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Ecosystem-based coastal defence in the face of global change

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The risk of flood disasters is increasing for many coastal societies owing to global and regional changes in climate conditions, sea-level rise, land subsidence and sediment supply. At the same time, in many locations, conventional coastal engineering solutions such as sea walls are increasingly challenged by these changes and their maintenance may become unsustainable. We argue that flood protection by ecosystem creation and restoration can provide a more sustainable, cost-effective and ecologically sound alternative to conventional coastal engineering and that, in suitable locations, it should be implemented globally and on a large scale.

Coastal flood disasters are an ever-present threat to coastal societies. Recent examples include the flooding caused by Hurricane Katrina in 2005 in New Orleans, Cyclone Nargis in 2008 in southern Myanmar, Hurricane Sandy in 2012 in New York, and Typhoon Haiyan last month in the central Philippines. Such flood disasters are caused by extreme storm surges that can raise the local sea level by several metres through severe wind, waves and atmospheric pressure conditions[1]. Coastal flood risks are likely to increase over the coming decades owing to global and regional changes that include increasing storm intensity[2,3], accelerating sea-level rise and land subsidence[4] (Fig. 1). Growing coastal populations mean more people will be exposed to these increasing flood risks[5]. At least 40 million people and US$3,000 billion of assets are located in flood-prone coastal cities today, and these are expected to increase to 150 million people and $35,000 billion by 2070 (ref. 5) (Fig. 2).

Conventional coastal engineering, such as the building of sea walls, dykes and embankments, is widely perceived as the ultimate solution to combat flood risks. However, these defences are seriously challenged in many locations as their continual and costly maintenance, as well as their heightening and widening to keep up with the increasing flood risk are becoming unsustainable. Furthermore, conventional coastal engineering often exacerbates land subsidence by soil drainage[4] and hinders the natural accumulation of sediments by tides, waves and wind, thereby compromising the natural adaptive capacity of shorelines to keep up with relative sea-level rise (Fig. 1).

In recent years, ecosystem-based flood defence has been brought into large-scale practice as a regional solution that is more sustainable and cost-effective than conventional coastal engineering. It is applied at locations that have sufficient space between urbanized areas and the coastline to accommodate the creation of ecosystems, such as tidal marshes, mangroves, dunes, coral reefs and shellfish reefs, that have the natural capacity to reduce storm waves[6–8] and storm surges[9–11], and can keep up with sea-level rise by natural accretion of mineral and biogenic sediments[12,13] (Fig. 1). The latter process secures the long-term sustainability of ecosystem-based coastal protection. Furthermore, these ecosystems provide several added benefits[14], including water quality improvement, fisheries production and recreation, so that in the long term they could be more cost effective than conventional defences[15,16] (Table 1). This ecosystem-based approach is not suitable for all coastal areas and its global application is still scarce. On the basis of current knowledge, drawn largely from tidal wetland creation projects, we argue that the approach has the potential to protect many of the world's largest flood-prone coastal populations (Fig. 2).

Challenges to conventional coastal engineering

During past centuries, wetlands in river deltas and estuaries were reclaimed on a large scale and turned into rich agricultural, urban and industrial areas such as New York, New Orleans, Shanghai, Tokyo and, on a country scale, the Netherlands. Consequently, today's deltas and estuaries are host to the world's largest flood-prone coastal populations[5] (Fig. 2) and have lost most of their natural flood defences.

Wetland reclamation leads to the loss of storage area for flood waters so that storm surges rise higher and propagate faster and further inland through the remaining channels of a delta or estuary (Fig. 1). For example, in the inland part of the Scheldt estuary, Belgium, high water levels have increased by 1.3 m since 1930, which is about five times faster than the rise of high water levels at the coast[17]. This landward amplification of rising high water levels is exacerbated by extensive wetland reclamation (which diminishes the flood storage area and reduces resistance to landward flood propagation) and by channel dredging (which further facilitates flood propagation)[11]. Similar effects have been observed in other engineered estuaries and may rapidly increase in Asia, for instance, where deltaic wetlands are being reclaimed and channels engineered on large scales[4].

