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PERSPECTIVE

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Coastal adaptation with ecological engineering

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The use of combined approaches to coastal adaptation in lieu of a single strategy, such as sea-wall construction, allows for better preparation for a highly uncertain and dynamic coastal environment. Although general principles such as mainstreaming and no- or low-regret options exist to guide coastal adaptation and provide the framework in which combined approaches operate, few have examined the interactions, synergistic effects and benefits of combined approaches to adaptation. This Perspective provides three examples of ecological engineering — marshes, mangroves and oyster reefs — and illustrates how the combination of ecology and engineering works.

Because of increasing uncertainty in the face of multiple climate-induced stressors — including sea-level rise, storms and freshwater inputs — adaptation to one type of coastal stress/hazard/disaster may limit the capacity to respond to interacting or unexpected stresses. Instead of promoting one particular strategy, such as sea-wall construction, or defending against one type of hazard, scholars and practitioners encourage a combination of existing methods and strategies to promote synergistic effects. Combining strategies offers one way to be versatile and flexible, and helps to reduce the political, financial and infrastructural constraints that often accompany planning and decision-making[1].

The process of coastal adaptation is shifting towards dynamic responses to multiple stressors, in place of optimization and reliability, which are often seen in single, static systems[2,3]. Coastal adaptation in a changing climate, therefore, needs to take into account several future scenarios, unforeseen consequences, unknown causes and processes of environmental change that limit predictability. This Perspective calls for the robust, resilient and cost-effective solutions that combined strategies can offer to prepare people for a highly uncertain coastal environment in the future.

To integrate existing methods and strategies in the context of new vulnerabilities such as climate change, climate scientists and coastal managers promote mainstreaming and no- or low-regret options[4,5]. We discuss how these concepts relate to coastal adaptation and highlight the important role of combined strategies to manage increasing uncertainty and complexity, citing examples from ecological engineering.

ICZM and no- or low-regret options

In the case of the coastal zone, mainstreaming corresponds to the inclusion of climate change adaptation in the Integrated Coastal Zone Management (ICZM)[6,7] framework. This framework promotes integration of different coastal sectors and activities by coordinating relevant government agencies and the private sector. Combining climate change adaptation with ICZM fits well with its integrative efforts. The difficulties in implementing ICZM are, however, common in both developed and developing economies[8,9]. Inadequate financial commitment, ineffective coastal governance, politics and the nature of public participation can hinder the formation of ICZM regulations, and make it challenging to incorporate climate change into unstable ICZM regimes. Furthermore, the gap between the larger scale of ICZM planning that crosses institutional, political and sectoral boundaries, and the local scale of infrastructure design and execution may deter implementation efforts. For example, translating a large-scale plan into smaller projects and persuading locals of the plan's relevance and significance is not easy to achieve.

No- or low-regret options generate net social benefits with no or low regrets irrespective of the future outcome of climate change[10]. Low-regret measures based on the precautionary principle are first generation, or the easiest of measures to implement. The significance of these options rises in the context of high uncertainty. Given that all measures taken against a threat carry a certain amount of risk, coastal adaptation measures can be riskier, as climate change science carries high uncertainty. No- or low-regret measures, therefore, are touted as a better adaptation approach in coastal zones than 'regret-risking options' that are chosen in spite of shortcomings or negative consequences. In contrast to well-quantified and prioritized regret-risking options with large capital investment, no- or low-regret approaches require further evaluation and quantification of their effectiveness.

In the coastal zone, no- or low-regret options include revamping early warning systems, preventing land reclamation, offering beach nourishments and improving housing and transportation systems[4]. These measures generate co-benefits that are useful for multiple sectors and systems, and therefore serve multiple functions. No- or low-regret options are similar to capacity building, in that they emphasize nurturing of general capabilities — such as basic education, infrastructural development and poverty reduction — to reduce vulnerability and contribute to building resilience[11]. Ecosystem-based adaptation is also indicative of no- or low-regret options[12] in that it is congruent with the 'working with nature' approach[13,14] that is also promoted within the ICZM framework.

