5 More carbon sequestration in marine meadows and forests?

> Tidal marshes, seagrass meadows, mangrove and kelp forests cover far less than one per cent of the ocean and coastal area, but contribute significantly to natural carbon sequestration in the seabed. Plans to expand these coastal habitats in order to increase their natural carbon dioxide uptake will probably only be successful in particular oceanic regions. Nevertheless, they may well be worthwhile for multiple reasons.

Blue carbon – an approach yielding dual benefits

> Vegetation-rich coastal ecosystems such as tidal marshes, seagrass meadows, mangrove and kelp forests are the sites of at least 30 per cent of the organic carbon stored in the seabed. Worldwide, however, the area covered by these ecosystems is shrinking and with it their underground carbon stores. Where humans halt the decline of marine meadows and forests and restore destroyed areas, they not only force carbon uptake in plant communities, but also strengthen physiographic regions whose functioning and health are vital for humankind's survival.

Using nature's tools

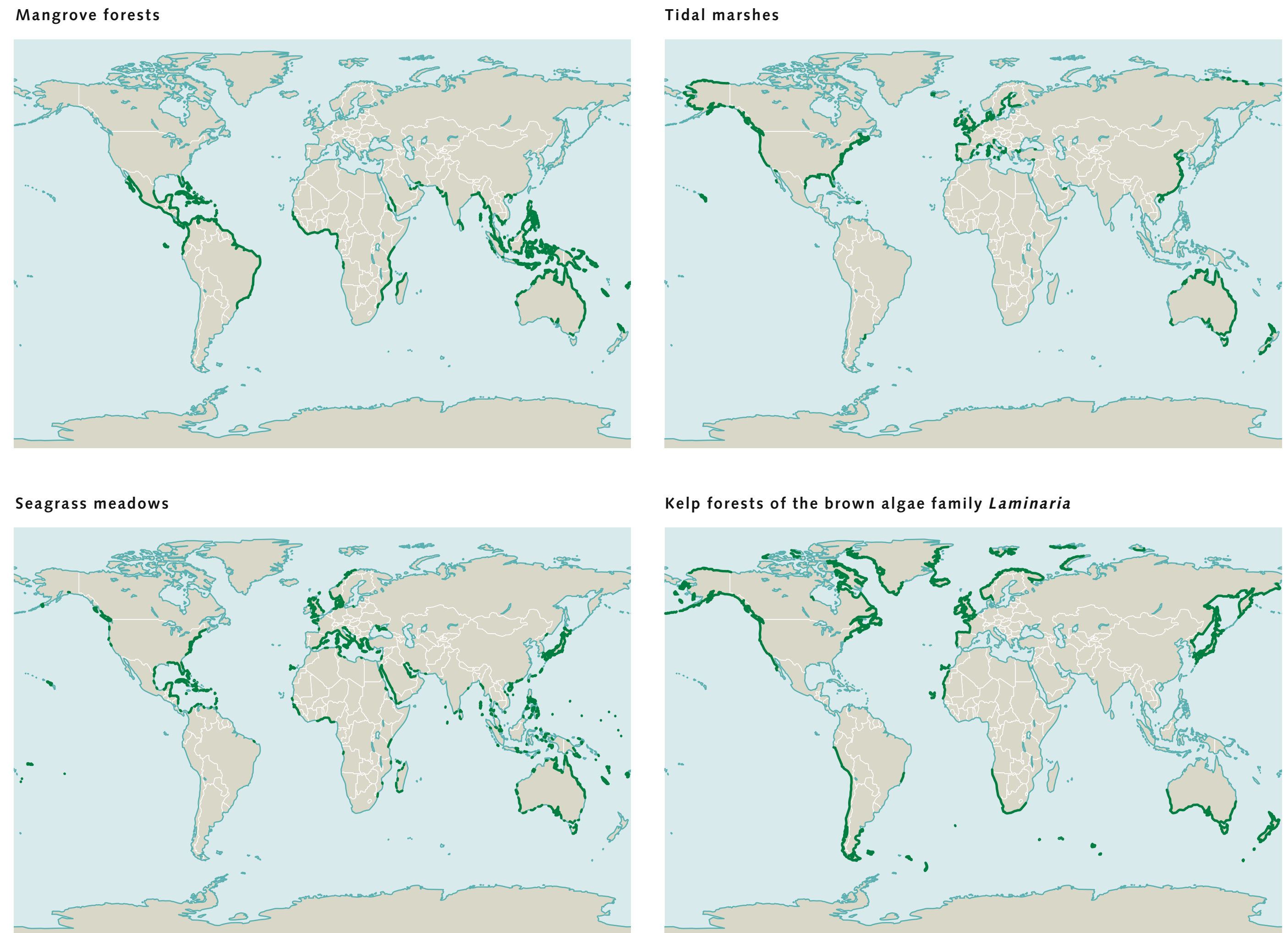
In the search for ways to increase the ocean's carbon dioxide uptake, it makes sense to first focus on the key players in the ocean's carbon cycle. In coastal areas, these include above all the vegetation-rich ecosystems in tidal and shallow waters (up to 50 metres of water depth), i.e. tidal marshes, seagrass meadows, mangrove forests and kelp forests. The combined area of these four ecosystem types accounts for less than one per cent of the world's ocean area, including the intertidal zone. However, because marine meadows and forests are highly productive ecosystems, they convert a lot of carbon dioxide into biomass and are responsible for at least 30 per cent of the organic carbon stored in the seabed.

Much as terrestrial plants do, marine plants or plants in the tidal zone absorb carbon dioxide in the course of photosynthesis and bind the carbon it contains. However, carbon dioxide is not only taken up from the air, but also from seawater, for example by seagrasses and kelp. Since the plant communities of mangrove forests, seagrass meadows and tidal marshes all form root systems and grow on sandy or muddy substrates, they are able to store a large part of the bound carbon in the marine subsoil – in part as living biomass in their own root systems and in part in the form of plant parts that have died off and which sink to the bottom and become incorporated into the coastal sediment.

Moreover, marine meadows and forests slow down the movement of water. As a result, they filter a lot of suspended particles out of the water and deposit these particles as well as dead animal and plant matter between their stalks and roots. Thanks to this constant input of particles, the plant communities continue to build up the substrate on which they grow. Mangrove forests and seagrass meadows, for example, gain two to five millimetres in height per year on a global average and can thus also buffer the impact of rising sea levels, but only as long as the ecosystems accumulate material faster than the sea levels are rising.