In addition, as reclaimed wetlands are cut off from the sea or estuary, the natural process of sediment deposition and land rise is inhibited (Fig. 1). Decreased wetland sedimentation may also result from reductions in river-borne sediment supply by upstream river dams, river diversions and the building of embankments between the river and wetlands. This has contributed to large-scale wetland submergence as the sea level rises, for example, in the Venice lagoon[18] and the Mississippi delta[19]. The increasing difference between sea and land levels is further exacerbated by soil subsidence due to compaction, soil drainage and extraction of groundwater, oil and gas[4]. For instance, subsidence over the twentieth century amounts to 5 m in Tokyo, 3 m in Shanghai, and 2 m in Bangkok[5]. In the Netherlands subsidence has resulted in 9 million people living below mean sea level[20].

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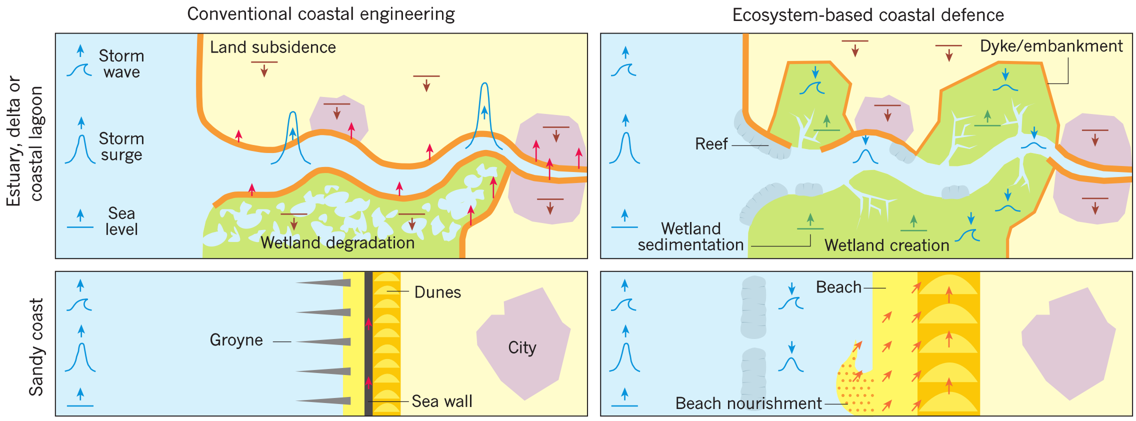

Figure 1 | Conventional coastal engineering compared with new ecosystem-based defence. The schematic maps illustrate global and regional changes that increase the risk of coastal flood disasters (blue arrows indicate an increase or decrease in intensity of storm waves, storm surge and sea level), and the basic principles of flood protection by conventional coastal engineering (left) and new ecosystem-based defences (right) for an estuary, delta or coastal lagoon (top) and a sandy coast (bottom). In the case of conventional defences, red arrows indicate the need for maintenance and heightening of dykes, embankments and sea walls with sea-level rise. In an engineered estuary, delta or coastal lagoon (top left), embankment of wetlands stimulates the landward heightening of storm surges and exacerbates land subsidence (brown arrows) due to inhibited sediment supply and soil drainage. In the case of ecosystem-based defence in an estuary, delta or coastal lagoon (top right), wetland and reef creation attenuate landward storm surge propagation and storm waves, and stimulate wetland sedimentation (green arrows) with sea-level rise. For an engineered sandy coast (bottom left), groynes and sea walls may provoke dune degradation due to hindered sand supply, whereas for ecosystem-based defence along a sandy coast (bottom right), reefs help to attenuate storm waves and surge, and offshore sand nourishment stimulates beach and dune sedimentation with sea-level rise (orange arrows).

