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The role of coastal plant communities for climate change mitigation and adaptation

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Marine vegetated habitats (seagrasses, salt-marshes, macroalgae and mangroves) occupy 0.2% of the ocean surface, but contribute 50% of carbon burial in marine sediments. Their canopies dissipate wave energy and high burial rates raise the seafloor, buffering the impacts of rising sea level and wave action that are associated with climate change. The loss of a third of the global cover of these ecosystems involves a loss of CO_2 sinks and the emission of 1 Pg CO_2 annually. The conservation, restoration and use of vegetated coastal habitats in eco-engineering solutions for coastal protection provide a promising strategy, delivering significant capacity for climate change mitigation and adaption.

The loss of natural CO_2 sinks and reservoirs results in about 12–20% of anthropogenic greenhouse gas emissions[1]. Strategies to mitigate climate change that are based on actions to prevent this loss have focused on the conservation of terrestrial sinks, primarily tropical forests[2]. Reports that vegetated coastal habitats rank among the most intense carbon sinks in the biosphere[3] lead to so-called blue carbon strategies[4] to explore their potential for mitigating climate change, stimulating an increase in papers on the topic from 30 studies published in 2005 to 110 papers in 2012. In parallel, the role of vegetated marine ecosystems in fighting climate change can be developed beyond conservation of CO_2 sink capacity[4–6] by considering their contribution to both mitigation of CO_2 emissions and adaption to sea-level rise, increasing wave energy and storm surges.

Here we present the scientific basis and opportunities for a comprehensive strategy to use vegetated coastal habitats to mitigate and adapt to climate change. We focus specifically on two aspects: the capacity of these habitats to act as CO_2 sinks, referring to recent reviews for further detail, and their ability to protect the coast against erosion from sea-level rise and increasing wave action (as well as providing sources of biodiesel). These are roles that hold considerable potential for climate change adaptation and mitigation strategies but that have not yet received sufficient attention.

Vegetated coastal habitats in the biosphere

Characterized by the presence of macrophytes, both submerged (seagrass and macroalgae) and partially emerged (mangroves and salt-marshes), these habitats occupy a narrow fringe — from the upper intertidal zone to about 40 m depth — along the shores of all continents. Globally, they extend over approximately 2.3–7.0 million km^2, with macroalgae being the largest contributors and mangroves accounting for the smallest area (Table 1). The global area and trends in area change of mangrove forests are reasonably well estimated, whereas those for seagrass meadows, which cannot be retrieved from remote sensing products, have much greater uncertainty. However, global estimates for salt marshes suffer from severe, 20-fold uncertainties (Table 1). This is surprising as salt marshes can be easily assessed by remote sensing, and these uncertainties probably derive from the amalgamation of salt marshes in the broader and ambiguous category of wetlands in the Ramsar Convention (Convention on Wetlands of International Importance)[7]. Specifically, category H (Intertidal marshes) in the Ramsar Classification System for Wetland Type combines freshwater and salt marshes (Recommendation 4.7 as amended by Resolution VI.5 of the Ramsar Conference of the Contracting Parties), which are reported jointly providing an impediment to assessments of the area occupied by salt marshes alone.

About 25% to 50% of the area covered by vegetated coastal habitats has been lost in the past 50 years (Table 1). Losses of seagrass, which are accelerating globally[8], have been mostly caused by increased nutrient inputs and coastal transformation[9], and salt-marshes and mangroves have been lost due to changes in land use, coastal transformation and reclamation[10,11]. Losses of seagrass[12,13] and kelps[14] associated with heat waves indicates that climate change may lead to loss of seagrass in some areas, such as the Mediterranean[15]. On the other hand, mangroves have been reported to extend their range polewards with climate change[16].

Submerged canopies reduce flow and turbulence[17,18], increase the bottom shear stress and dampen wave energy[19,20] and flow velocity[21], thereby promoting sedimentation and reducing sediment resuspension[22]. Partially submerged vegetation, such as salt marshes and mangrove forests in tidal areas, also affect flow speed[23], and reduce wave action[24] and sediment deposition[23–26]. More specifically, mangroves may trap about 80% of suspended sediment[25]. Through their high productivity and capacity to enhance sediment accretion, seagrass, salt marshes and mangroves build large carbon deposits while raising the sea floor (Tables 2 and 3), acting as important carbon sinks and mitigating the impacts of sea-level rise on coastline.

The ability of vegetated coastal habitats to engineer their environment underpins their remarkable capacity for supplying ecosystems services[26]. A pioneer survey of ecosystem services across the biosphere ranked vegetated coastal habitats among the most valuable ecosystems on Earth[27], primarily for their capacities to regulate nutrient fluxes, provide habitat[26] and climatic regulation, and for their function as CO_2 sinks[28] and coastal protection[26].