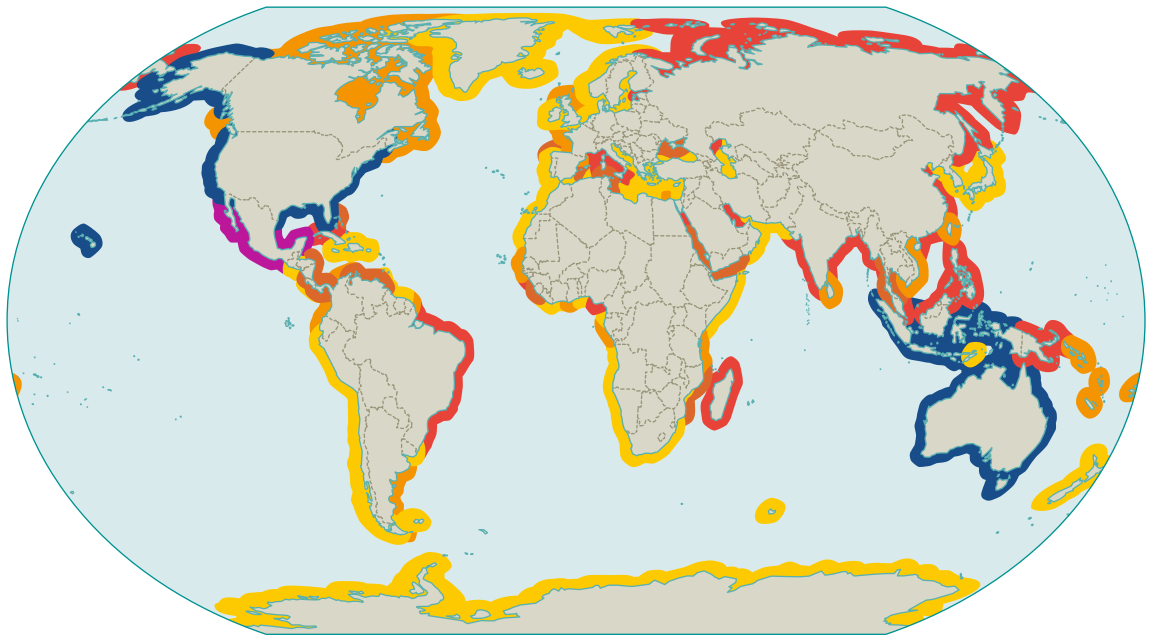
5.1 > Mangroves protect the coast from waves, sea-level rise and storm surges. But they cannot withstand all weather extremes. When Hurricane *Maria* swept across Costa Rica in September 2017, large parts of this mangrove forest died.

Global distribution of vegetation-rich coastal ecosystems



5.2 > While mangroves occur mainly in the tropics and subtropics, tidal marshes and kelp forests prefer cooler regions. Seagrass meadows, however, are found at both low and high latitudes.

Global carbon storage potential of vegetation-rich coastal ecosystems



5.3 > Mangroves, tidal marshes and seagrass meadows absorb carbon dioxide from the air, bind that carbon and store it in their biomass as well as underground. This map shows for all coastal countries the average annual carbon sequestration potential for the three ecosystems combined, under the proviso that the ecosystems are healthy.

These ecosystems not only store local plant matter, but also plant remains that are deposited from the landward side or washed up from other marine areas. Once the organic material is trapped in the subsoil, it is preserved, as the coastal sediment is saline and low in oxygen. Microbes in the seabed thus lack the oxygen they would need to quickly decompose the biomass.

Both the carbon storage in the root system and the deposition of animal and plant litter in an oxygen-deprived environment result in the tidal marshes, mangrove forests and seagrass meadows accumulating more and more organic material underneath them over time. In some mangrove forests, the upper layer of the seabed contains 95 to 98 per cent carbonaceous material.

These underground carbon stores can be more than ten metres thick and keep growing as long as the ecosystems above them thrive. Ideally, they remain in place for many centuries, sometimes even millennia. Tidal marshes, mangrove forests and seagrass meadows are many times more efficient at carbon uptake and underground storage than terrestrial forests. Compared to tropical rainforests, for example, depending on their location they can store five to 30 times the amount of carbon underground per unit area. In contrast, kelp forests, i.e. forests of brown algae (the *Laminariales*), cannot store the carbon they bind directly in the subsoil, because brown algae do not have roots but rather grow attached to rocky substrates, so loose or dead algal material is carried away by ocean currents. It washes up on the coasts or sinks into deep waters, where some of it is then deposited in the seabed sediment.

How large are the carbon stores and for how long do they persist?

Currently, vegetation-rich coastal ecosystems remove an estimated 85 to 250 million tonnes of carbon per year from the atmosphere and the sea. The range of this esti-

5.4 > Twice daily the Atlantic tidewaters wash over and around the tidal marshes at Northton on the south-western coast of the Scottish island of Lewis and Harris. The species-rich saltmarshes grow in sheltered coastal areas where the tides form sandbanks as a substrate for the plants to grow.

mate is so wide partly because many processes and interactions within the very complex plant communities and their ecosystems are not yet properly understood. For example, one of the as yet unanswered research questions is how much carbon dioxide mangrove and kelp forests, tidal marshes and seagrass meadows in different regions of the earth absorb and store in the form of organic carbon, and what proportion of this they release again in the course of their life cycle.

Marine meadows and forests release carbon dioxide through respiration. The carbon they have captured is also released when manatees, sea urchins and the many other marine organisms consume the plant matter and convert it into energy and carbon dioxide as part of their metabolism. When microbes decompose the organic material stored in the coastal sediment, not only carbon dioxide is released, but also methane and nitrous oxide under certain conditions. What quantities of these two climate-damaging gases are released from coastal ecosystems under which conditions is not yet well understood. What is certain, however, is that where carbon dioxide, methane or nitrous oxide escape from coastal sediments, the underground carbon stores of coastal ecosystems shrink and drive climate change.

For this reason, it is essential to understand for how long the vegetation-rich coastal ecosystems “lock away” the carbon they absorb. Scientists know that the duration of carbon storage depends on where it is stored. Carbon stored by plants as part of their above-ground biomass in leaves, stalks, twigs and branches is removed from the atmosphere for anything from weeks to decades. In contrast, the underground carbon stores, which are often hermetically sealed, can persist for several centuries or even millennia if the vegetation protecting them remains intact. In the Spanish Portlligat Bay, for example, there are seagrass meadows whose carbon stores are more than 6000 years old.

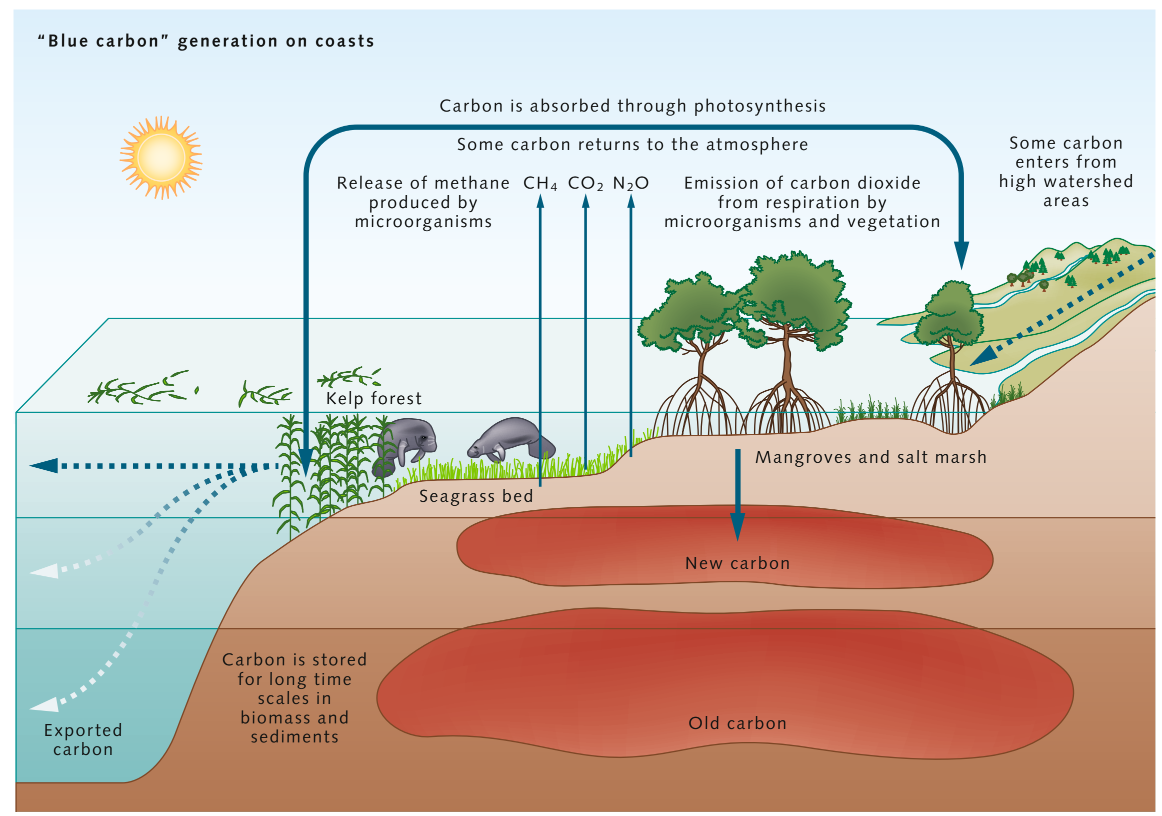
5.5 > In order to accurately survey the distribution of seagrass meadows off the coast of the Bahamas, scientists equipped tiger sharks with tiny sensors and cameras. The sharks hunt in and above the seagrass meadows. The data they collected helped to reveal that the world’s largest seagrass meadows grow off the Bahamas, covering a total area of 66,900 square kilometres, which roughly equates to 75 times the size of Berlin.