Conventional engineering solutions — hard structures such as sea walls and embankments — are used to protect today's populated and vulnerable coastlines, but they are seriously challenged by ever rising maintenance costs and unwanted ecological side effects. For example, adjustments to the Dutch flood defence system that are required to cope with increasing flood risks, are expected to cost up to €1.6 billion per year by 2050, whereas the potential damage from insufficient defence may amount to €3,700 billion[20]. Conventional engineering of deltas and estuaries has culminated in projects such as the Delta Works in southwest Netherlands or the Thames barrier in London, where complete estuaries were cut off from the sea by permanent dams or movable storm surge barriers. However, as the Dutch example has shown, these projects can have serious economic and ecological drawbacks, including the erosion of tidal habitats and the occurrence of toxic algal blooms that kill aquatic life in the enclosed or semi-enclosed estuaries[21]. In the case of sandy coasts, conventional coastal engineering — such as groynes and sea walls — can block the wave- and wind-driven supply of sand, thereby compromising the long-term build-up of beaches and dunes with rising sea levels (Fig. 1).

New ecosystem-based flood defence

The creation or restoration of large coastal ecosystems provides a new alternative or add-on to conventional coastal defences, as coastal ecosystems attenuate storm waves[6–8] and surges[9–11], and accumulate sediments with sea-level rise[12,13]. The viability of different ecosystem-based approaches depends on the type of coastal area and location of the city at risk (Fig. 1).

For cities located in estuaries or deltas — such as New Orleans, London and many large Asian cities (dark green and pale green in Fig. 2) — the creation or restoration of large tidal marshes or mangroves between the city and the sea provides extra water storage areas and friction, which attenuates the landward propagation of storm surges[9–11] and reduces flood risks in the densely populated hinterland. Local marsh restoration for natural habitat conservation is reasonably widespread in several countries, but large-scale, estuarine-wide implementation of wetland restoration mainly for flood defence is very limited. In the Belgian Scheldt estuary up to 4,000 ha of historically reclaimed wetlands are being converted back into floodplains, of which about 2,500 ha will become tidal marshes[22]. The first marsh was created in 2006 and the total project should be completed by 2030 at an expected cost of around €600 million[16]. By comparison, the yearly risk of flood damage is estimated at €1 billion[16] by 2100, if this flood defence project is not implemented. The marshes are created by landward displacement of historical dykes (Fig. 1) or by building sluices through the dykes that allow tidal flooding and marsh development on the previously reclaimed land[23,24] (Fig. 3). Similar projects are being deployed in UK estuaries, such as in the Humber estuary, where conversion of historically reclaimed land into marshes for coastal defence is called 'managed coastal realignment'[15]. In the United States several large projects are underway, including the restoration of around 8,000 ha of tidal marshes in San Francisco Bay, California[25]. And, in the Mississippi delta, large marshlands have been restored to protect New Orleans from hurricane flooding on the basis of studies reporting that every kilometre of marshland reduces hurricane surge levels by 5 to 10 cm[9,19]. Degraded marshes are restored with dredged sediment and by diverting the sediment-laden Mississippi water back into the delta[19]. In tropical regions, such as southeast Asia, mangrove forest plantations are being considered as protection against storm surges[26]. A recent study in Florida has shown that hurricane surge level can be reduced by 40 to 50 cm per kilometre of mangrove forest width[10].

For cities behind sandy coastlines (yellow in Fig. 2), such as Amsterdam, Abidjan in the Ivory Coast and Lagos in Nigeria, beach and dune barriers are crucial defences against coastal flooding. As part of the Building with Nature programme in the Netherlands — a combined initiative between national authorities, dredging contractors, engineering consultants and research institutes — a large hook-shaped sand peninsula has been created by depositing 21 million cubic metres of sand on the shoreface off the coast of Holland[27]. The aim of this project is to combat coastal erosion along a 17-km stretch of coastline over several decades. This is achieved by the natural distribution of artificially deposited sand by tide, wave and wind force towards beaches and dunes. This approach avoids the need for more conventional beach nourishment, whereby local habitat is disturbed by the frequent direct deposition of sand onto beaches. The creation of oyster reefs is another example of an ecosystem-based coastal defence project. These reefs have been constructed from gabions filled with oyster shells on eroding sand flats in the Eastern Scheldt estuary[28]. Oyster larvae attach themselves to the shells in the summer to form robust, living oyster reefs that reduce waves, currents and erosion[29] and at the same time generate other services, such as essential fish habitat.