Carbon sequestration

Despite the small fraction of the ocean surface occupied by salt marsh, mangrove and seagrass ecosystems, they account for 46.9% of the total carbon burial in ocean sediments[3,4]. Most macroalgal stands develop on hard, rocky substrates, and — despite their high productivity (Table 1) and capacity to trap suspended particles — do

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Table 1 | Extension, production and losses of vegetated coastal ecosystems.

Ecosystem	Global extension (km²)	Local net primary production (g C m⁻² yr⁻¹)	Global net primary production (Pg C yr⁻¹)	Global loss rate (% yr⁻¹)	Percentage of area lost since the Second World War
Salt marshes	22,000–400,000[5] 200,000[98]	440[29]	0.01–0.18	1–2[61]	–
Mangroves	137,760–152,361[5] 152,308[100]	400[29]	0.06	1–3[61] 0.7–1.7[98]	30–50[10,99] >25[100]
Seagrasses	177,000–600,000[5]	278[29]	0.05–0.17	0.9[8]	30[8]
Macroalgae	2,000,000[100]–6,800,000[29]	94[29]	0.19–0.64	–	–

Superscript numbers indicate the reference sources of data. For some parameters and habitats more than one estimate (or range of estimates) is available.

Table 2 | Carbon burial and soil stocks in vegetated coastal ecosystems.

Ecosystem	Local C burial rate (g C m⁻² yr⁻¹)	Local C stock in soil (Mg C ha⁻¹)	Global C burial rate (Tg C yr⁻¹)	Global C stock in soil (Pg C)
Salt marshes	218±24[5]	162 (259)[65]	4.8–87.3[5]	0.4–6.5
Mangroves	163[35]	255[64] (683.4)[38]	22.5–24.9[35]	9.4–10.4
Seagrasses	138±38[5]	139.7 (372)[39]	48.0–112[5]	4.2–8.4[39]

Mean and, when available, standard error of the mean (±s.e.m.) of organic carbon (C) burial and stock within the top 1 m of soil. Maximum local C stock is provided in brackets. Global C stocks are estimated from local C stocks and ecosystem extension (Table 1) unless indicated. Superscript numbers indicate the reference sources of data.

Table 3 | Sediment accretion and elevation rates in vegetated coastal ecosystems.

Ecosystem	Accretion rates (mm yr⁻¹)					Elevation rates (mm yr⁻¹)				
	Range	Average	Median	s.d.	*n*	Range	Average	Median	s.d.	*n*
Salt marshes	0.39–61.1	6.73	5.5	0.7	98	–6.92–25	3.76	2.01	1.33	22
Mangroves	0.34–20.8	5.47	4.5	0.38	123	–9.5–11.3	1.87	1.4	0.53	58
Seagrasses	0.61–6	2.02	1.48	0.44	12	–5.2–10.2	–0.08	–5.17	5.14	3

Range, average, median, standard deviation (s.d.) and number of observations (*n*) for a compilation of representative values of sediment accretion and elevation rates compiled from the published literature[101].

not develop significant carbon deposits. Community primary production generally exceeds respiration in vegetated coastal habitats[3,28] leading to their capacity for producing excess organic carbon and acting as CO_2 sinks (Fig. 1). Carbon sequestration in vegetated coastal habitats is further enhanced by their unique ability to trap particles from the water flow and store them in the soil[29] (Fig. 1). As a result, burial rates of organic carbon in salt marsh, mangrove and seagrass ecosystems are exceptionally high (Table 2), exceeding those in the soils of terrestrial forests by 30–50 fold[5]. Globally, coastal vegetated habitats bury a similar amount of organic carbon to terrestrial forests annually, despite the extent of coastal marine vegetation being less than 3% of that of forests.

The carbon buried in coastal vegetated ecosystems can be preserved over millennia, as demonstrated by radiocarbon dating of seagrass[30], salt marsh[31] and mangrove soils[32]. The efficient preservation of the carbon under these habitats is due to: slow decomposition rates[33]; low nitrogen and phosphorous concentrations in plant tissues; low oxygen levels in the sediments; and the allocation of a large fraction, often exceeding 50%, of plant biomass production to roots and rhizomes that are buried into the soil[34]. In addition, the entangled network of roots (and rhizomes) and the dense canopy of coastal vegetation protect soil carbon deposits from erosion (Fig. 1). Indeed, some vegetated coastal habitats can support organic-rich soils[5] that deserve conservation measures.