Carbon sink, coastal protection, nursery – the many services provided by coastal ecosystems

Experts often refer to the carbon sequestered by seagrass meadows, tidal marshes and mangrove and kelp forests as “blue carbon”. However, human societies not only benefit from healthy, vegetation-rich coastal ecosystems because they remove carbon dioxide from the atmosphere and the sea. They are also “ecosystem engineers” that form three-dimensional structured habitats in which numerous other species of marine and coastal flora and fauna find sufficient protection and food. For example, 4000 square metres of seagrass meadows can provide refuge and food sources for about 40,000 fish and around 50 million invertebrates such as lobsters, mussels and shrimp. Moreover, their dense tangle of leaves is a nursery habitat for the young of popular culinary fish species, such as Pacific herring and Atlantic cod.

But that’s not all. Tidal marshes, seagrass meadows and mangrove and kelp forests produce oxygen. They filter out pathogens, suspended matter, dirt and pollutants from the seawater, slow down ocean currents, waves and storm surges and thus protect the coasts from erosion and, through the accumulation of sediment, from rising sea levels. At the same time, they reliably provide food (fish, mussels, crustaceans), offer recreational settings and contribute to people’s health, and attract tourists in many places, thus creating additional jobs and income sources for coastal communities. Moreover, they hold spiritual or mythological significance in many regions of the world.

Through this multitude of services, healthy vegetation-rich coastal ecosystems help coastal communities to



5.6 > The amount of carbon that coastal ecosystems store underground in the long term depends on a number of factors. These include inputs of material from terrestrial sources or from other marine regions as well as the amount of biomass consumed by animals or decomposed by microorganisms.

5.7 > Seagrass meadows are hotspots of species diversity, providing shelter, food and habitat for countless marine organisms, including leafy seadragons (a syngnathid fish species), starfish and predators such as the American crocodile.

adapt to climate change in the best possible way. Measures to protect existing marine meadows and forests and to restore degraded coastal ecosystems are therefore win-win solutions. They help to both mitigate climate change and minimize its impacts.

Dying coastal ecosystems

Despite the importance of the ecosystem services they provide, vegetation-rich coastal ecosystems are declining in area worldwide. Once again, humans are responsible. Up to 50 per cent of all tidal marshes, about one third of all seagrass meadows and about 35 to 50 per cent of mangrove forests have been lost over the past 100 years as a result of climate change, coastal development and construction, agriculture and aquaculture, marine degradation, overfishing and other intensive uses. Of the world's kelp forests, 40 to 60 per cent are experiencing obvious declines in area.

When scientists recently analysed satellite images of vegetation-rich coastal ecosystems dating from 1999 to 2019, they realized that in those two decades tidal marshes, mudflats and mangrove forests combined had been lost over a total area of 13,700 square kilometres. Over the same period, however, new coastal ecosystems gained some 9700 square kilometres, either by expanding naturally or by human intervention in the form of plantings. But this did not fully offset the losses. Ultimately, the global extent of the coastal ecosystems studied declined by 4000 square kilometres – an area the size of the Spanish Mediterranean island of Mallorca.

Where ecosystems disappear, their carbon stores also largely disintegrate. For example, between 2000 and 2015 some 30 to 120 million tonnes of stored carbon were lost worldwide as a result of mangrove deforestation. The mangrove forest soil was no longer protected and stabilized by vegetation, resulting in microbes decomposing the material stored underground and releasing the carbon back into the atmosphere in the form of greenhouse gases. Converted into carbon dioxide (carbon mass multiplied by 3.664), this corresponds to greenhouse gas emissions amounting to 110 to 450 million tonnes of carbon dioxide. By comparison, the Federal Republic of Germany emitted greenhouse gases with the warming potential of 746 million tonnes of carbon dioxide in 2022.

Monetary value of selected ecosystem services provided by coastal ecosystems in south-eastern Australia

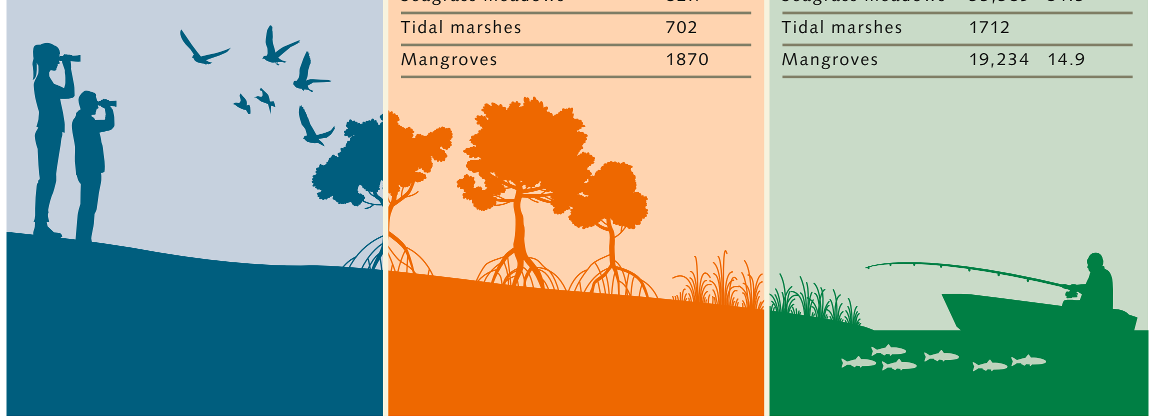
Recreation
BCEs are visited frequently by birdwatchers and fishers. In two popular Melbourne bays, seagrasses generate leisure and recreational effects for fishers worth 33.1 million Australian dollars (AUD) annually, while a visit to the tidal marshes and mangroves provides fun and entertainment worth 158 Australian dollars per visit.

