POLICY PERSPECTIVE

Coastal Ecosystems: A Critical Element of Risk Reduction

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Abstract

The conservation of coastal ecosystems can provide considerable coastal protection benefits, but this role has not been sufficiently accounted for in coastal planning and engineering. Substantial evidence now exists showing how, and under what conditions, ecosystems can play a valuable function in wave and storm surge attenuation, erosion reduction, and in the longer term maintenance of the coastal profile. Both through their capacity for self repair and recovery, and through the often considerable cobenefits they provide, ecosystems can offer notable advantages over traditional engineering approaches in some settings. They can also be combined in "hybrid" engineering designs. We make 10 recommendations to encourage the utilization of existing knowledge and to improve the incorporation of ecosystems into policy, planning and funding for coastal hazard risk reduction.

The risks and costs of coastal hazards to people and infrastructure are increasing. The landfall of "Superstorm" Sandy in New York on 30 October 2012, just a few months after Hurricane Isaac hit the Louisiana coast (on the 7th anniversary of Katrina's landfall) reignited public discourse on the role of climate change in altering storm distribution and intensity. While academic debate in this arena continues (e.g., Villarini *et al.* 2011), action may still be a prudent response. This was well captured in the words of the New York mayor Michael Bloomberg following the devastation of Sandy: "while the increase in extreme weather we have experienced in New York City and around the world may or may not be the result of it [climate change], the risk that it may be—given the devastation it is wreaking—should be enough to compel all elected leaders to take immediate action" (Bloomberg 2012). Further impetus for action is that an increasing number of people and economic investments are vulnerable to such disasters as coastal populations expand (Mendelsohn *et al.* 2012). This has led to a growing reliance on risk reduction through engineered solutions. Unfortunately, such solutions give little consideration to ecosystem-based coastal defense.

Risk reduction strategies need to be robust, safe, cost-efficient, and adaptive to deal with uncertain future scenarios. There is now substantial evidence describing how ecosystems can reduce impacts such as wave action, erosion, and flooding. These services can stand alone, but can also be incorporated into hybrid engineering solutions, where ecosystems are utilized alongside engineered defenses. The utilization of salt marshes to protect dykes traces back millennia on the Atlantic coast of Europe (Davy *et al.* 2009), while recent decades have seen the growing utilization of managed realignment in northern Europe and North America, often as a direct effort to improve coastal protection or to reduce coastal engineering costs (Rupp-Armstrong & Nicholls 2007). Many of the extensive areas of mangrove restoration worldwide have cited expected coastal protection benefits (Macintosh *et al.* 2012).

Despite these examples, the utilization of ecosystems as a key component of coastal defense planning and engineering remains far from routine, and most examples are still small-scale. There is an urgent need to build operational frameworks for coastal defense planning and implementation which operate across the natural and social sciences, combining the expertise of ecologists with that of planners and engineers to optimize risk reduction. Such interdisciplinarity may be fostered by changes to policy and project implementation, and in the funding to support such collaboration. Such change also needs to become embedded in the research agenda, and in graduate education programs. Here, we provide a brief review of the key ecosystem services in coastal risk reduction and make recommendations for immediate implementation.

Inundation risk mitigation and erosion reduction services of ecosystems

Wave heights can be rapidly reduced over distances of just a few tens or hundreds of meters as they pass over or through morphologically complex ecosystems (Kench & Brander 2006; Koch *et al.* 2006; Spencer & Möller 2013). This attenuation is nonlinear both spatially and with water depth, with the greatest reduction in the first meters of transit (Koch *et al.* 2009; Gedan *et al.* 2011), and with reduced dissipation under increasing water depths, when canopies become submerged (Möller 2006). Numerical models are beginning to capture the complexity of these processes (Suzuki *et al.* 2012; Yao *et al.* 2012). By attenuating waves, ecosystems also reduce wave set-up and run-up which can otherwise increase flooding levels considerably. While wave attenuation can be reduced when ecosystems are submerged during storm surge events, mangroves, supratidal vegetation, and coastal forests will continue to reduce waves in these circumstances. In many coastal settings multiple ecosystems such as mangroves, seagrasses, and reefs are found in sequence across the coastal profile and may play an additive, even synergistic role in coastal defense (Koch *et al.* 2009).

