benefits from these systems are likely to accrue in a non-linear manner (Koch et al., 2009). Although we cannot yet model such influences, even a basic understanding of the importance of these factors represents a critical advance for policy and planning purposes, enabling decisions to be taken in a more site-specific manner.

3.2. The role of coral reefs

The highly distinctive structures built by coral reefs – some rising from considerable depths to the ocean surface, and in many areas running parallel to coastlines for 10 s or 100 s of kilometres – often place them on the front line of coastal defense. The influence of reefs on waves and currents is a function of the physical geometry and roughness of the reef structures. This complex structuring is, in turn, a function of the biotic growth of habitat-forming species, notably hard corals and coralline algae. Reef roughness plays an important role in the mass transfer of energy from overlying waters into the reef structure, significantly dampening wave action (Kench and Brander, 2006; Monismith, 2007), and has been shown to have an important influence on reducing coastal erosion (Sheppard et al., 2005).

During extreme storm events, common in many tropical regions, coral reefs are immensely important in dissipating wave energy. However, there may be circumstances where the physical structure of fragmented reef patches and channels can serve to locally accelerate or focus wave energy (Cochard et al., 2008; Fernando et al., 2008). It is also important to realise that the

Table 1
Important drivers of variance in the coastal protection function of coastal wetlands and coral reefs. Wetlands data are based on (Gedan et al., 2011; Lacambra et al., 2008; McIvor et al., 2012a, 2012b; Shepard et al., 2011). Coral reef data are based on (Brander et al., 2004; Cochard et al., 2008; Gourlay, 1996a, b; Kench and Brander, 2006; Lacambra et al., 2008; Sheppard et al., 2005).

	Coastal wetlands	Coral reefs
Abiotic variables	• Wave characteristics • Adjacent land use • Soil characteristics • Presence and frequency of disturbances • Topography • Slope • Bathymetry • Water depth over plants • Drainage systems • Prevailing tides • Distance to shore • Distance from sediment source • Distance to other ecosystems • Exposure	• Wave characteristics • Topography • Slope • Bathymetry • Water depth • Prevailing tides • Distance to shore • Exposure
Ecosystem variables	• Habitat width • Plant density • Vegetation structure, mangroves: canopy height, aerial root physiognomy, age class distribution, sub-canopy elements • Vegetation structure, salt marshes: plant height, vegetation stiffness • Resistance and resilience (capacity to survive or recover from impacts) • Fragmentation • Dominant species	• Reef width • Reef surface depth • Reef profile • Meso-scale structure – channels, fragmentation • Roughness • Levels of bioerosion • Resistance and resilience (capacity to survive or recover from impacts) • Dominant species (corals and calcareous algae) – skeletal morphology, growth rates, disease resistance • Presence and proximity of other ecosystems (e.g. seagrass)

storms themselves are likely to impact the habitat and modify the nature of coastal protection provided by the reefs (Woodley, 1992).

Another important question concerns the growth of reef structures, including associated beaches and islands, in the face of rising sea levels. Coral reefs can have rapid rates of accretion, with geological records from the Great Barrier Reef showing sustained growth rates of 0.3 to 0.9 m/100 years (Perry and Smithers, 2011), although such growth, of course, depends on continued reef health (see section 4.0, below). In many areas land itself has been created from sediments derived directly from coral reefs, often shaped into beaches and islands by storms and sometimes enhanced by wind-blown sediments (Woodroffe, 2008). There is evidence that these processes may be sufficient to enable continued island growth or maintenance under certain scenarios of sea level rise: a large-scale study of Pacific islands has shown that while some islands are decreasing in area and many show dynamic boundaries, the total area of coral islands appears to have actually increased under the modest sea level rise that has taken place to date (Webb and Kench, 2010), although such processes may also be altered by future impacts of coastal development and climate change, particularly ocean acidification. From a human perspective of course, increases in the movements of island sediments, together with the threat of salinization of groundwater, are serious threats even if land area itself is not rapidly diminished (Briguglio, 2003; Moore, 1999; Woodroffe, 2008).

As with coastal wetlands, there is considerable spatial variability in the influence of reef structures on coastal protection. The primary known drivers of variability are listed in Table 1. Improved understanding and quantification of these drivers will be tremendously important to fully understanding the extent of protection that any particular reef provides.