Coastal protection
Coastal ecosystems reduce wave energy by 37 to 71 per cent, providing 2.7 billion Australian dollars in value in avoided damages to coastal property.

BCE	AUD million
Seagrass meadows	82.7
Tidal marshes	702
Mangroves	1870

Fisheries enhancement
Coastal ecosystems provide 61 per cent of diet for edible fish targeted by fishers. BCEs enhance fish abundance relative to unvegetated areas.

Number of fish per hectare and year		AUD million
Seagrass meadows	55,589	31.5
Tidal marshes	1712	
Mangroves	19,234	14.9



5.8 > People benefit in many different ways from ecosystem services provided by vegetation-rich coastal ecosystems, also known as Blue Carbon Ecosystems or BCEs. This overview summarizes the monetary added value that mangroves, tidal marshes, seagrass meadows and kelp forests in south-eastern Australia generate for a coastal community and its visitors.

Strategies to increase carbon dioxide removal by marine forests and meadows

There is also some good news: Damaged or lost mangrove forests and tidal marshes can be restored, as a number of exemplary restoration projects have shown. The replanting of seagrass meadows, in contrast, is very costly and far less likely to succeed. There is still much need for research and development in this regard, just as there is for the restoration of kelp forests. Nevertheless, researchers hope to increase carbon dioxide uptake and carbon storage by tidal marshes, seagrass meadows, mangrove forests and kelp forests in the long term through three sets of measures. What is common to all three of these sets is that they promote the plant communities' growth and thus their ability to photosynthesize, sequester carbon and store it in the seabed for the long term.

Under even greater pressure – how climate change multiplies the risks for coastal ecosystems

Climate change poses a major threat to coastal ecosystems. In response to rising air and water temperatures, plants and animal populations are shifting polewards. Heat stress increases their susceptibility to disease. As a result of rising sea levels, former tidal areas are permanently flooded and lost as habitat. Ocean acidification and oxygen depletion put further pressure on life under water.

In many places, extreme events such as severe storms and ocean heatwaves also cause enormous damage. Wind and waves can uproot mangroves, tear sea grasses from the seabed and sometimes wash away salt marshes and macroalgae forests. Marine heatwaves particularly affect kelp forests and seagrass meadows and, according to the IPCC (Intergovernmental Panel on Climate Change), have in recent years led to large-scale die-offs of local plant communities in various regions of the world.

Weather extremes and their impacts on site are difficult to predict. In addition, the impacts of climate change are exacerbated by other human-induced stressors and disturbances. These include bottom trawling, marine pollution and massive coastal development. The construction of dams along major rivers also often increases stresses on ecosystems in the rivers' lower reaches. Barrages prevent the input of sediments, which mangrove forests in particular need to expand their coverage and to grow in height (thus adapting to sea-level rise). All of these stressors reduce the ability of coastal ecosystems to compensate for climate impacts and adapt to change.

It is therefore reasonable to ask in which of the world's regions vegetation-rich coastal ecosystems will survive at all in the future and may be able to contribute to climate change mitigation through their carbon dioxide uptake, and where investments in their protection and possibly in their large-scale expansion would be sensible and promising.

Research is also needed into which innovative processes could protect extant, restored and newly established plant communities from climate change impacts. It would be conceivable, for example, to cultivate more heat-resistant brown algae and sea grasses. However, given the complexity of marine ecosystems it is still uncertain whether such an approach would succeed and make ecological sense.

These measures embrace:

- *The protection and improved management of existing vegetation-rich coastal ecosystems:* If rivers can flow freely towards the sea, their water is no longer polluted by fertilizers and other nutrients or pollutants, and dams do not prevent them from carrying sand and other sediments into the coastal waters, mangroves

5.9 > At the southern tip of San Francisco Bay, researchers and environmentalists are working hand in hand to restore more than 60 square kilometres of salt marshes that were destroyed during the gold rush and in the course of industrial development. Their approach appears to be paying off, as this comparison of satellite images from 2002 and 2015 shows.

and seagrasses find much better conditions than in coastal regions where these conditions do not exist. Intact food webs are also needed to ensure that, for example, there are enough predators to keep the number of potential pests low.

- *The restoration of marine meadows and forests that were lost due to human intervention:* This includes, for example, the replanting of mangrove forests and seagrass meadows and the removal of dikes so that salt marshes can be re-established in newly created intertidal areas.
- *The expansion of existing ecosystems:* This would require the creation of new mangrove forests, seagrass meadows, kelp forests and tidal marshes, including in areas where they do not naturally occur and may never have occurred in the past. In addition, plant species would have to be selected and assembled that, as a community of species, would most efficiently deliver the desired ecosystem services.

Experts refer to the approach of expanding or creating new ecosystems as ecosystem design. It is believed that ecosystem design can meet three objectives at the same time:

- To increase the carbon dioxide uptake of vegetation-rich coastal ecosystems and offset part of the residual carbon dioxide emissions caused by humans.
- To increase species diversity in coastal waters, provided correct approaches are taken.
- To offer humans and nature significantly better opportunities to adapt to climate change and defy the dangers it causes, thanks to the many additional ecosystem services provided by coastal ecosystems (nutrition, water quality, coastal protection, etc.).

However, an expansion of vegetation-rich coastal ecosystems would always be at the expense of other neighbouring local ecosystems, such as sandy beaches or tidal flats, if they were planted under mangroves or converted into tidal marshes.

Moreover, an expansion would entail disruptions to the lives of coastal populations, precisely because people around the globe use coastal areas intensively, and in many populated regions there is little open space left.

On German coasts, for example, it would be conceivable that dikes would have to be dismantled and the pastureland behind them abandoned to create more space for tidal marshes. Bays where seagrass meadows are newly planted would have to be closed to bottom trawling and perhaps also to boat traffic, at least temporarily. In order to establish new kelp forests along the North Sea coast, many tonnes of rock would have to be moved into the sea, because brown algae only grow on rocky substrates.

Previous experience with restoration projects has shown that measures aimed at nature conservation and climate change mitigation can only be successfully implemented together if the interests of the local communities are taken into account from the outset, if the local communities are involved in all decision-making processes, if they can contribute their own knowledge and expertise, and if they derive particularly strong benefits from the conservation measures.

A useful tool for climate change mitigation?

Investments in the protection, restoration and expansion of marine meadows and forests only pay off in terms of climate policy if they actually lead to additional carbon uptake and long-term storage in the seabed. This effect must be quantifiable and attributable to tangible measures. Otherwise it will be difficult to reward those in charge of the measures taken – for example by issuing carbon credits, i.e. tradable certificates for the additionally sequestered carbon dioxide.

Moreover, it must be ensured that the additionally sequestered carbon remains permanently in the seabed and is not released again after a few years as a result of microbial decomposition. Climate experts define “permanently stored” as carbon that is securely removed from the atmosphere for at least 25 years, at best several hundred years. Whether vegetation-rich coastal ecosystems are capable of this would need to be monitored by means of sophisticated observation systems – and over equally long periods of time.

It is already known that after the restoration or replanting of a seagrass meadow or mangrove forest it takes at least ten or 20 years for the new ecosystem to absorb and store as much carbon annually as healthy extant ecosystems. For every newly created vegetation-rich coastal ecosystem, this means that only after one to two decades can it be verified whether the actual performance of this new or expanded ecosystem in terms of carbon removal matches the initial expectations.