Over wide expanses (kilometers rather than meters) mangroves and other coastal wetlands can reduce storm surge water levels and inundation extent across low-lying coastal areas on their landwards margins (e.g., Wamsley *et al.* 2009; Zhang *et al.* 2012). Much was also written about the role that mangroves may have played in coastal defense following the 2004 Asian Tsunami, but overall the conclusions were mixed (Cochard *et al.* 2008). Extreme events can overwhelm both natural and human defenses, but there remains clear evidence that in some places wide mangrove forests, seagrass beds or coral reefs may reduce flooding extent and associated damage in the case of surges associated with storms or small to moderate tsunamis (Tanaka 2009; Gelfenbaum *et al.* 2011; Zhang *et al.* 2012).

Ecosystems can also reduce erosion and build sediments, in some cases maintaining or increasing the surface elevation of the substrate. Most generate organic and/or mineral sediments such as carbonate sands, and vegetation detritus (e.g., McKee 2011). By reducing wave energy, they lower water velocities and shear stress near the sea bed, reducing erosion and enhancing particulate deposition (de Boer 2007). Erosion may be further reduced through mechanical protection provided by biofilms, roots, and rhizomes, or through alteration of the mechanical and chemical properties of the substrate (e.g., Murphy & Tolhurst 2009). The importance of erosion reduction in saltmarshes was recently highlighted in the Gulf of Mexico: rapid erosion occurred where marsh-edge plants had been killed by oiling but this slowed again following ecosystem recovery (Silliman *et al.* 2012). In the same region oyster reefs are being actively restored along eroding coastlines and have reduced erosion along marsh edges (Scyphers *et al.* 2011).

Self-repair and adaptive capacity of ecosystems

Perhaps the most striking difference between ecosystems and engineered structures is that ecosystems are highly dynamic in response to physical changes and in many