Potentials and limitations

Ecosystem-based flood defence has several additional benefits compared with conventional engineering approaches, including the improvement of water quality, carbon sequestration, the production of fisheries, nature conservation and the creation of recreational space (Table 1). For example, tidal wetlands improve the water quality of estuaries by delivering scarce nutrients such as silica[30] and by acting as a sink for abundant nutrients such as nitrogen and contaminants such as heavy metals[31]. This improvement in water quality suppresses the growth of toxic algae and stimulates phytoplankton growth, which is essential for the food web. Mangroves and marshes are important sinks for atmospheric CO_2 and therefore contribute to climate change mitigation[32]. However, the experience in the United Kingdom indicates that it may take several decades before created tidal marshes function in a similar biogeochemical way to naturally occurring marshes[33]. Wetlands and reefs promote fisheries production by providing an indispensable habitat for juvenile fish, shellfish and crustaceans[14]. Natural sedimentation ensures that ecosystem-based projects are better self-sustained when exposed to sea-level rise in the long term[24]. Tidal wetlands may become submerged, however, in regions where the tidal range and the sediment supply are critically low and subsidence rates are high[12]. Ecosystem-based projects can be more cost effective in the long run than continued conventional defence. A cost–benefit analysis for the Humber estuary, UK, revealed that after 25 years tidal marsh restoration on reclaimed land is economically more beneficial than maintaining dykes[15]. A similar study for the Scheldt estuary that compared conventional engineering with marsh creation concluded that an ecosystem-based approach is more cost effective and will have recovered the initial costs of implementation after a period of 20 years[16].

However, there are important limitations to the wider implementation of ecosystem-based flood defences (Table 1). These defences tend to require more space than conventional structures. In particular, in highly urbanized coastal areas, such as New York or Tokyo, space is so scarce that only conventional coastal engineering seems to be feasible. The more space that is available between the sea and the urbanized areas at risk, the higher the efficiency of ecosystem-based flood defence. This applies to several of the world's largest flood-prone cities located far inland in deltas or estuaries (Fig. 2). In these locations, large mangroves or marshes between the sea and the city could significantly contribute to storm surge protection (Fig. 1). For cities closer to the mouth of estuaries and deltas, a combination of ecosystem-based and engineered defences would be more appropriate. Where little space is available on land, seaward ecosystem creation — such as off-shore reef creation — could be an option. However, projects should ensure that they do not destroy or disturb the existing sequence of ecosystems along the sea-to-land transition, including off-shore reefs, intertidal flats and wetlands.

At present, the nature of the created ecosystem and its effectiveness for flood defence remains, in part, uncertain because too few long-term studies exist. So far, most of our experience is of tidal marsh creation. In locations with low site elevation and high tidal inundation frequency and duration, the growth of marsh vegetation is not necessarily successful[34]. This could also be a problem for the creation of mangrove forests; however, even less data exists for tropical regions[35,36]. Therefore, wetland-creation sites should be carefully selected on the basis of suitable elevations. If only low elevation sites are available, tidal inundation can be reduced with the help of hydraulic structures such as weirs or sluices (Fig. 3) — as has been applied in the Scheldt estuary[23,24] — or the sites can be raised with dredged sediments or river-borne sediment supply, such as in the Mississippi delta[19]. This, of course, increases the overall cost, but the cost–benefit balance is still positive — as for the Scheldt estuary project[16], for which sluices are built to create tidal marshes

Figure 2 | Global need for coastal flood protection, and large-scale examples and potential application of ecosystem-based defence. The map shows only cities with more than 200,000 people exposed to coastal flood risks by 2070 worldwide (predictions are based on data from ref. 5). We classified all cities into four categories according to the potential application of ecosystem-based defence: cities in estuaries or deltas and more than 50 km from the sea (dark green) can be well-protected from flooding by marshes or mangroves and moderately protected by reefs, in addition to conventional engineering; cities in estuaries or deltas but less than 50 km from the sea (pale green) can be moderately protected by marshes or mangroves and by engineering, and somewhat protected by reefs; cities more than 5 km from the sea and behind a sandy coast (orange) can be well protected by dunes and protected to some extent by engineering; cities right at the coast (blue) can be protected by engineering and to some extent by reefs. Existing examples of large-scale applications of ecosystem-based flood defence are shown in red.