Seagrass, salt marshes and mangroves accumulate enough carbon and mineral particles to support characteristic sediment accretion rates exceeding 10 cm per century, with the highest accretion rates found in salt marshes (Table 3, Fig. 1). Recent (that is, twentieth century) accretion rates in mangrove forests have been reported to average 28 cm per century[35]. Moreover, sediment accretion responds to climate change through feedbacks that involve increased plant growth and production, which are conducive to faster accretion rates with increasing CO_2 (ref. 36) and sea-level rise[37]. Indeed, recent models indicate that climate change will increase salt marsh carbon burial and accretion rates in the first half of the twenty-first century[38].

The long-term preservation and continuous accretion of carbon in the soil of coastal habitats with sea-level rise leads to the development of organic carbon deposits several metres thick[30,38]. The magnitude of carbon deposits under the top metre of soil in a salt marsh or seagrass meadow is similar, on average, to that in the upper 1-m soil in terrestrial forests (Table 2), whereas the top metre of soil in mangrove forests stores more than three times the organic carbon contained in the upper soil under forests on land[39]. Globally, salt marsh, mangrove and seagrass ecosystems store about 10 Pg C each in their top 1-m soil layer[39] (Table 2). This is one order of magnitude lower than the soil carbon stock under terrestrial forests, but still large enough to play a role in the global carbon cycle.

Protection against coastal flooding and erosion

The risks of accelerated sea-level rise with climate change are further enhanced by associated increases in the frequency of extreme sea level, waves and the strength of storm surges[40], resulting in a higher intensity and frequency of flooding and erosion of vulnerable coastal areas. Observations and numerical reanalysis have shown that significant wave-height variations are clearly linked to climate modes[41,42] and that wave heights have increased in the North Pacific, North Atlantic and Southern Ocean during the past century[43–45]. Sea level has been rising globally at an average rate of 1.6±0.2 mm yr⁻¹ since 1901[46], and moderate emission scenarios project a future global mean sea-level rise of 0.21–0.48 m by 2100 (Intergovernmental Panel on Climate Change scenario SRES A1B for 2090–2099)[47], with some recent projections exceeding a global mean sea-level rise of 1 m (ref. 48). Even if wave projections carry substantial uncertainty, the direct connection between wind and storminess indicates that climate change is likely to have a significant impact on wave heights and other wave parameters[49]. As a result, coastal flooding and erosion will be, and are already becoming, a major threat to coastal areas, demanding the introduction of sustainable measures to cope with this problem.

Coastal protection measures against wave action are purely based on the principle that the incident wave energy flux — defined as the wave energy multiplied by the velocity of a wave group — has to be balanced by the total energy reflected, transmitted and dissipated at the protection element[50]. Formulated in a simple way, the wave energy flux that is not reflected offshore or dissipated is transmitted onshore, thereby inducing flooding, erosion or damages to infrastructure, goods and services, or loss of lives. Vegetated coastal habitats, through their capacity to provide coastal protection[26], could assist in mitigating the impacts of sea-level rise and the associated increase in wave action.

The function of vegetated coastal habitats for coastal protection involves the attenuation of wave transmission onshore (Fig. 1), which can be achieved by: (1) inducing wave breaking as the main damping mechanism[19]; (2) dissipating energy through flow separation[51]; (3) dissipating energy through friction on rough surfaces; (4) dissipating energy through porous friction[52,53]; (5) producing a barrier effect that reflects energy in the offshore direction — and a combination of the above mechanisms.

The capacity of vegetated coastal habitats for protecting the coast against the different dynamics considered (waves, storm surges, tsunamis and currents) is highly dependent on both the large- and small-scale characteristics of these ecosystems (Supplementary Table 1). The relevant elements of natural ecosystems are their location and geometry with respect to the incoming dynamics, which may affect shoaling, refraction, diffraction, blocking or breaking. Wave attenuation will be dependent on the freeboard of the vegetated field, namely the relationship between the submergence and total water depth (h); the relative wave height (H/h, where H is wave height), the width (b) of the field with respect to the incoming wavelength (L) (the longer the wave, the wider the domain needs be to achieve damping), the vegetation density, the nature of the substrate and the quality and abundance of the aboveground biomass. The geometry of each individual plant (roots, stems and canopies), its buoyancy, stiffness and degrees of freedom also affect wave attenuation[50,54].