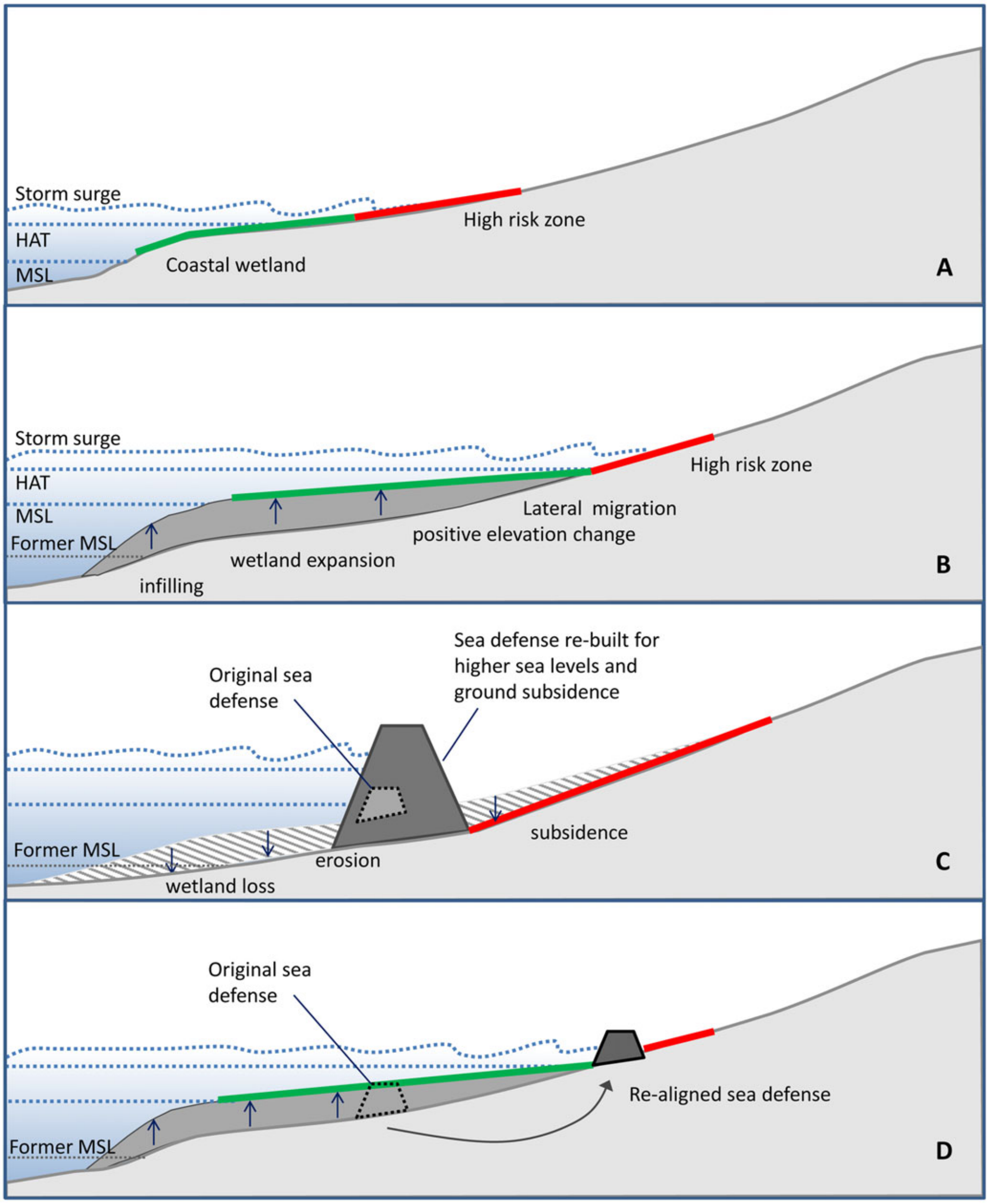

Figure 1 Graphic representation of how elevation of coastal marshes might be expected to vary in response to increases in relative sea level. (A) Contemporary natural shoreline. (B) Natural shoreline following sea-level rise in locations where growth and sediment supply allow some degree of positive elevation change, as well as lateral (landwards) migration. (C) Hard engineering solutions "holding the line" of contemporary coastlines through increasingly large interventions. (D) Hybrid interventions (see Figure 2), where space is allowed for the maintenance of natural coastal defenses.

cases may be able to recover and regenerate following damage (e.g., Paling *et al.* 2008). Over longer timeframes, the generation and capture of sediments by ecosystems can also contribute to increases in elevation which may be of considerable importance in the face of rising sea levels. Sedimentary records show that in some settings mangroves, reefs, and saltmarshes have been able to maintain surface elevation in relation to rising seas, even at rates greater than currently being experienced (e.g., Montaggioni 2005; McKee *et al.* 2007). Ecosystems can also migrate laterally both landwards and seawards. Although such migration may not be possible in many managed landscapes, where allowed it ensures continued provision of hazard risk reduction in future sea-level scenarios (Rupp-Armstrong & Nicholls 2007), as illustrated in Figure 1.

Extremes of disturbance can of course make recovery difficult or unlikely (e.g., the "phase shift" from a hard [coral-dominated] to a soft [algal-dominated] reef; Done 1992). Alterations to sediment input or tidal flows, through the installation of hard engineering or changes in riverine inputs, can lead to wetland loss due to subsidence (Syvitski *et al.* 2009). Additionally, the prevention of landwards migration by engineered sea defenses can accelerate wetland loss through coastal squeeze as sea-levels rise. Figures 1C and D illustrate potential engineering interventions, some of which can "lock" managers into ever more challenging future investments (Figure 1C).

Costs and cobenefits

In the face of global climate change and growing vulnerability, the design, building and maintenance costs of coastal engineered structures are increasing. While ecosystem restoration or ongoing management will likely incur some expenses, many existing coastal ecosystems already provide some degree of protection with no installation costs (Barbier *et al.* 2013). Additionally, compared to monofunctional engineered flood defense infrastructure, coastal ecosystems provide multiple ecosystem services; thus shoreline defense may be only a small fraction of their total value (Barbier *et al.* 2011; Grabowski *et al.* 2012). Effective valuation of this array of benefits is critical in coastal planning—the loss of cobenefits that may occur with the implementation of hard engineering may be considerable.

Cautions

Ecosystems will not always provide adequate coastal defense services. Spatial variability in risk reduction will be influenced by geomorphic setting (including bathymetry, coastal typology, geology, and sediment supply), oceanography (including currents and tides), the dimensions and structure of the habitat, and the local risk environment. Anthropogenic degradation is another driver of spatial variability, through direct modification of structural ecosystem components, but also driven by impacts on key species such as grazers or predators (e.g., Silliman *et al.* 2005; Altieri *et al.* 2012). Engineering design already utilizes critical environmental variables, enabling reasonable modeling capacity for particular hazards. Similar levels of specificity are needed for the utilization of ecosystems in risk reduction, recognizing the key role of local ecosystem characteristics, alongside physical variables. While some of this information is becoming available, gaps in current understanding remain.