Table 1 | Potential and limitations of conventional compared with ecosystem-based coastal defence

Affected variable	Conventional coastal engineering	Ecosystem-based coastal defence
Natural habitat	Degradation or destruction	Conservation or restoration
Sediment accumulation (after sea-level rise)	Disturbed or stopped by embankments, groynes, dams, and so on.	Sustained (if enough sediment is available)
Land subsidence	Exacerbated by wetland reclamation, soil drainage, groundwater and gas extraction	Counterbalanced by sediment trapping, but continues behind ecosystems
Storm surge propagation through an estuary or delta	Wetland reclamation reduces water storage and friction, enhancing inland storm surges	Wetland restoration enlarges water storage and friction, lowering inland storm surges
Long-term sustainability	Low: regular maintenance is needed at high cost	High: ecosystems are self-maintaining (if enough sediment is available)
Cost–benefit appraisal	Moderate to high	Mostly high due to added benefits
Water quality of estuary, delta and coastal sea	May degrade by organic matter accumulation and toxic algal growth in closed-off estuaries	Improved and sustained by nutrient and contaminant cycling in restored wetlands
Climate mitigation through carbon sequestration	None	Mangroves and marshes are important carbon sinks
Fisheries and aquaculture production	Reduced: less habitat for young fish, shellfish and crustaceans due to wetland reclamation	Improved: more habitat for young fish, shellfish and crustaceans due to wetland and reef restoration
Human recreation potential	Negative perception of artificial landscape	Positive perception of natural landscape
Required space	Moderate	High, therefore, not applicable for cities on the coast
Difficulty of creating the defence structure	Moderate	Relatively high due to natural dynamics and variability
Existing implementation and experience	Substantial, but many failures in the past	Limited so far. More research is urgently needed
Social and political acceptance	Widely accepted	So far, only accepted in certain areas (Europe and United States)
Health hazards (other than flooding)	None	Wetlands with stagnant water may facilitate breeding of mosquitoes that could spread disease

on low elevation sites (Fig. 3). Soil properties and their effect on water logging, wind waves and biotic factors such as seed dispersal, bioturbation and grazing may also hamper wetland development[34,35]. To maximize the success of ecosystem creation, a step-wise implementation is advised: starting with small-scale pilot projects with intensive interdisciplinary monitoring and expanding these to large-scale projects with a suitably adjusted design and implementation[23]. Absolute success of ecosystem-based flood defences cannot be guaranteed, but this is also true for conventional flood defences.

Public perception may seriously hinder the realization of large-scale ecosystem-based flood defence. The idea that valuable land, laboriously reclaimed by previous generations, should be turned back into wetlands could provoke considerable public opposition. For example, although Belgium and the United Kingdom are converting reclaimed land into tidal marshes on a large scale, there is much more social and political objection to similar projects in the Netherlands, where more than 50% of the Dutch population live below sea level and struggle against the water is strongly embedded in the nation's cultural heritage. The examples from Belgium and the United Kingdom show that societal opposition can be overcome by clear communication of the benefits of ecosystem-based defences between scientific, political and governmental institutions, local stakeholders and the general public. Other obstacles for public acceptance may include the fear that wetlands facilitate mosquito breeding and disease transmission, especially in subtropical or tropical areas. Socio-economic factors must also be considered and may partly explain why ecosystem-based defence on a large scale has only been implemented in Europe and the United States and on a much smaller scale in Asia. Despite the considerable need for flood protection and the high potential for ecosystem-based solutions in many areas of Asia (Fig. 2).