Wave breaking is closely controlled by the relationship between H and h, the ratio of which increases as waves propagate towards the shore by the combined effect of wave shoaling and shallower depths. Breaking takes place when a certain threshold of H/h has been reached. Therefore, changes in the bathymetry may contribute to dissipation. Hence, the capacity of vegetated coastal habitats to raise the sea floor at speeds that can match or exceed current sea-level rise (Table 3), thereby counterbalancing the effect of sea-level rise on h, allows them to remain effective in breaking waves with moderate to high scenarios of sea-level rise, in areas where subsidence and other processes that lower the elevation of the shore are not important.

Flow separation occurs at the edges of large structures, or on the lee side of small structures. The turbulent wake generated is a sink of energy. Flow separation is controlled by the Reynolds number (ratio between inertial and viscous forces), the Keulegan–Carpenter number (ratio between drag and inertia forces) and the relative roughness of the body surface. The parameters considered to define the contribution of each of the forces depend on the process considered. Fields of slender, vertical rigid or flexible elements such as seagrass, kelp, salt-marshes

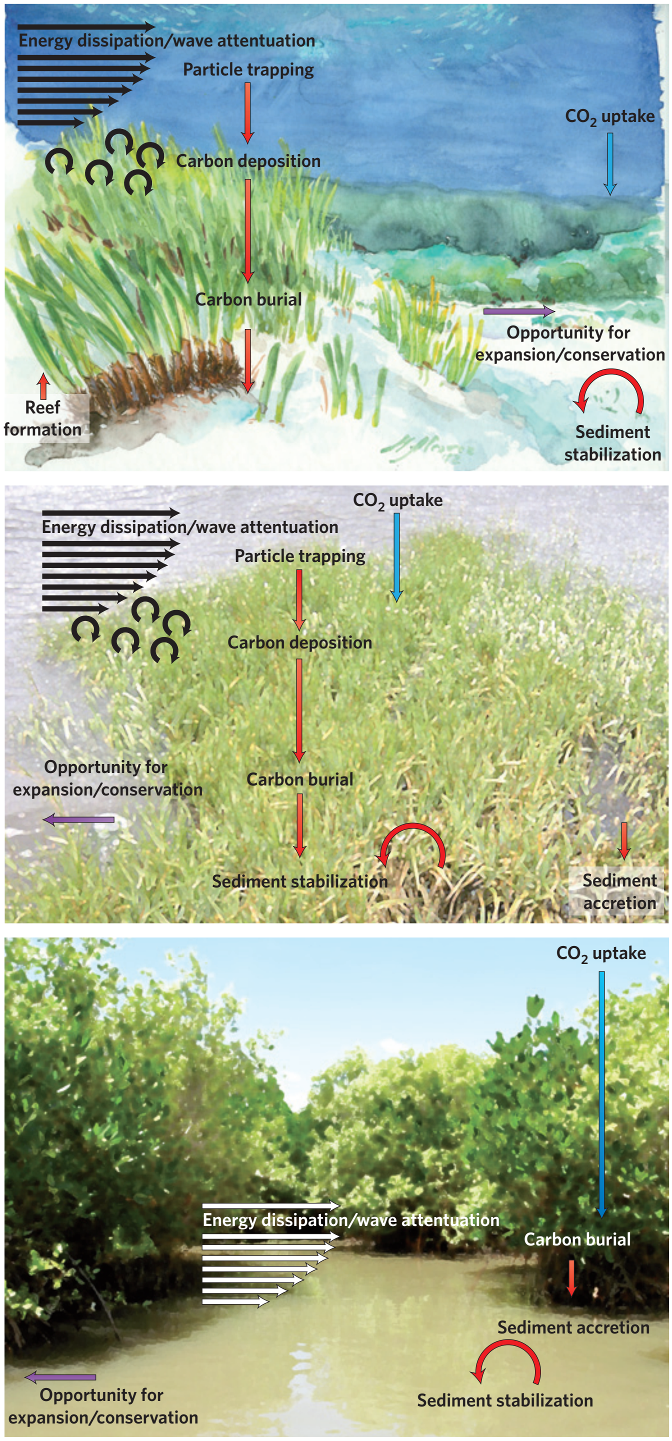

Figure 1 | Key processes of vegetated coastal habitats for climate change mitigation and adaptation. Processes that affect the capacity for climate change mitigation (CO_2 sinks) and adaptation (shore line protection from rising sea level) are shown for seagrass meadows (upper panel), salt marshes (middle panel) and mangrove forests (lower panel). Blue arrows indicate transport of atmospheric or dissolved material, red arrows show transport of particulates and purple arrows indicate vegetative growth. Images reproduced with permission: Top, *Posidonia* meadow, water colour by Miquel Alcaraz; middle, *Spartina* in Rattekaai salt marsh, photo by Iris Hendriks; bottom, Mangrove Forest, photo by Rohan Arthur.

or mangroves are typical sources of this kind of dissipation[55]. Vegetated coastal habitats can thus dissipate wave energy through flow separation.