Although ICZM can encompass climate change adaptation and no- or low-regret options are available, ICZM and no- or low-regret options are not easy to implement. Because of the challenges of ICZM and the lack of information on the effectiveness of no- or low-regret options, they provide more of a conceptual framework than concrete adaptation strategies. Combined measures of existing strategies and methods for coastal protection offer specific

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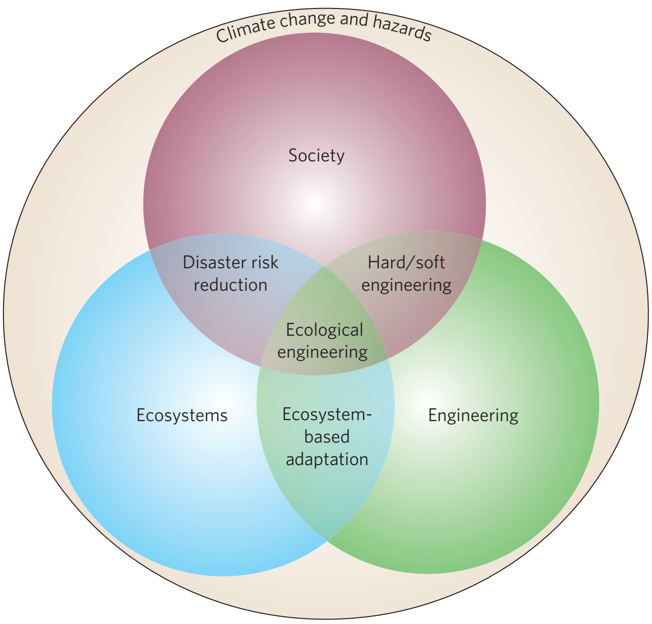

Figure 1 | Combining strategies for coastal adaptation. This diagram describes the interactions of society, ecosystems and engineering in response to changing climate and coastal hazards, and delineates the overlapping areas that provide opportunities for combined adaptation strategies.

instances of low-regret options, and complement the general capabilities of coastal protection. In this light, one of the most developed areas in practice is ecological engineering.

Ecological engineering

Traditionally, practitioners employ engineering approaches to protect coastal areas from ocean-derived threats[15]. They involve identifying a threat or set of threats to the shoreline (for example, sea-level rise or waves) and use synthetic, engineered structures (such as sea-walls, rock revetments and levees) to reduce that threat. In the process of building these structures, natural ecosystems including marine and terrestrial grasses, trees and structure-forming animals (for example, oysters) are destroyed and replaced by sea-walls and rock revetments. Although these structures have been successful in protecting local areas from deterioration at times, they tend to erode neighbouring coastal areas[16,17] and can damage or destroy surrounding ecosystems. Subsequently, traditional engineering approaches may lead to negative or regretful impacts on morphology, hydrodynamics and sediment and nutrient budgets, as well as local economies at several scales.

These widespread undesired effects have resulted in a worldwide need for a new approach to coastal protection that minimizes non-target impacts[18]. Ecological engineering has taken on this challenge and aims to consider both people and the environment in approaches to protect people and property[19,20]. Roy *et al.*[20] stated that the field of ecological engineering and the study of social–ecological systems share a similar objective in linking social and ecological systems. Similarly, Jones *et al.*[12] called for increased interaction between social sciences and ecological engineering, as this has seldom occurred.

Ecological engineering for coastal protection is largely based on the emerging theory in conservation and restoration that emphasizes the positive interactions that generate synergies[21–23]. Positive interactions are those in which at least one species benefits from the presence of another species, without harm to either. Recent research in ecology has revealed that purposefully incorporating these interactions into designs of restoration projects and ecosystem recovery experiments can increase community recovery and stability by orders of magnitude[21]. For example, in mangrove restoration, when transplants are planted in close proximity rather than in the more typical spread arrangement, a shared benefit or positive interaction occurs that greatly increases plant growth[23]. Incorporating these interactions into conservation actions can also increase resilience to stress at the community level (for example, seagrasses planted with clams in their roots grow twice as fast), while simultaneously providing services at the ecosystem level (seagrasses and clams combined increased the total amount of fixed carbon, for instance)[24]. These findings have led to a call for a paradigm change in coastal conservation and engineering, from an overwhelming focus on reducing threats to conservation targets, to a framework concentrated on both reducing threats and maximizing positive interactions between the target and its ecological neighbours.

Ecological engineering therefore leaves behind traditional engineering-only approaches and uses a combined method for ecosystems that are inherently self-sustaining and responsive, and generates positive species interactions. It provides possibilities for multiple-use design that incorporates coastal defence, recreation and ecosystem services, and merges climate-adaptive coastal management and disaster management in this framework (Fig. 1). The three examples discussed below illustrate the ways that a mix of ecology and engineering can operate to generate synergistic effects, adaptive management and ecosystem services.