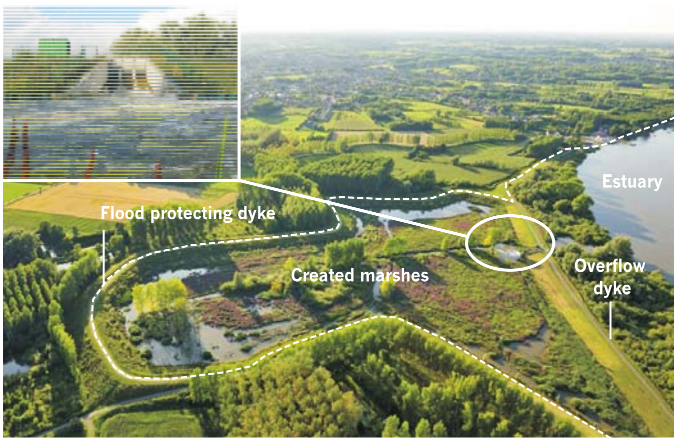

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Figure 3 | Ecosystem-based flood defence. A man-made marsh in the Scheldt estuary, Belgium, protects more landward, densely populated areas from storm surge flooding. The sluice (inset) allows daily tidal flooding of the marsh.

Wider implementation

Global and regional changes have forced us to search for sustainable adaptation strategies to protect against coastal flood hazards. Ecosystem-based strategies can be used to remedy the limitations of continued conventional engineering in suitable coastal settings, particularly in deltas that host the world's largest flood-prone populations. Recent implementations of these strategies demonstrate that ecosystem-based flood defence can be more sustainable and cost-effective than conventional flood defences, with additional benefits and with fewer side effects. These findings should further stimulate joint research by ecologists and engineers, and motivate governments and industry to support the wider implementation of ecosystem-based flood defence. ■

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1. Resio, D. T. & Westerink, J. J. Modelling the physics of storm surges. *Phys. Today* **61,** 33–38 (2008).
2. Knutson, T. R. *et al.* Tropical cyclones and climate change. *Nat. Geosci.* **3,** 157–163 (2010).
3. Lin, N., Emanuel, K., Oppenheimer, M. & Vanmarcke, E. Physically based assessment of hurricane surge threat under climate change. *Nature Clim. Change* **2,** 462–467 (2012).
4. Syvitski, J. P. M. *et al.* Sinking deltas due to human activities. *Nat. Geosci.* **2,** 681–686 (2009).