Seagrass and other vegetated coastal habitats also provide protection by the dissipation of wave energy thanks to friction resulting from their presence increasing the bottom roughness, reducing near-bed flow velocity and elevating the bottom boundary layer[56]. Vegetated coastal habitats with their particular stem density and flexibility also provide a porous medium with a large energy dissipation capacity[57]. Turbulent and laminar flow inside porous structures is an important sink of wave energy that is controlled by the Reynolds number, the size of the porous elements and the porosity[58].

Hence, vegetated coastal habitats act on all of the mechanisms that dissipate wave energy (Supplementary Table 1). However, their contribution to bathymetric changes through sediment accumulation (Supplementary Table 1 and ref. 59) and shoreline accretion is key to shoreline protection, aside from direct damping of the incoming waves.

Climate change mitigation

The conservation and protection of ecosystems that act as carbon sinks are among the cheapest, safest and easiest solutions to reduce greenhouse gas emissions and promote adaptation to climate change[6,60]. High loss rates of vegetated coastal habitats (Table 2), ten times faster than those of tropical forests[61], represent a major loss of natural CO_2 sink capacity and coastal protection and therefore contribute to the component of increased greenhouse gas emissions that is termed land-use change[1]. Specifically, by combining specific loss rates (Table 1) with estimates of global CO_2 sink capacity (Table 2), the loss of vegetated coastal habitats is found to represent a loss of CO_2 sink capacity of approximately 7–20 Tg CO_2 yr^{-1}. The fate of soil carbon stored in tidal wetlands that are submerged when vegetation is lost is an open question that requires research. However, there is evidence that soil carbon stores can be destabilized when mangroves and salt marsh cover is removed, leaving soils exposed to the atmosphere — the unvegetated habitats act as sources of CO_2 and CH_4 to the atmosphere[62–64]. Pendleton *et al.*[65] estimated that 0.15–1.02 Pg CO_2 are being released annually from loss or conversion of vegetated coastal habitats, assuming that all of the organic carbon in biomass and the top metre of soils is lost. This estimate, which carries considerable uncertainty, is equivalent to 3–19% of that from deforestation globally, and results in economic damages of US$6–42 billion annually from loss of CO_2 sequestration alone[65], not accounting for the damages associated with the loss of coastal protection capacity. The uncertainty in the loss of carbon sink capacity and in emissions released by habitat losses is dominated by uncertainties in the global extent and loss rates of these habitats, with the rough estimates available (Table 1), which are particularly coarse in the case of salt marshes, propagating unverified across citation networks. Improved estimates of the global extent and loss rates of vegetated coastal habitats are urgently needed to assess the potential of conservation and restoration of these habitats as an element of climate change mitigation strategies.

The use of vegetated coastal ecosystems to protect and restore lost CO_2 sink capacity and prevent the loss of deposits to mitigate climate change — Blue Carbon initiatives — was proposed in 2009[4]. One aim is to encourage various carbon trading programmes to credit activities in tidal wetland and seagrass ecosystems. For example, there is interest in extending the REDD+ (Reducing Emissions from Deforestation and Forest Degradation), including conservation, sustainable management of forests and enhancement of forest carbon stocks) programme — a UN programme drawing from voluntary payments and market CO_2 taxes to pay land-owners to conserve forests[66] — to the coastal ocean. Avoidance of losses in vegetated coastal habitats that are threatened by local human activity (for example, aquaculture, waste-water discharges to coastal water, coastal tourism developments and reclamation) could help to maintain CO_2 sinks and therefore be considered within the REDD+ mechanism.

Blue Carbon initiatives could broaden the participation in the current REDD+ scheme, as small island states — who are eager to mitigate the climate change that threatens their livelihoods through sea-level rise — have reduced opportunities at present to participate in REDD+ due to limited land space. However, island states often have extensive shallow platforms (for example, the Bahamas, the Maldives and Cuba) that support vegetated coastal habitats, where conservation initiatives funded by a Blue Carbon extension of REDD+ could be successfully deployed and contribute to climate change mitigation. As vegetated coastal habitats are intense carbon sinks (Table 2), even conservation and revegetation projects that involve relatively limited areas can be significant.