Apart from these challenges, there are seven other serious arguments that have so far made it difficult to realistically classify and soundly evaluate carbon dioxide removal processes based on the restoration, creation or expansion of vegetation-rich coastal ecosystems. These include:

1. huge regional differences in carbon uptake and sequestration by individual ecosystems,
2. lack of standards for measuring carbon sequestration,
3. unresolved questions as to the origin of the stored organic material,
4. lack of knowledge regarding the generation and release of methane and nitrous oxide,
5. uncertainties as to the amount of carbon dioxide that is released or sequestered when calcifying inhabitants of coastal ecosystems build up their calcareous shells and exoskeletons and when these dissolve again,
6. lack of detailed knowledge about the future effects of climate change impacts and other human-induced stressors on marine meadows and forests, and
7. unanswered questions as to the cost and scalability of potential restoration and expansion measures.

Major regional differences in carbon sequestration

Carbon uptake and storage by marine meadows and forests is influenced by various biological, chemical and physical environmental factors. These not only affect the photosynthetic performance of local plant communities, but also determine the amounts of organic material that are filtered, deposited, decomposed or permanently trapped in the coastal sediment.

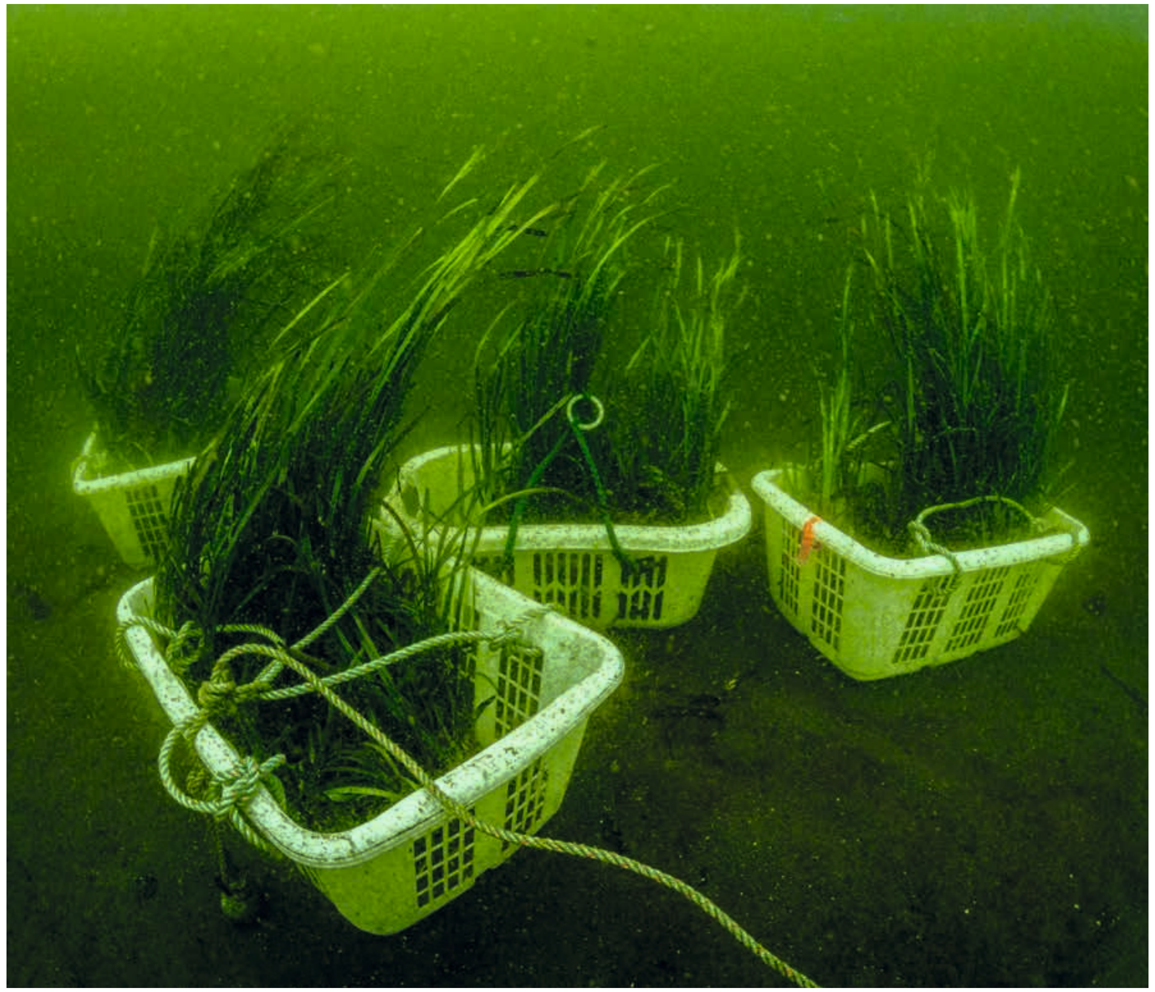
This dependence on local environmental conditions has a major bearing on the amount of carbon that individual marine meadows and forests actually absorb and store. Experts speak of a high variability of carbon storage in this context. There are, for example, highly productive salt marshes that store up to 600 times more carbon than less productive salt marshes. In the case of seagrasses, the differences can be 76-fold, and 19-fold in the case of mangroves.

Based on this knowledge, scientists conclude that the restoration or expansion of vegetation-rich coastal ecosystems for the purpose of increased carbon dioxide removal from the atmosphere will only make sense and be expedient at those sites where the conditions for high sequestration rates are met or can be established by means of targeted human intervention. This, however, calls for detailed data sets on the carbon storage rates of all marine meadows and forests. But such measurements have so far only been taken at a small number of selected sites.

Lack of standards for measuring carbon sequestration

Measuring carbon uptake and sequestration directly, both on land and in coastal regions, is a difficult and lengthy endeavour and technically complex. For this reason, most data on carbon storage in vegetation-rich coastal ecosystems has so far been collected by means of indirect measurements. This means that researchers took coastal sediment samples – usually down to a depth of one metre – analysed their carbon content and then calculated the average carbon storage using a variety of parameters such as current velocity and sedimentation rate.

However, the error rate of these indirect methods can be very high for various reasons. For example, if one day a dam is built in a river containing large mangrove forests in its delta, the water's flow velocity and sediment load are reduced. For the mangroves in the river delta, this change means that from that point forward they have significantly less material available to trap animal and



5.10 > The restoration of seagrass meadows is complex and often costly because the grasses have to be transplanted by hand. In a restoration project on the Atlantic coast of the US state of Virginia, the organizers use laundry baskets to transport the seagrass seedlings from the propagation tanks to their future growth site.

plant remains in the seabed. As a result, the mangroves grow more slowly. At the same time, the total size of their carbon stores will be ever less indicative of their current carbon sequestration rate – unless the relevant measurements are taken using methods that have not yet been established as a global standard.

The same is true for coastal wetlands where humans begin to practise arable farming, or if the water quantity or quality in river deltas and coastal waters change as a result of climate change or human use. Another factor to be taken into account is bioturbation, i.e. the extent to which organisms living on or in the seabed burrow through the subsoil and thus the carbon stores. As a result, the trapped organic material is more likely to decompose and degrade. Moreover, intensive bioturba-tion makes it more difficult for researchers to determine the sediment deposition rate. If they leave bioturbation out of their calculations, the carbon deposition rate may be overestimated by 50 to 100 per cent. Underestimation is also possible. Carbon sequestration data from soil samples should therefore always be interpreted with great caution, experts note.