3.3. The role of other coastal ecosystems

Beaches, dunes and barrier islands built of sand all serve to dissipate wave energies and provide important sediment reserves which can support the maintenance of coastlines and even some degree of adaptation to sea level rise (Defeo et al., 2009). Barrier islands of course provide the additional benefit of providing a solid barrier to waves, but also have wave reduction capacity where they form only a discontinuous barrier (Feagin et al., 2010; Wamsley et al., 2009). The importance of dunes in reducing wave and storm surge impacts during extreme events has been well documented (Ba Thuy et al., 2009; Ranwell and Boar, 1986; Roelvink et al., 2009; Sanjaume and Pardo-Pascual, 2005; van der Meulen and Salman, 1996). The presence of vegetation is a critical component of the structure and stability both of dunes and barrier islands, and their coastal protection function can be reduced by vegetation removal or introduction of exotic species (Bhalla, 2007; Feagin et al., 2010).

Shallow nearshore habitats also provide coastal protection. Seagrass beds are known to attenuate both waves and currents (Bradley and Houser, 2009; Fonseca and Cahalan, 1992; Koch and Gust, 1999). They can also increase the settlement, capture and storage of sediments, in some cases leading to vertical accretion of the sea bed (Cochard et al., 2008; Gacia et al., 1999; Koch et al., 2006; van Keulen and Borowitzka, 2003). Loss of seagrass habitat has been shown to diminish these processes and increase erosion (Peterson et al., 2002).

Reef building shellfish species such as oysters and mussels also have the ability to trap sediment, reduce current velocities and dampen waves (Borsje et al., 2011; Meyer et al., 1997; Piazza et al., 2005; van Leeuwen et al., 2010). These processes can enhance and maintain adjacent habitats such as salt marsh and seagrasses (Meyer et al., 1997; Smith et al., 2009), further increasing shoreline stabilization. The physical structure and natural growth of oyster

reefs has led to consideration of oyster reef breakwaters as a cost effective alternative to limestone rock breakwaters. Living oyster breakwaters are an attractive alternative as they can be constructed using sustainable native materials, have the potential to increase in size over time, and are less likely to require long term replenishment to remain effective (Piazza et al., 2005). The establishment and effectiveness of these reefs for shoreline protection is influenced by local hydrodynamic regimes, with the most protective benefits being documented in low energy environments (Borsje et al., 2011; Meyer et al., 1997).

4. Coastal habitat loss and adaptation

Maintaining healthy, functioning ecosystems is important for maximizing their effectiveness in reducing human vulnerability and supporting adaptation to climate change, but the reality is that in many locations coastal habitats are being degraded and lost. Mangrove habitats are declining at a rate of 0.66% per year, a rate 3–4 times faster than global forest loss; some 75% of the world's coral reefs are rated as threatened; 85% of oyster reefs have been lost globally, and local, regional and global reviews point to equally worrying levels of impact across all coastal ecosystems (Beck et al., 2011; Burke et al., 2011; Ralph et al., 2006; Silliman et al., 2009; Spalding et al., 2010; Waycott et al., 2009).

Coastal ecosystems are threatened by both direct and *ex situ* impacts. The former include habitat loss or fragmentation, notably from land claim, conversion to aquaculture and mangrove harvest, as well as overfishing and destructive fishing, both of which can lead to major changes in ecosystem structure and function. Indirect or *ex situ* impacts include many land-based activities that affect sediment, nutrient and pollutant levels in coastal waters. Conversion of natural lands to agriculture and poor agricultural practices frequently lead to changes in freshwater runoff and sediment delivery. Intensive irrigation and dams can reduce freshwater flows. In addition, climate change also impacts coastal ecosystems. Widespread coral bleaching has already affected every coral reef region (Veron et al., 2009), and ocean acidification could pose a significant threat to coral and shellfish reefs. Loss of living coral cover across Caribbean reefs since the 1970s has already led to remarkable declines in surface complexity, or rugosity, that are likely to have reduced the coastal protection function of reefs in many areas (Alvarez-Filip et al., 2009). Continued urbanization is of considerable concern, especially as sea level rises, as it prevents natural landwards migration of coastal wetlands and habitats are lost through “coastal squeeze”.

5. Incorporating coastal ecosystems into adaptation strategies

In many areas the coastal protection benefits provided by natural ecosystems are considerable, but they are often overlooked and/or are undermined. A more coherent and holistic utilization of natural coastal protection within the framework of climate adaptation is needed. Here we outline some of the critical steps to ensure this:

5.1. Build the case for natural coastal protection

Though there is enough evidence and knowledge to recommend the use of natural ecosystems for coastal protection, large scale uptake of this adaptation option requires improved information in two critical areas:

5.1.1. Advance coastal protection science

Understanding of ecosystem based coastal protection is advancing rapidly, but there is a continuing need to build on this

research, synthesize existing literature and build better models. Such models must incorporate the complexity of natural environmental variation, including the influence of both the abiotic and ecosystem variables outlined in Table 1. We need to clearly understand how much protection a given ecosystem will provide to the communities and infrastructure that lie behind it.