One feature of engineered approaches is that high levels of risk reduction can often be achieved with relatively small spatial footprints. This may be of particular importance adjacent to highly developed shores. Some ecosystems, by contrast, may require a much larger spatial footprint, while uncertainty about their effectiveness may require the incorporation of even greater safeguards, for example in adjacent land-use planning, and may indeed preclude their use in certain areas of highest risk or highest vulnerability. Optimal coastal management may include both engineered and ecosystem components, to ensure acceptable levels of risk reduction while also reducing costs and maintaining ecosystem cobenefits.

Both natural and engineered structures have limits or thresholds to their functional performance. For example, wave attenuation by coral reefs or by submerged breakwaters will be diminished with increasing water depth over the structure (Kench & Brander 2006), and during very high storm surges their role in wave attenuation may be much reduced. The quantification of thresholds of both external forcing and internal resilience are a priority if the level of risk reduction by ecosystems is to be assessed accurately, particularly given our understanding of the existence of nonlinearities in risk reduction discussed above (Koch *et al.* 2009).

The most extreme coastal hazards can lead to loss of living cover in mangroves, reefs, and other ecosystems. While we note that ecosystems often have a regenerative capacity, this is not immediate. Such storms are a natural occurrence and can help in the maintenance of wetlands and dunes, but can also lead to more extreme changes of elevation (erosion or deposition) and to the replacement of ecosystems (e.g., Howes *et al.* 2010). More typically, conditions remain amenable to recovery, although timeframes may be years to decades (Alongi 2008; Silliman *et al.* 2012). Regenerative capacity and overall ecosystem resilience may also be compromised by poor ecosystem health (e.g., Hughes 1994). By contrast, recovery rates may be enhanced by anthropogenic interventions such as replanting (e.g., Borja *et al.* 2010).

Engineered structures have a design life, typically 20–50 years, and are built for projected environmental, climatic, and anthropogenic conditions over that period. Ecosystems typically remain in place for much longer (hundreds or even thousands of years), although such persistence may be challenged by climate change and more proximal human impacts. Thus, coral bleaching and ocean acidification may threaten the longer term future of coral reefs. Even if this is the case, however, reefs are likely to maintain their critical coastal protection function at least for the 20–50-year time scales of most coastal planners.

Recommendations

Increasing hazards, growing populations, and inappropriate development combine to create a growing imperative to develop appropriate coastal defense strategies. We believe that ecosystems can play an important role in these strategies. Integrated coastal defense planning, with ecological and engineering approaches coming together into a single, holistic planning framework, can offer increased levels of risk reduction. The use of ecosystems to reduce coastal risk will expand the options for management, with potentially significant economic benefits, and with cobenefits to coastal communities and to biodiversity.

Such ideas are yet to become mainstream. Recent and ongoing work has begun to draw attention to the role of ecosystems in hybrid engineering efforts including the Building with Nature work in the Netherlands (Borsje *et al.* 2011) and living shorelines work in the United States (Wallendorf *et al.* 2011). A number of agencies and communities have also begun to utilize natural processes through ecosystem conservation, restoration, and managed realignment (Luisetti *et al.* 2011; Scyphers *et al.* 2011). Beyond these practical efforts there is a small, but growing, interest at the policy level, including the U.S. Army Corps of Engineers (USACE) Engineering with Nature approach and the Systems Approach to Geomorphic Engineering (SAGE) initiative led by USACE, the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration. In the United Kingdom, Shoreline Management Plans (SMPs), first developed in the 1990s and now in their second generation phase, seek to institutionalize new coastal management strategies and draw some attention to environmental improvement and managed realignment (DEFRA 2006).

To more deeply embed these ideas in policies and planning and to work toward increasing combined natural and engineered flood risk reduction infrastructure we make the following recommendations:

(1) The risk reduction benefits of ecosystems need to be quantified at the site level. Generic predictions about hazard mitigation are of limited use. The quantification and modeling of variation in service provision relating to geomorphological influences (including tidal and sediment regimes), ecosystem morphology and hazard context are needed to better assess risk reduction. Such detailed information must be built into local planning and engineering approaches as well as into conservation and restoration initiatives. This will also allow an objective comparison of ecosystems with engineered structures.