The question as to the origin of the stored organic material

In order to one day be able to determine the quantity of carbon that has been extracted and stored in the subsoil as a result of an individual blue carbon measure, it is important to know where the organic material trapped in the coastal sediment originated. Was it produced by the seagrass meadows or tidal marshes on site or transported by wind and ocean currents from far away? A number of different studies show that the proportion of material brought in from afar can be high. In mangrove forests in Vietnam, for example, it was found to account for 24 to 55 per cent of the carbon stored below ground. In the case of Australian seagrass meadows, it was as high as 70 to 90 per cent. Some experts argue that if that much material comes in from the outside, there is a risk that the carbon dioxide removal potential of local coastal ecosystems may be overestimated. After all, the carbon was absorbed from the atmosphere elsewhere and stored in the form of organic material. Admittedly, this attribution detail is more of a statistical problem. It is irrelevant to the question of how much organic material is stored. It does become relevant if one day there is a debate as to who can take credit for the carbon drawdown.

The generation and release of methane and nitrous oxide

When animal and plant remains are trapped in oxygen-free coastal sediment, microbial decomposition of this organic material produces the climate-damaging greenhouse gases methane (CH_4) and nitrous oxide ($N2_O$). It is estimated that the world's vegetation-rich coastal ecosystems together emit more than five million tonnes of methane per year. If this were true, it would be sufficient to cancel out the positive climate effect of marine meadows and forests due to carbon uptake and sequestration.

However, it is as yet impossible to say whether coastal ecosystems actually emit that much methane, because important baseline knowledge about the degradation and release processes in coastal sediments under marine meadows and forests is lacking. Studies investigating these aspects are currently being conducted as part of various research projects. For decisions on the possible use of these ocean-based CDR processes, it is essential to understand whether and, if so, how the restoration or expansion of vegetation-rich coastal ecosystems may change their methane and nitrous oxide emissions. Moreover, if such measures were to be implemented one day, fine-meshed monitoring networks would have to be established to monitor the emissions balance of newly created or expanded marine meadows and forests on a full-coverage basis.

Emissions balance of calcification and dissolution in vegetation-rich coastal ecosystems

When calcifying organisms such as corals, calcareous algae, foraminifera, mussels or true conchs form their exoskeletons and shells from calcium carbonate (lime, $CaCO_3$), the corresponding chemical reaction generates carbon dioxide, which then dissolves in the water. This release causes the carbon dioxide concentration in the water to rise and the greenhouse gas to escape into the atmosphere when at some point the water rises to the sea surface. The reverse happens when lime dissolves in seawater. In the course of the corresponding chemical reaction, those solution products are released that are needed to chemically bind carbon dioxide dissolved in the water. As a result, the carbon dioxide concentration in the water decreases and the ocean can absorb new carbon dioxide from the atmosphere.

Vegetation-rich coastal ecosystems are habitats for many calcifying organisms. However, scientists are currently still discussing how their calcification (which releases carbon dioxide) and possible dissolution processes of the calcareous shells and exoskeletons (which bind carbon dioxide) affect the overall carbon balance of coastal ecosystems and what consequences this may have for the climate. Measurements taken off the coast of the US state of Florida, for example, have shown that marine organisms in one of the world's largest seagrass meadows formed more calcium carbonate during the study period than was dissolved again through chemical reactions. As a result, the coastal ecosystem was estimated to have released three times more carbon dioxide than it was able to remove from the atmosphere by storing the shell and skeletal remains in the coastal sediment.

Uncertain climate change impacts on marine meadows and forests

The Intergovernmental Panel on Climate Change notes that climate-related changes such as rising temperatures, more frequent and more intense ocean heatwaves, ocean acidification, storms and sea-level rise have mostly detrimental effects on coastal ecosystems, threatening their continued existence as carbon stores and providers of many other ecosystem services.

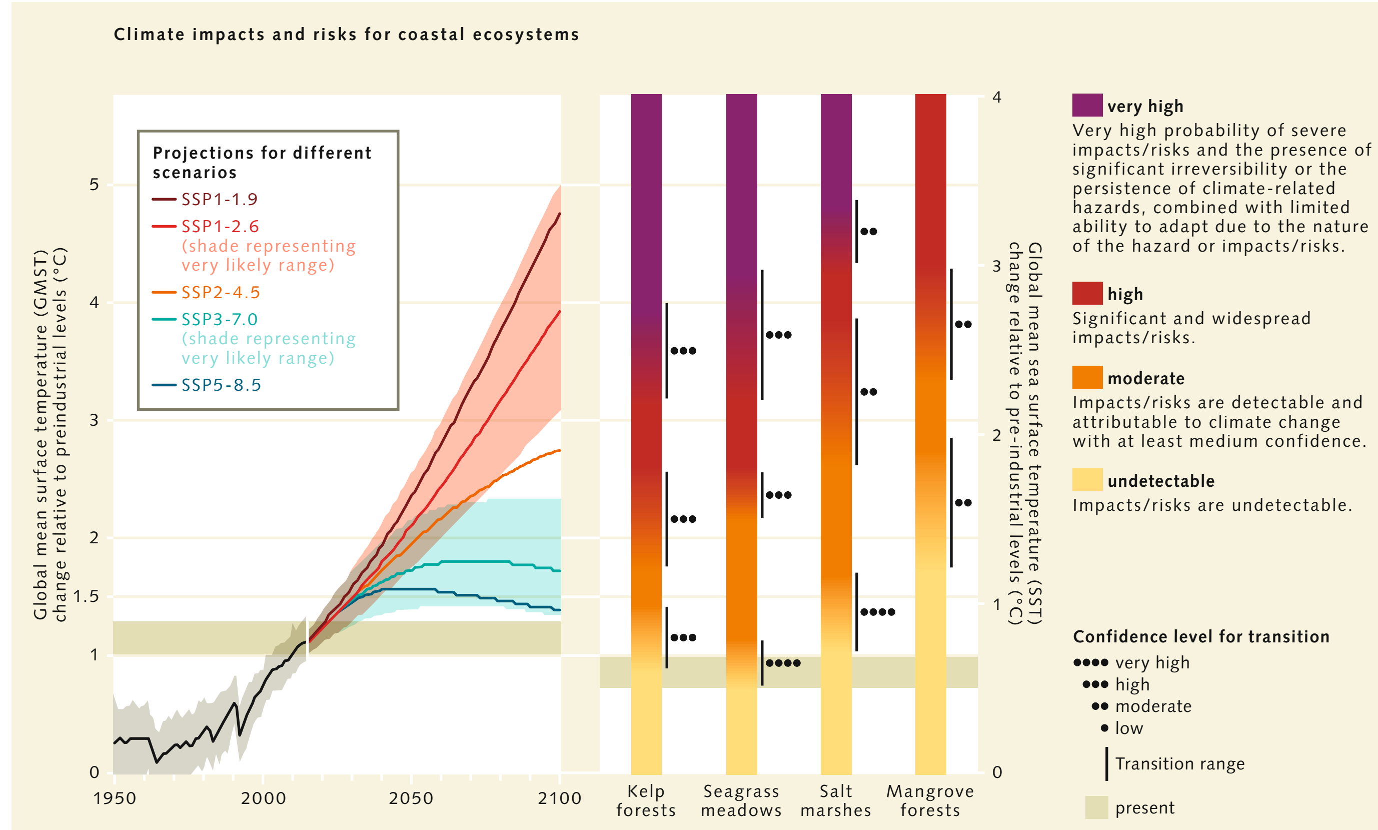
A potentially increased uptake of carbon dioxide from the atmosphere can probably only be expected where marine meadows and forests shift inland – if there is room for them to do so – and then possibly form larger ecosystems than before. If large-scale spatial shifts are not possible due to space constraints and ecosystems decline in area or disappear, their carbon stores in the coastal sediments would also be at risk.