Marshes

In the Netherlands, where for more than 2,000 years humans have cooperated to keep the ocean at bay, coastal engineers have been building with nature to maximize its positive effects and increase the resilience of their man-made structures to oceanic disturbance[25,26]. For example, levees built to prevent flooding during storms are maintained terrestrially with a thick grass cover to increase their integrity, and wetlands seaward of the levees reduce exposure to wave action[25].

Likewise, along coastlines that are threatened by the rise of mean sea-level, conservation and restoration of salt marshes facilitate deposition of sediments and accretion of organic matter that can raise the marsh platform and keep pace with sea-level rise to a certain extent[27]. Marshes also decrease shoreline erosion, as the expansive root system produced by marsh grasses increases soil integrity and resistance to wave-driven erosion[27,28]. In addition, marshes dampen waves, suppress erosion rates[29] and thereby reduce wave impact on adjacent levees. Because of these positive effects, marshes enable a levee design that is more nature friendly — one that allows for gradual slopes and layering with grasses on the outside instead of hard stones or asphalt, increasing landscape attractiveness.

The benefits of engineering efforts that exploit the positive interactions that are generated by habitat-building organisms go beyond natural ecosystems enhancing the integrity and efficacy of man-made structures, as the services of the planted ecosystems are not limited to this one interaction. Salt marshes, for instance, increase fishery production in surrounding areas[30,31], enhance carbon sequestration into marine sediments[32] and decrease terrestrial run-off in estuaries[33]. Human use of the shorelines also rises, as the natural ecosystems planted on top of and around the man-made structures attract people seeking places for outdoor activities. Grass-layered levees are often grazed by sheep for maintenance[15], servicing the production of meat and milk.

Mangroves

Mangrove planting and restoration are increasingly viewed as an adaptation strategy to sea-level rise and coastal storms[34] because mangroves can both facilitate sedimentation and dampen wave stress. For example, the aftermath of the 2004 Indian Ocean tsunami brought anecdotal accounts of mangroves providing coastal protection from inundation. Although the extent of their effectiveness is controversial, mangroves do alleviate the impact of moderate tsunami waves[35–37]. In addition, the roots of mangroves trap sediments[38], add to the surface elevation[39,40] and provide protection against sea-level rise —Alongi[36] showed that the sedimentation rate in mangroves is almost equal to the rate of sea-level rise.

To facilitate mangrove restoration, a sustained supply of sediments and the establishment of suitable conditions for sediment accretion are essential. Mangroves grow well in the fine sediments that are found in muddy tidal flats, and these sediments can be obtained naturally or artificially to establish mangrove habitats. For example, on the low-lying Ganges–Brahmaputra Delta, silt flows into flood-prone ponds and increases the accumulation of sediments[41], creating high grounds for agricultural use as well as for coastal protection. Mangroves also trap silt and increase elevation in Hatiya Island at the mouth of the Meghna River in Bangladesh[42]. To generate sediments artificially, a pilot project team in Singapore used mud-filled biodegradable bags in eroded areas[43]. Stones of various sizes were then loosely placed in front of them. Mangroves, mainly *Rhizophora*, were planted between these stones, and a line of mangrove poles was established seaward to dissipate wave energy. In time, mangroves are expected to stabilize the shore across the rocks and continue spreading along the existing coastline. Although importing sediments is practical and provides initial substrate, identifying ways to repeatedly enable the local supply of sediment through fluvial processes as seen in the Ganges Delta and Bangladesh is preferable to artificial construction and exemplifies ecological engineering.

The co-benefits of mangrove restoration (in addition to the protection from coastal inundation) range from the provision of local employment and fish breeding ground to reforestation after extensive deforestation, carbon sequestration and the regulation of rainfall patterns[44–46]. To maintain mangrove forests, one critical issue is the identification of alternative energy sources for fuel-wood in places like Pakistan[47]. In the long-term, it is important to involve local stakeholders, such as shrimp farmers, to help protect mangroves and prevent deforestation[48].

Oyster reefs

Oyster reefs are another example of an ecosystem that can be ecologically engineered to reduce the impact of sea-level rise and coastal inundation. Once settled and fully grown, oyster reefs help to protect shorelines by reducing incoming wave energy and marsh erosion[49], and enhancing shoreline accretion[50]. The successful construction of oyster reefs depends on the identification of suitable sites with a reliable freshwater inflow, supply of larvae and an adequate circulation to maintain favourable salinity regimes between 5 and 25 parts per trillion (ref. 51). To avert shoreline erosion caused by the currents that the reefs generate[52,53], they need to be built sufficiently far from the shoreline[54,55].