5.1.2. Quantify ecosystem services in addition to coastal protection

Natural systems provide a host of additional benefits alongside coastal protection – fisheries, timber and recreation being key amongst those. Understanding and quantifying this full suite of benefits will help to “make the case” for maintaining and managing coastal ecosystems. Economic analyses comparing hard (or “grey”) and green infrastructure should account for long-term maintenance and potential co-benefits/losses of ecosystem services. These analyses should be simple and accessible to all levels of decision makers, and relevant to decisions that engineers and planners have to make. Non-monetary values should also be examined, including considerations of food security, livelihoods, vulnerability and culture.

5.2. Bring ecosystems into mainstream decision making processes

Often, ecosystems are considered only within the limits of environmental planning and decision-making. In order to account for the full potential of these systems to protect coastlines, and to maximize their ability to support human communities, we must avoid compartmentalization between sectors, and find ways of integrating these considerations into mainstream development planning processes.

5.2.1. Consider ecosystems in vulnerability assessments of coastal communities

Social and economic vulnerability assessments have often been limited to direct impacts of climate change. In coastal areas, this means identifying communities that could be impacted by sea level rise and coastal storms. In addition, these assessments should explicitly factor in levels of social, economic and cultural dependence on coastal ecosystems and natural resources for food, income, employment or recreation (Lacambra Segura, 2009). Vulnerability assessments should also factor in future change, including projected human impacts from climate change and other more local impacts, but also social, demographic and economic change, arising from tourism or fishing sectors, residential or industrial development patterns and the like – such future change is likely to greatly alter temporal trends and spatial patterns in vulnerability to sea level rise (Oliver-Smith et al., 2009). Linked to this, the consideration of coastal engineering solutions into vulnerability assessments needs to move away from the simplistic assessment of construction costs to a holistic consideration of the cascading impacts for entire coastlines, and the losses of ecosystem services to communities as ecosystems are impacted (Airoidi et al., 2005; Airoidi et al., 2009).

5.2.2. Develop scenarios and tools that model complex combined risks

Projections of both climate change and natural hazards present a complex setting for predicting risk. In many areas risks are interdependent or conditional, with complex interactions. Furthermore, low-likelihood but high impact events are highly problematic for simple modelling and for many traditional cost-benefit approaches. Progress is being made in the insurance sector with models that include combined conditional probabilities of the effects of multiple stressors acting on coasts (Bresch and Mueller, 2013; CCRIF, 2012) and efforts are needed to ensure that ecosystems are incorporated into these models. Such approaches

are becoming highly influential in determining coastal development and risk management, and are driving new investment mechanisms such as risk pooling.

5.2.3. Build decision support systems to help communities visualize impacts of and solutions for coastal adaptation

Coastal hazards and climate change can be difficult to plan for because they are infrequent or in the future. Moreover many critical coastal decisions are made at local levels where access to planning resources can be limited. Increasingly tools and decisions support systems (e.g., www.coastalresilience.org) are being developed to help communities visualize the ecological and socio-economic impacts of coastal hazards and climate change and to consider solutions to these impacts. These tools often incorporate location-specific predictions of sea level rise and storm hazards that are tied to IPCC consensus models of climate change. They can help communities assess risk as well as social and economic vulnerability. For example, they can help identify critical infrastructure at greatest risk and people least likely to get out of harm's way. More importantly they can help communities evaluate solutions that can reduce risk, vulnerability and costs associated with natural hazards and climate change. These solutions can inform coastal development planning, land use zoning, restoration, hazard management plans, or other resource management plans (Ferdña et al., 2010).

5.2.4. Engage stakeholders

Engaging stakeholders provides opportunities for vulnerable coastal communities to employ local knowledge and participate directly in developing and applying adaptive solutions and policies. It also helps in building a constituency for management responses, agreeing upon and understanding the consequences of the decisions made.

5.2.5. Enact policies to ensure environmental integrity

The adoption of “no regret” adaptation policies – i.e. those that are beneficial even if climate change impacts are less than projected – is one of the best and most urgent first steps in adaptation planning (USAID, 2009). In coastal areas, “no regret” measures could include the adoption or enforcement of buffer zones and coastal development setbacks, the protection and management of critical coastal ecosystems (such as coral reefs and mangroves), and watershed management and control of urban pollution, as well as strengthening and enforcing regulations regarding destruction of coastal ecosystems (e.g. mining of coral reefs, illegal fishing and logging). In addition, adopting policies that ensure environmental integrity in both development and adaptation planning are needed, such as requirements for environmental impact assessments and strategic environmental assessments for new development plans and activities as well as large-scale adaptation options or infrastructure. Tools such as **marine spatial planning** and **integrated coastal management** recognize the need for multiple uses of ocean and coastal space and provide broader and often more systematic approaches to broad sectoral uses.