Worst-case estimates indicate that carbon stores amounting to 3.4 gigatonnes could be lost this way by 2100.

Of the four vegetation-rich coastal ecosystems under discussion, seagrass meadows react most sensitively to rising temperatures, so that even today, with global warming of 1.15 degrees Celsius, marine heatwaves in particular cause them great harm. For example, as a result of such temperature extremes lasting for weeks or even months, 36 to 80 per cent of the local seagrass meadows in the US Chesapeake Bay, in the western Mediterranean and in Sharks Bay in Western Australia have died in recent years. Because heatwaves occur more frequently, last longer and reach higher temperatures with increasing climate change, the climate risks and the extent of the damage caused will continue to escalate in the coming years. Researchers predict that many of the existing seagrass meadows will die if the global surface temperature rises by more than 2.3 degrees Celsius.

Climate change impacts on tidal marshes are at a medium level with a warming of 1.2 degrees Celsius, but

5.11 Climate risks for coastal ecosystems increase with global warming. Kelp forests and seagrass meadows are more temperature-sensitive than salt marshes and mangroves and are therefore already exposed to moderate to high risks with 1.5 to two degrees Celsius of warming.



5.12 > More than 1000 species of flora and fauna live in the kelp forests around the Channel Islands, a group of islands off the Pacific coast of the US state of California. Of the 27 species of kelp worldwide, nine can be found in this marine area alone, including the largest of all brown algae, the giant kelp or bladder kelp (*Macrocystis pyrifera*).

at 3.1 degrees Celsius or more, experts predict that these will also suffer severe damage. One of the effects will be that plant communities are going to die out where they are permanently flooded in the future as a result of sea-level rise.

For mangroves, the thresholds for moderate and severe impacts are two and 3.7 degrees Celsius of global warming respectively. In Australia there are however mangrove forests that are already being affected by climate change, especially when heatwaves, droughts and a short-term drop in sea level, such as due to changes in currents, occur simultaneously. In some other areas, mangroves have been spreading polewards for decades, mingling with or overgrowing tidal marshes. New research results from the central tropics also indicate that a warming of up to two degrees Celsius is likely to lead to increased carbon storage by mangroves, at least in that region.

Current and future climate impacts must be taken into account from the outset when restoring and expanding coastal ecosystems. However, experts still find it very difficult to make predictions about temperature-related species migration.

They therefore recommend that projects to restore or re-establish marine meadows and forests should be carried out primarily at the cooler margins of their current range.

Vulnerability to other man-made disruptions and stressors

Even if humankind were to succeed in limiting climate warming to well below two degrees Celsius, the continued existence of many coastal ecosystems and the success of restoration projects or new plantings would be threatened by many other man-made disturbances and stressors. These include, above all, land-use change such as coastal construction in the course of the expansion of coastal cities, mangrove deforestation, for example for the construction of aquaculture installations, the diking and agricultural use of tidal marshes, and the eutrophication of coastal waters through fertilizer and wastewater inputs.

Whether or not measures to restore or replant tidal marshes, seagrass meadows, kelp forests and mangrove forests succeed also depends on whether appropriate sites and plant species were chosen and on whether the rights, needs and knowledge of the local communities were taken into account during planning and implementation. After all, local people bear the responsibility for ensuring that marine meadows and forests are protected in the long term and utilized in a sustainable manner. Experts are also calling for sufficient funds to install monitoring systems and implement protective measures to ensure that the vegetation-rich coastal ecosystems continue to fulfil their important climate function for a long time to come.

Would extension and restoration measures be economically viable and widely applicable?

Whether measures to expand or restore tidal marshes, seagrass meadows, kelp and mangrove forests are economically worthwhile depends on the standpoint from which experts evaluate the services provided by coastal ecosystems. Do they focus solely on the potential increased carbon dioxide uptake of restored or expanded marine meadows and forests, or do they also take into consideration the many other services that ecosystems provide to humans? There are numerous uncertainties associated with both approaches. These include the difficulty of providing evidence of actual additional carbon dioxide uptake. At the same time, the costs of new plantings or extensions vary significantly by vegetation type and coastal region. This is mostly due to different methods being employed, the different wages for the requisite divers, experts and support workers, and whether or not the long-term monitoring costs for the restored or expanded coastal ecosystem are taken into account.

Moreover, there is the question as to the proportion of the marine meadows and forests destroyed by human activities that could realistically be restored – experts refer to the scalability of restoration measures in this regard. Large stretches of coastline where tidal marshes, seagrass meadows or mangrove forests once grew are now built on, diked off or used for farming. So if these former habitat sites cannot be reclaimed, there is simply no room

Blue carbon as a component of emissions trading – a difficult undertaking

It always makes sense to protect, restore and, if necessary, expand vegetation-rich coastal ecosystems, precisely because they serve nature and millions of people in so many different ways. Nonetheless, only a few countries and companies have invested in such projects to date. Many project initiators therefore hope to tap new sources of funding for their protection and restoration measures through the sale of "blue carbon credits". The US computer manufacturer Apple, for example, has been working together with the environmental organization Conservation International and local coastal communities since 2018. Apple is investing in the restoration and protection of a 110 square kilometre mangrove forest in Colombia. In return, the company receives a certain number of emission certificates, known as carbon credits. These represent either a certain amount of prevented emissions or carbon dioxide absorbed by the mangrove forest, which Apple uses to compensate for a corresponding amount of its residual, hard-to-avoid emissions.

Voluntary and mandatory markets

When actors such as Apple and Conservation International enter into agreements of this kind and carbon credits are issued, this interaction takes place on one of the numerous emissions trading platforms or through bilateral transactions that can be assigned to the "voluntary market". This market has developed without legal requirements for offsetting emissions and the rules and standards for carbon offsetting are defined by the market participants themselves. Simply put, any actor can issue certificates and sell them if they find a buyer who trusts that the money will actually go towards the protection, restoration or expansion of coastal ecosystems, thus resulting in the long-term removal of additional carbon dioxide from the atmosphere. So far, these certificates have rarely been resold. Carbon offsetting for air travel has been functioning along the same lines for many years now, except that those payments have so far mainly gone into measures to avoid emissions in emerging and developing countries, as well as into reforestation measures on land. Anyone buying products in the supermarket that are labelled "carbon-neutral" can assume that the corresponding emissions offsets have been made through transactions in the voluntary market.