5. Nicholls, R. J. *et al. Ranking of the World's Cities Most Exposed to Coastal Flooding Today and in the Future* (OECD, 2007).
This report provides a comprehensive global assessment of people and assets in coastal cities exposed to storm surge flood risks in 2005 and expected by 2070.
6. Barbier, E. B. *et al*. Coastal ecosystem-based management with nonlinear ecological functions and values. *Science* **319,** 321–323 (2008).
This paper highlights the wave attenuation function of several coastal ecosystem types, and that this protective function is nonlinearly related to ecosystem size.
7. Gedan, K. B., Kirwan, M. L., Wolanski, E., Barbier, E. B. & Silliman, B. R. The present and future role of coastal wetland vegetation in protecting shorelines: answering recent challenges to the paradigm. *Clim. Change* **106,** 7–29 (2011).
8. Shepard, C. C., Crain, C. M. & Beck, M. W. The protective role of coastal marshes: a systematic review and meta-analysis. *PLoS ONE* **6,** e27374 (2011).
9. Wamsley, T. V., Cialone, M. A., Smith, J. M., Atkinson, J. H. & Rosati, J. D. The potential of wetlands in reducing storm surge. *Ocean Eng.* **37,** 59–68 (2010).
10. Zhang, K. Q. *et al.* The role of mangroves in attenuating storm surges. *Estuar. Coast. Shelf Sci*. **102–103,** 11–23 (2012).
11. Temmerman, S., De Vries, M. B. & Bouma, T. J. Coastal marsh die-off and reduced attenuation of coastal floods: a model analysis. *Global Planet. Change* **92–93,** 267–274 (2012).
12. Kirwan, M. L. *et al*. Limits on the adaptability of coastal marshes to rising sea level. *Geophys. Res. Lett.* **37,** L23401 (2010).
13. Fagherazzi, S. *et al*. Numerical models of salt marsh evolution: ecological, geomorphic, and climatic factors. *Rev. Geophys.* **50,** RG1002 (2012).
14. Barbier, E. B. *et al*. The value of estuarine and coastal ecosystem services. *Ecol. Monogr.* **81,** 169–193 (2011).
15. Turner, R. K., Burgess, D., Hadley, D., Coombes, E. & Jackson, N. A cost-benefit appraisal of coastal managed realignment policy. *Glob. Environ. Change* **17,** 397–407 (2007).
16. Broekx, S., Smets, S., Liekens, I., Bulckaen, D. & De Nocker, L. Designing a long-term flood risk management plan for the Scheldt estuary using a risk-based approach. *Nat. Hazards* **57,** 245–266 (2011).
17. Temmerman, S., Govers, G., Wartel, S. & Meire, P. Modelling estuarine variations in tidal marsh sedimentation: response to changing sea level and suspended sediment concentrations. *Mar. Geol*. **212,** 1–19 (2004).
18. Carniello, L., Defina, A. & D'Alpaos, L. Morphological evolution of the Venice lagoon: evidence from the past and trend for the future. *J. Geophys. Res.* **114,** F04002 (2009).
19. Day, J. W. *et al*. Restoration of the Mississippi delta: lessons from hurricanes Katrina and Rita. *Science* **315,** 1679–1684 (2007).
20. Kabat, P. *et al*. Dutch coasts in transition. *Nat. Geosci*. **2,** 450–452 (2009).
21. Verspagen, J. M. H. *et al.* Water management strategies against toxic Microcystis blooms in the Dutch delta. *Ecol. Appl.* **16,** 313–327 (2006).
22. Sigma Plan. http://www.sigmaplan.be/en (Sigmaplan, 2011).
23. Maris, T. *et al*. Tuning the tide: creating ecological conditions for tidal marsh development in a flood control area. *Hydrobiologia* **588,** 31–43 (2007).
24. Vandenbruwaene, W. *et al.* Sedimentation and response to sea-level rise of a restored marsh with reduced tidal exchange: comparison with a natural tidal marsh. *Geomorphology* **130,** 115–126 (2011).
25. United States Environmental Protection agency. *San Francisco Bay Delta Watershed* http://www2.epa.gov/sfbay-delta (EPA, 2013).
26. Schmitt, K., Albers, T., Pham, T. T. & Dinh, S. C. Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Vietnam. *J. Coast. Conserv*. **17,** 545–558 (2013).
27. van Slobbe, E. *et al*. Building with nature: in search of resilient storm surge protection strategies. *Nat. Hazards* **65,** 947–966 (2013).
28. Ecoshape. *Oyster reefs for tidal flat protection in the Eastern Scheldt* http://www.ecoshape.nl/oyster-reefs-eastern-scheldt.html (Ecoshape, 2012).
29. Scyphers, S. B., Powers, S. P., Heck, K. L. & Byron, D. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS ONE* **6,** e22396 (2011).
30. Struyf, E., Temmerman, S. & Meire, P. Dynamics of biogenic Si in freshwater tidal marshes: Si regeneration and retention in marsh sediments (Scheldt estuary). *Biogeochemistry* **82,** 41–53 (2007).
31. Teuchies, J., Beauchard, O., Jacobs, S. & Meire, P. Evolution of sediment metal concentrations in a tidal marsh restoration project. *Sci. Total Environ*. **419,** 187–195 (2012).
32. Mcleod, E., G. L. *et al*. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2 *Front. Ecol. Environ.* **9,** 552–560 (2011).
33. Burden, A., Garbutt, R. A., Evans, C. D., Jones, D. L. & Cooper, D. M. Carbon sequestration and biogeochemical cycling in a saltmarsh subject to coastal managed realignment. *Estuar. Coast. Shelf Sci*. **120,** 12–20 (2013).
34. Wolters, M., Garbutt, A. & Bakker, J. P. Salt-marsh restoration: evaluating the success of de-embankments in north-west Europe. *Biol. Conserv.* **123,** 249–268 (2005).
35. Friess, D. A. *et al*. Are all intertidal wetlands naturally created equal? Bottlenecks, thresholds and knowledge gaps to mangrove and saltmarsh ecosystems. *Biol. Rev. Camb. Philos. Soc.* **87,** 346–366 (2012).
36. Balke, T. *et al.* Seedling establishment in a dynamic sedimentary environment: a conceptual framework using mangroves. *J. Appl. Ecol*. **50,** 740–747 (2013).

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