(2) Models and planning approaches also need to account for the cumulative benefits of multiple ecosystems—risk reduction capacity may be greatly enhanced across a sequence of habitats such as seagrass beds, shellfish reefs, and marshes. Such ecosystem combinations are common, and the relative influence of different elements will alter with water depth. During high wave and storm events, supratidal systems, including vegetated dunes and coastal forests, may also play an important role in hazard mitigation.

(3) Engineering solutions to coastal hazards need to recognize the close links between biotic and physical processes, and incorporate ecosystems into designs for coastal risk reduction. Such hybrid approaches will, in many settings, reduce risk while maintaining many valuable additional ecosystem services and conservation benefits.

(4) Ecosystems should be managed or restored to maintain or enhance risk reduction properties. This may include ecological restoration of key structural components of the ecosystem (mangrove, seagrass, saltmarsh plants, and corals), or the restoration of functional processes or keystone species. It may also include physical interventions such as the restoration of water and sediment flows and the removal of pollutants.

(5) Monitoring of ecosystem-based and hybrid coastal defense interventions—including key ecosystem state parameters, such as surface elevation, geomorphological adjustment, and species richness and composition—is needed to build our understanding of risk reduction by ecosystems. This needs to be long term (multiyear) to allow for natural variability and should be a requirement of all new projects including hybrid engineering, habitat management and restoration projects. Recent restoration work on saltmarshes, for example, in San Francisco Bay (Brand *et al.* 2012) and at Wallasea Island in the United Kingdom (Dixon *et al.* 2008), provide examples of how such monitoring can be developed and utilized. A primary focus should be to generate metrics of utility for coastal defense planning and engineering, rather than ecology.

(6) Investment decisions including loans by the World Bank and International Development Banks for climate adaptation and disaster risk reduction, and investment by agencies such as FEMA, should be informed not only by direct costs and benefits, but also by the suite of associated ecosystem service benefits that may be lost with hard engineering solutions or gained with hybrid approaches. The challenges associated with the monetization of ecosystem

services have been widely discussed (e.g., Burkhard *et al.* 2010), but such monetization is now being attempted at multiple scales (e.g., de Groot *et al.* 2012) including site-based methods and models (e.g., Guerry *et al.* 2012). Even where reliable economic models cannot be developed, minimum or precautionary values should be utilized, rather than assuming zero values.

(7) Where ecosystems offer acceptable levels of risk reduction, funds such as FEMA's hazard mitigation grants, or international support such as Climate Adaptation Funds, should target habitat conservation and restoration measures, and/or the utilization of hybrid solutions rather than focusing solely on hard defense solutions. The scientific basis for ecosystem-based risk reduction is well enough advanced to allow partial assessments in most settings and models are constantly improving, including broader scale, multiecosystem models (Wamsley *et al.* 2009).

(8) Insurance sector models should also build in ecosystem-based risk reduction. Interest is growing in this sector, and the industry has contributed to studies that have highlighted the potential contribution of ecosystems in adaptation frameworks (e.g., CCRIF 2011). One key challenge here will be to facilitate access to existing physical models to better quantify ecosystem benefits in terms of risk and economic costs. Where appropriate, property owners should receive incentives for ecosystem conservation/restoration.

(9) The contribution of ecosystems to risk reduction must be calculated with levels of certainty approaching those informing structural engineering. While the existing knowledge-base around ecosystems and risk reduction has been underutilized, and remains a rapidly advancing field, there remain important gaps. These should be a focus for research, notably on:

- hazard reduction in different settings, which should support the continuing development and parameterization of numerical models;
- the limits of ecosystem resilience, and the thresholds for sudden failure;
- the influence of ecosystem condition on hazard reduction capacity, including the potential differences between natural and restored ecosystems;
- the needs and possibilities for long-term ecosystem maintenance, either in natural settings, or in restored or hybrid settings, and the costs of such maintenance, particularly in the face of rising sea levels; and
- the connections between fine-scale processes (spatial and temporal) and whole system/long-term processes.

This research needs to be interdisciplinary. A further critical element of such research is rapid and wide communication of findings to appropriate audiences. In particular, existing and new research needs to be collated and incorporated into coastal planning and defense manuals for managers and engineers, alongside information on practical methods of intervention.