To quantify the amount of wave-energy attenuation achieved by fully grown reef structures, the profile of the wave height shoreward of the reef can be estimated, and simulated with and without reefs. For example, for structures that have a trapezoidal shape, Campbell[56] and Allen and Webb[57] show that the van der Meer formula[58] can reliably estimate transmitted wave heights by these ecologically engineered structures. Depending on the relative submergence of those structures and the size of the incoming wave, they can potentially attenuate up to 95% of the incoming wave height[58].

Oyster reefs not only protect the coast from waves, but also generate other services. They play a significant role in controlling turbidity, water quality and primary production by removing algae, bacteria and suspended organic matter[59,60]. This filtration capacity from restored oyster reefs can create new economic opportunities

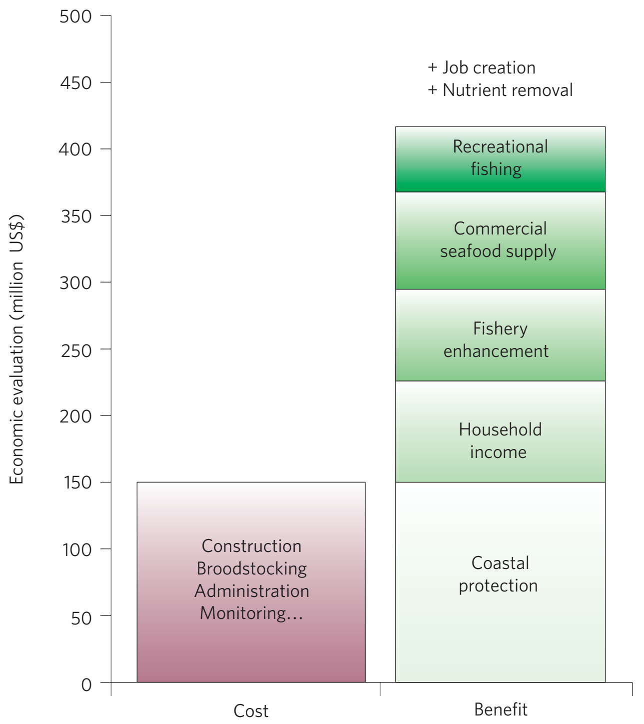

Figure 2 | Economic evaluation of an oyster reef restoration project in an estuary in the northern Gulf of Mexico. Costs are calculated on the basis of the establishment of a series of oyster reefs that is 100 miles long in total. Benefits are estimated over a 10-year period. Job creation and nutrient removal are extra benefits that are not translated into monetary terms. Data from ref. 63.

in the trade of pollution credits in coastal watersheds[61]. Oysters help to retain nutrients in estuarine ecosystems and provide food sources for other species, leading to the maintenance of a diverse and stable food web[60]. In addition, oyster reefs are ecologically valuable as an essential fish habitat by providing nursery and refuge ground for many recreationally and commercially valuable organisms, and supporting production of economically important species, such as blue crabs, red drum, spotted seatrout and flounder in the Northern Gulf of Mexico[62,50] (Fig. 2). These ecologically engineered structures interact with the environment and coastal community to affect not only the long-term stability of the shoreline, but also the overall health of the ecosystem and economy.

Outlook

Ecological engineering uses combined adaptation strategies to protect against coastal inundation. This integrative approach is consistent with the paradigm shift in restoration biology to focus equally on reinforcing and harnessing positive interactions at all levels of biological organization to maintain ecosystem services and resist multiple stressors. The efforts to build with nature by growing marshes around armoured structures, restoring mangroves as natural barriers to inundation and establishing oyster reefs as submerged breakwaters align well with recent conservation endeavours to sustain social–ecological systems.

Regular monitoring and evaluation of these ecological structures are necessary to measure their effectiveness. Some quantitative studies are available, as in the case of oyster reefs. It is, however, difficult to quantify many of these approaches into traditional cost–benefit analysis that is used when assessing the efficiency and effectiveness of hard engineering structures. Although quantifying benefits can be challenging, such efforts are critical to document the benefits of ecological engineering in monetary terms.

To facilitate better decision-making and prioritization of options for coastal adaptation, there should be a continued and increased merger of traditional and ecological engineering approaches. Ecological engineering reflective of low- and no-regret measures can become more quantitative with monitoring and evaluation, pilot studies and natural experiments, whereas traditional engineering approaches can be more nature-based and experimental. This may narrow the disciplinary gap between engineers and scientists (including ecologists and oceanographers), and ease the transfer of knowledge and expertise.

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