5.3. Incorporate proven management interventions

Many proven management tools, if applied in the context of adaptation planning, can be put into place quickly to bolster and maintain coastal protection.

Marine Protected Areas (MPAs) already cover over 12% of the world's coastlines (Spalding et al., 2008), 25% of mangroves (Spalding et al., 2010) and 27% of coral reefs (Burke et al., 2011). Typically MPAs aim to protect habitats and biota *in situ*, and thus can serve to protect the structural components of habitats critical for coastal protection purposes. MPAs are less effective at controlling ex

situ and climate change impacts, but even here there is some evidence of increased resilience of corals, with more rapid recovery in MPAs following climate disturbance (Mumby and Harborne, 2010). Improving the design and management of MPAs and MPA networks for increasing the resilience of coastal communities and maintenance of natural coastal protection services is urgently needed (Brock et al., 2012; Dudley et al., 2010; Toropova et al., 2010).

Habitat restoration to provide coastal protection is increasingly being undertaken world-wide (Nellemann and Corcoran, 2010; Silvestri and Kershaw, 2010). Spalding et al. (2010) document over 375,000 ha of mangrove restoration work, and note that in cases from Bangladesh to the Philippines a primary reason for restoration is for coastal protection. Specific studies of restored mangroves in Vietnam (IFRC, 2011) and on restored oyster reefs in the US (Scyphers et al., 2011) have joined a growing body of evidence from natural settings of the coastal protection function of ecosystems. Not all restoration involves the active rebuilding of habitats, and hydrological and sediment flow restoration can play a critical role in allowing ecosystems to recover.

Managed Realignment. Increasingly it will be necessary to allow the natural movement of coastal ecosystems – most typically landward migration. In many areas such movement will be prevented by adjacent human land use, however **managed realignment** is increasingly being undertaken as an alternative to costly and sometimes risky maintenance of artificial sea defenses. Here coastal lands are deliberately re-connected to the tidal system by opening seawalls and filling drainage channels. Results vary, but in many areas natural regeneration of salt marsh or mangrove has taken place and processes of accretion have been re-established (Linham and Nicholls, 2010; Luisetti et al., 2011). A key challenge to managed realignment is reluctance of landowners to abandon property, quite often even in the case of powerful economic arguments, incentives or considerable risk.

Hybrid Engineering Structures. Natural coastal protection may not offer sufficient security in many areas. At the same time, the economic and social costs of engineered solutions may also be unacceptable in some areas. Increasing our knowledge of natural systems will open up possibilities for hybrid solutions where hard engineering is combined with natural ecosystems. Examples might include building artificial structures to support restoration of natural shellfish reefs (Scyphers et al., 2011) or coral reefs (Precht, 2009). At smaller scales experiments have been undertaken to create concrete constructions to encourage settlement of more diverse and productive benthic communities. By contrast, at very large scales entire dune systems and salt marsh communities can be built or enhanced through sand nourishment or engineering of dykes and artificial channels to encourage sediment precipitation (Borsje et al., 2011; Jones et al., 2010; van Slobbe et al., 2013).

5.4. Build capacity for implementation

The need for adaptation is being widely discussed and built into planning, and indeed into ongoing coastal investment and future budgeting. Such approaches have been encouraged under the UNFCCC's call for National Adaptation Plans (NAPs), but to date coastal adaptation plans have tended to focus on engineered solutions. Policy tools are needed to encourage appropriate consideration and uptake of ecosystem-based coastal defence, utilising the approaches and interventions described above. Such approaches may be encouraged through economic arguments including additional economic benefits from other ecosystem services. Critical to success, will also be the strengthening of capacity at local and national levels to access and utilise relevant information in both planning and implementation of natural or hybrid coastal defence planning.

6. Conclusion

Coastal hazards and climate change are already impacting communities. These impacts affect lives, livelihoods, and investments both private and public. There is increasing evidence that coastal ecosystems can play an important and cost-effective role in reducing vulnerability. As with all coastal protection schemes, what is needed are more field tests of these ecosystem-based coastal protection approaches so that we can better understand the conditions under which they can be most effective. We also need a better understanding of the full range of other ecosystem services provided by coastal ecosystems, and of the costs of losing them through poorly designed hardened shoreline solutions. This information needs to be coupled with better estimates of social vulnerability and it needs to be made accessible, including through integration into mainstream planning and development processes. Together, these actions will continue to improve decisions made in coastal management and promote the use of ecosystem-based adaptation solutions to reduce vulnerability and costs associated with coastal hazards and climate change.

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