(10) Ecosystems should be an integral part of coastal planning and engineering, with ecosystem conservation, enhancement, restoration, managed realignment, and more fully hybrid solutions all joining the list of options available to planners. The combination of ecosystem and engineered responses should become a normative framework in most large bays or landscapes. This might be fostered through the demands of funding agencies, and could be further encouraged by the inclusion of interdisciplinary approaches into education and research programs. There should be a move from partnerships between areas of expertise toward a holistic framework where engineers understand and work with ecosystems as a routine approach.

Risk reduction in any given coastal area is typically achieved through a combination of approaches. These include structural interventions such as the building of walls or breakwaters; soft engineering such as beach nourishment; the establishment of legal frameworks such as building codes and land-use zoning; and the encouragement of social and behavioral modifications including early warning and evacuation plans—as illustrated in Figure 2. Ecosystems already form a critical but rarely acknowledged part of this risk reduction framework in many areas and their utilization comes with potential cost-savings and the assurance of continued cobenefits over the long-term. Bringing these ecosystem services into the general planning approach for coastal areas is an urgent priority, both to ensure the maintenance or enhancement of such natural coastal defense, but also to avoid inappropriate coastal modification, such as land claim or aquaculture development which might lead to the degradation or loss of such benefits. New efforts and funding for coastal adaptation are rapidly being developed and allocated; if appropriate natural solutions are overlooked, the economic and social costs for future generations will be significant.

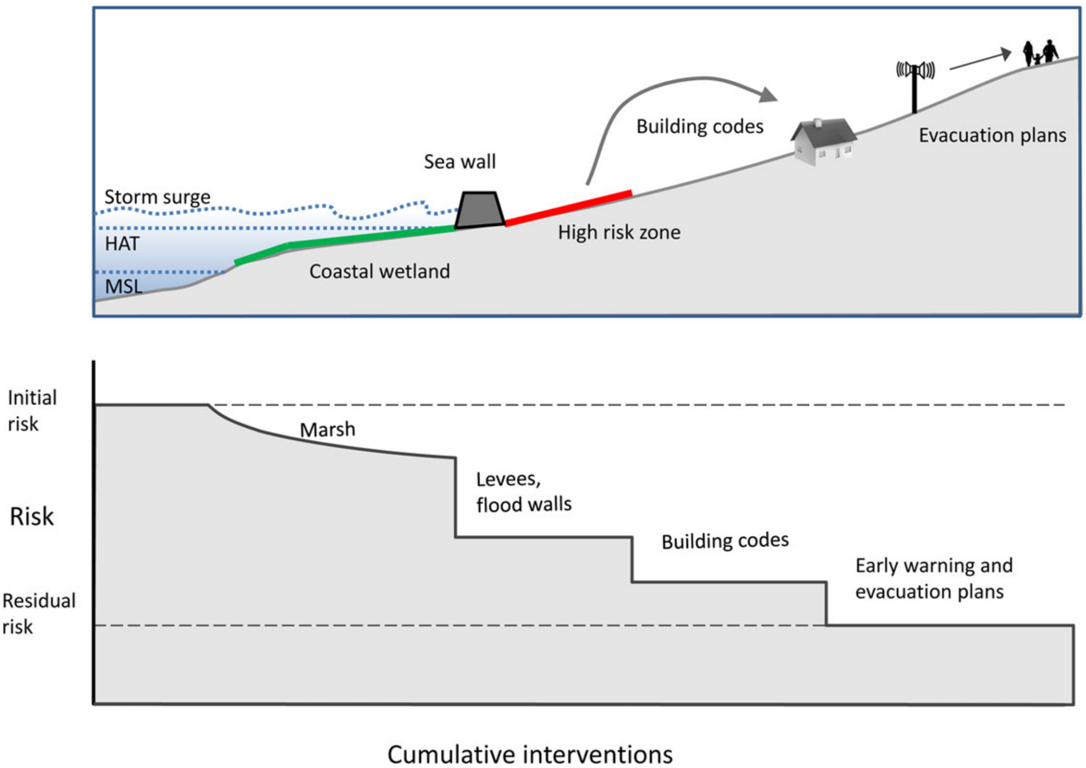

Figure 2 Ecosystems can form an important part of risk reduction, which is typically achieved through a combination of environmental, engineered, social, cultural, and legal approaches as illustrated in the upper figure. Cumulative interventions (lower figure) cannot remove risk, but rather reduce it to an acceptable level of residual risk.

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