Unlike lost forests, which were largely transformed to cropland and pastures, most lost coastal habitats have not been transformed to other uses and generally lack property rights. They are therefore available for recolonization by coastal vegetation. Indeed, vegetated coastal habitats can be restored at a large scale. The best demonstration is the complete reforestation of the Mekong Delta mangrove forests (which were completely destroyed by the US Air Force in the war 40 years ago) through the initiative of the Vietnamese government, arguably the largest ecosystem restoration ever undertaken[67]. Likewise, large-scale mangrove afforestation programmes have been successful in Thailand and — more recently — India; and large-scale salt marsh restoration schemes are in place in China[68] and the USA[69]. Seagrass transplants can, because of their clonal nature, return several million shoots per site after a few years[70], even at a typical success rate of 30%. No carbon burial estimates are available for seagrass revegetation projects, but one study found that sediment carbon accumulation by a revegetated seagrass meadow doubled that in bare sediments 9 years after planting[71]. However, studies conducted over the past decade have shown that carbon burial rates in restored mangrove forests[72] and salt marshes[73] are similar to those in undisturbed habitats, despite sediment carbon pools in revegetated mangroves, salt marshes and seagrass meadows being lower than in undisturbed habitats 9 (ref. 71), 20 (ref. 72) and 28 (ref. 73) years after planting. Hence, restoration of coastal vegetation has been proposed to be a sound strategy to mitigate climate change[74].

However, extending the REDD+ programme to encompass coastal vegetation is not without challenges. Current REDD+ accountings only consider the carbon stored as aboveground biomass, where much of carbon capture by forest is bound. In contrast, coastal habitats store most of the carbon that is sequestered in sediments (for example, 68% for mangroves and 95% for seagrasses[39]). Accounting for soil carbon within REDD+ also requires knowledge of the origin of the carbon stored in sediments. Although this is possible through stable isotope analysis of sediment carbon in seagrass meadows[28], apportioning carbon between allochthonous and autochthonous sources in salt marsh and mangrove sediments is not as straightforward.

Expanding REDD+ to vegetated coastal habitats requires the development and acceptance of protocols for measuring, reporting, verifying and monitoring the carbon stored in sediments. Revegetation programmess, which are an option for coastal wetlands, are not currently considered in REDD+, which focuses on conservation. Revegetation projects require that suitable conditions be re-established and, in the case of seagrass, can be met with mixed success. The need for monetary compensation may also preclude revegetation programmes where habitats have been converted to other uses (for example, aquaculture farms, coastal infrastructure or reclaimed areas). Finally, although payments under REDD+ conservation approaches can be immediate, revegetation methods may require decades before carbon credits can be collected. An extended REDD+ programme may not be applicable to coastal habitats that are particularly vulnerable to sea-level rise, as losses of the associated carbon sinks cannot be avoided through conservation. Specifically, although carbon accumulation in salt-marshes increases with sea-level rise, it does so until a critical rate is reached, beyond which the marsh vegetation is drowned, halting carbon accumulation[75]. The fate of carbon deposits lost to submergence is not known, but the question is important for understanding the full impact of tidal wetland feedbacks on climate.

Blue biofuels. Macroalgal beds dominate the global area and production of vegetated coastal habitats (Table 1), but most macroalgal communities grow on hard substrates and do not contribute to carbon sequestration except for the biomass that may be exported to the deep sea[76]. Yet macroalgae can play a role in mitigating climate change if either wild or aquaculture crops are used to derive biofuels. The development of biofuels from mass aquaculture of macroalgae is a new, vibrant area of research[77,78], which has the potential to contribute to climate change mitigation. The production of 'blue biofuels' has many advantages over that based on land crops (green biofuels), generating multiple environmental and societal impacts[79,80]. Blue biofuels do not compete for arable land and water with food crops, whereas green biofuels have co-opted both essential resources from agriculture, becoming a threat to food security[81]. Moreover, blue biofuels are not currently staples of global significance, and so the production does not negatively affect food prices in the global market. In contrast, the development of green biofuels has diverted crops otherwise used as staples (corn or palm oil) away from the food market into fuel production, becoming an element in the recent global rise of food prices[81]. Moreover, neither pesticides nor fertilizers are used in most seaweed farms, which remove nutrients often found in excess in coastal waters, generating environmental benefits in coastal areas affected by eutrophication. In areas where nutrient availability is insufficient for macroalgae farming, such as in the Yellow Sea (China), large kelp production is supported by multi-species polycultures, where kelps benefit from nutrients released by scallops, oysters and/or mussels. Fertilizer production and application are a significant component of greenhouse gas emissions, as the Haber–Bosch reaction — used to produce ammonia for fertilizers — is an energy-intensive process and excess fertilizer application is a major source of N_2O (ref. 82), a major greenhouse gas. Finally, phosphorus reservoirs are being depleted, so replacing land with marine biofuels without fertilizer application will allow more phosphorus to be used to produce food. Hence there is a potential for wild and cultured macroalgae to help mitigate climate change, while generating significant additional benefits.

Climate change adaptation

Vegetated coastal ecosystems are important in protecting the coast against flooding and erosion due to waves and storm surges under mean and extreme conditions, including hurricanes (Supplementary Table 1 and ref. 59). Seagrasses have a particularly high capacity to dissipate wave energy, whereas salt marshes and mangroves have a high capacity to protect from surges. Moreover, these ecosystems often occur in juxtaposition with seagrass in subtidal areas and salt marshes or mangroves (depending on latitude) in the intertidal zone, thereby increasing their combined effectiveness in protecting from waves and surges.

Benefits of ecosystem-based coastline protection. Artificial coastal protection structures are constructed with an expected service life spanning several decades. Whereas extreme events are considered in their design, the statistics of extreme events is now affected by climate change and may alter during their operational life. As climate change was not generally considered in the design of most coastal defences that are now in place, an intense upgrade of coastal defence structures during the coming decades will be needed worldwide, requiring a huge investment to provide adaptation to an uncertain level of climate change[83]. Unlike artificial structures, vegetated ecosystems can naturally adapt to changes in sea levels and wave storminess if they are not severely affected by human action, as demonstrated by their capacity to adjust accretion rates to sea-level rise[37]. Hence, the adaptive capacity of vegetated coastal habitats helps maintain their capacity for coastal protection at a negligible cost, while conserving the ecosystems and maintaining their services[84,85]. The potential of a coastal ecosystem to protect the coastline does not increase linearly with its size, but varies nonlinearly[19,86]. The effectiveness of sediment accretion by vegetated coastal habitats in adapting to sea-level rise is dependent, however, on both the rates of accretion, which vary 10-fold within habitat types (Table 3), and local processes such as compaction, subsidence and local rates of sea-level rise. Indeed, reported elevation rates for vegetated coastal habitats tend to be lower than accretion rates, and the two available estimates that report elevation rates for seagrass meadows indicate net subsidence (Table 3 and ref. 59).

Adaptation strategies that include the conservation, restoration or introduction of vegetated coastal ecosystems provide a cost-effective option for addressing the increased risk from flooding and erosion under climate change in vulnerable areas. Moreover, producing vegetated coastal protections, unlike cement-based structures, generates limited CO_2 emissions and in fact removes atmospheric CO_2. However, CO_2 emissions may be generated where machinery is involved in preparing the terrain and revegetating the coast. In addition, salt marshes and mangrove forests, particularly newly created ones, can release CH_4 and N_2O that may partially offset the carbon sequestered[87]. Accordingly, best practices to minimize greenhouse gas emissions from eco-engineering projects need be developed. The adaptation of vegetated coastal habitats to increased CO_2 and higher sea level involves an increase in sediment accretion, also enhancing their capacity to act as carbon sinks. Lastly, vegetated coastal habitats have a high capacity to produce carbonates and other materials that contribute to sediment accretion, beach nourishment and to dune formation on land[54,88], further preventing coastal erosion.

Coastal vegetation may not always offer sufficient protection, as the capacity of natural ecosystems for shoreline protection varies due to seasonal and interannual variations in the development of the vegetation. In addition, the requirements for successful development of coastal vegetation — such as elevation, currents and wave exposure[85,89] — are not met everywhere, restricting the areas where protection based on coastal vegetation can be successful. Finally, the particular circumstances of an event (that is, tidal conditions and the track of a storm) can also affect the effectiveness of coastal vegetations in shoreline protection.

Costs. Conserving and restoring vegetated coastal habitats is also relatively inexpensive and is affordable to all countries, including developing ones. According to the International Federation of the Red Cross and Red Crescent (ref. 90), replanting mangroves in Vietnam has helped to reduce the cost of dyke maintenance by US$7.3 million a year for an investment of US$1.1 million over the period 1998–2002. Indeed, existing coastal wetlands in the USA have been estimated to provide a value of US$23.2 billion a year at present in storm protection services[91] at only the (minor) cost of conserving these habitats.

Artificial coastal structures provide limited or no extra benefits beyond the function for which they were built, and may generate negative impacts — possibly including a role in promoting jellyfish blooms[92]. In contrast, vegetated coastal habitats add benefits such as nutrient cycling, food provision and biodiversity regulation to their capacity for coastal protection[26], thereby further increasing the value and positive externalities of defence strategies that involve these habitats. For instance, mangrove expansion has been shown to improve the yield of fisheries[93]. In turn, conserving vegetated habitats for their capacity to sequester CO_2 or their role in enhancing biodiversity will

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Table 4 | Eco-engineering solutions for coastal areas in the Netherlands.

Environment	Problem	Eco-dynamic design	Area		
Tidal	Erosion of the intertidal area	Surplus Sand nourishment[a] Shellfish reefs[b] Circle-shaped nourishment[c]	Delfland Eastern Scheldt Eastern Scheldt	a	
	Coastal erosion	Sand dunes Wetlands		b	
	Flooding (waves)	Optimizing texture of dykes by ecological growth	North Sea	c	
Non-tidal	Flooding (storms)	Semi-natural floodplains Willow floodplains[d]	IJsselmeer Noordwaard	d	

a–d refer to the photographic examples of eco-dynamic design shown on the right. Eco-dynamic designs are based on the dynamics of the natural environment: developing hydraulic engineering infrastructure and at the same time creating opportunities for nature and the environment. Sand nourishment is a technique where extra sand is deposited in an (intertidal) area to counter losses from erosion. In the Delfland Sand Engine experiment, a larger than normal (surplus) nourishment of 21.5 million m^3 of sand was introduced, rising up to 7 m above mean sea level. The sand is gradually redistributed by natural processes over the shoreface beach and dunes[102]. http://www.ecoshape.nl/en_GB/delfland-sand-engine.html Images courtesy of: 1, Joop van Houdt/Rijkswaterstaat; 2–4 Ecoshape.

increase coastal protection as a side benefit. Therefore, the restoration and preservation of these ecosystems can be considered a cost-effective strategy due to the combined services provided for climate change mitigation and adaptation.

Conclusion

For decades vegetated coastal ecosystems have remained the poor relations of biological conservation[61]. However, recent findings on their remarkable capacity for CO_2 sequestration and storage, and their capacity for sediment accretion and coastal protection, have converged to identify these habitats as essential elements of a strategy that combines both climate change adaptation and mitigation.

Unfortunately, the role of vegetated coastal habitats as a valid alternative in the portfolio of measures for climate change mitigation and adaptation has not been sufficiently considered by coastal managers, who still opt for hard adaptation measures and on-land mitigation options. Strategies that involve vegetated coastal habitats are now being included in an eco-engineering approach to climate change. Eco-engineering emerged in the early 1960s[94], but it has only recently gained broad recognition as a new paradigm. The original starting point to use natural energy sources as the predominant input to manipulate and control environmental systems was broadened by Mitsch and Jørgensen[95] to 'the design of sustainable ecosystems that integrate human society with its natural environmental to promote both'. Examples of experiments and successful implementations of eco-engineering in coastal protection projects[89,96] can be found for example in the Netherlands, a country challenged by sea-level rise (Table 4). The preceding discussion points at a huge opportunity to develop projects and training curricula in coastal eco-engineering through options that are based on vegetated coastal habitats to mitigate and adapt to the impacts of climate change.

A comprehensive coastal eco-engineering programme could strike a rational balance between mitigation and adaptation instruments based on protecting and restoring or introducing different vegetated coastal ecosystems to maximize the potential synergies between them. Indeed, the separation between adaptation and mitigation strategies may lead to lost opportunities and to underestimate the value of conservation, as is clearly the case for a REDD+ extension focused on vegetated coastal ecosystems, which would need to account for their role in coastal protection, with a value likely to exceed that of CO_2 sequestration by at least an order of magnitude. Moreover, cost–benefit analyses should not focus on benefits that are associated with climate change mitigation and adaptation alone, but should encompass the broad suite of services that vegetated coastal habitats provide[26]. Eco-engineering approaches that involve wetland creation can provide habitat for threatened species, as exemplified by the refugia that mangrove forest offers to critically endangered felids and primates in Africa and Asia[97], thereby delivering conservation benefits beyond those associated with coastal protection or carbon stocks. The eco-engineering approach could become societally and economically efficient and may offer greater opportunities for countries — especially developing ones — to achieve sustainable targets even under limited financial resources and capacity.

Coastal eco-engineering through vegetated coastal ecosystems represents a new paradigm, whose significance can be best understood by drawing a parallel with material science. Coastal engineering has introduced a new material whose production, unlike that of cement, does not lead to CO_2 emissions, but rather CO_2 removal. It can achieve comparable efficiency for coastal protection to cement-based solutions; can repair itself; can grow; and can adapt to shifting conditions. This newly discovered material is none other than marine plants.

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Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence should be addressed to C.M.D.

Competing financial interests
The authors declare no competing financial interests.