The voluntary markets thus differ fundamentally from the centrally organized "mandatory markets". These include, for example, the European Union Emissions Trading System (EU ETS), which records the emissions of some 11,000 energy industry facilities and energy-intensive industries across Europe. A certain number of emission certificates are issued for them, which the participating companies then trade among themselves. The number of available certificates is limited and reduces over time, forcing companies to either reduce their emissions or pay ever higher prices for each tonne of carbon dioxide equivalent emitted (more on this topic in Chapter 9). It is important to note that the listed companies are not allowed to use carbon credits purchased in the voluntary market to offset their emissions in their EU ETS balance.

Rules against greenwashing

There are as yet no uniformly binding regulations, accounting or control mechanisms for voluntary markets that issue blue carbon certificates. However, there is increasing pressure to introduce such regulations and mechanisms because in the digital age, no financier can afford to invest in projects that end up not being carried out at all, carried out improperly or to the detriment of the environment or the local community. Investments of that kind are referred to as "greenwashing" and are highly damaging to the investors' image.

To prevent this, a number of companies and experts are currently developing programmes and framework guidelines intended to making the issuance of and trade in emission certificates in voluntary markets transparent and comprehensible. They also aim to ensure that all related measures are implemented in an environmentally sound and socially equitable manner. At best, experts say, the end result would be a market guided by clear rules and uniform procedures to measure carbon dioxide removal that prevent abuse and fraud. This level of caution is warranted because the demand for emission offsets is steadily increasing. It is estimated that in 2030 carbon credits worth up to 50 billion US dollars could be traded in voluntary markets.

Basic principles for the allocation of carbon credits

One of the proposed rulebooks sets out ten basic principles for the allocation of carbon credits. They were developed by the Task Force on Scaling Voluntary Carbon Markets. Among other things, the principles are designed to ensure that:

- the emission avoidance or carbon dioxide removal achieved has actually been "additional", i.e. the impact would not have been realized if the project had not been carried out;
- there is no double accounting, for example, by both the investing company and the government of the country in which the measure is undertaken;
- investors publish comprehensive information, comprehensible to laypersons, on their emission offsets, including information on the impact of the financed measures on the environment and the local community;
- there is permanence or durability to the achieved avoided emissions or carbon dioxide removal;
- all issued emission certificates are reported to a central registry so that they can be clearly identified and traced at any time; and
- independent experts regularly review the awarding system and its mechanisms and use scientific methods to check whether the promised measures are actually being implemented and contributing to climate change mitigation.

A small but steadily growing market

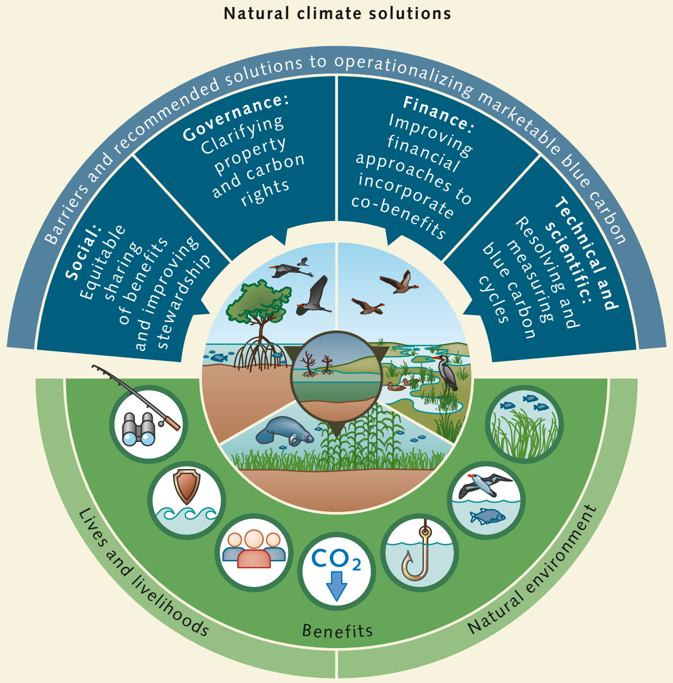
Many blue carbon projects have not yet been able to meet these requirements. A difficulty may be, for example, that it is hard to prove exactly how much additional carbon dioxide is being removed from the atmosphere. For this reason, the amount of blue carbon credits issued is still comparatively small. Between 2013 and 2022, blue carbon credits for a mere one million tonnes of carbon dioxide equivalents were issued in voluntary markets. This sum corresponded to a market share of 0.7 per cent.

However, the number of projects working towards issuing blue carbon credits is steadily increasing. A critical factor in this regard has been the revision of a set of rules for the verification of emission avoidance and carbon dioxide removal through forest protection and (re)afforestation (Verified Carbon Standard REDD+ Methodology Framework). It now also includes emission accounting standards for tidal marshes, seagrass meadows and mangrove forests that are being protected, restored or newly created.

In addition, project initiators are increasingly trying to convince investors to invest not only in the ecosystems' carbon removal functions, but additionally in their many ecosystem services such as coastal protection and conservation of species diversity. This also makes the projects interesting for those financiers who wish to invest in environmental protection.

An unanswered question: Who owns coastal ecosystems?

In many places, however, it is unclear who owns the tidal marshes, seagrass meadows, mangrove and kelp forests, who may decide on their future and who may make money with them. Is it the local communities whose behaviour is a basic prerequisite for the preservation of coastal ecosystems, or could regional, national or even global actors be allowed to decide on their future? And to what extent would they then have to involve the coastal people and pass on financial benefits? There are as yet no consistent answers to these and many other legal and regulatory questions, a situation that has so far discouraged financiers from undertaking extensive investments in the protection and restoration of vital coastal ecosystems.



5.13 > Before a global market for blue carbon credits can emerge, social and financial aspects as well as regulatory framework conditions and control mechanisms must be clarified.

5.14 > Three of the four coastal ecosystems grow on soft substrates, form roots and are therefore able to accumulate carbon in the substrate. In contrast, kelp grows on rocks and can only store the carbon they take up in their algal biomass.

The four vegetation-rich coastal ecosystems compared

	Salt marshes	Mangroves	Seagrass meadows	Kelp forests
Global area	To date, not all the world's tidal marshes have been mapped, so their total area can only be estimated. According to one of the most comprehensive studies to date, tidal marshes occur in 43 coastal countries and probably cover an area of some 55,000 square kilometres / 5.5 million hectares	147,359 square kilometres / 14.7 million hectares (as at: 2020)	The exact total area of seagrass meadows is not known. According to current data, it is between 160,387 and 266,560 square kilometres	Ca. 1,500,000 square kilometres / 150 million hectares
Habitat location	Intertidal zone	Intertidal zone	Shallow water area of sandy and sheltered marine bays	Shallow water area of rocky coasts
Size of the existing carbon deposits	An estimated 862 to 1350 million tonnes of carbon	1900 to 8400 million tonnes of carbon in the top metre of the soil column; the amount of carbon stored in living biomass is estimated to be in the order of 1230 to 3900 million tonnes	Estimates range from 1732 to 21,000 million tonnes of carbon. This very wide range is due to uncertainties in seagrass meadow mapping, methodological differences in carbon measurement and different characteristics of the individual seagrass meadows	Kelp forests do not form their own carbon deposits in the seabed. Instead, dead organic material is transported away by wind and currents
Amount of carbon stored annually	12.63 million tonnes (globally) 28 kilograms to 17 tonnes (per hectare)	41 million tonnes (globally) 560 kilograms to 11 tonnes (per hectare)	35.31 million tonnes (globally) 25 kilograms to 1 tonne (per hectare)	Solid data for kelp forests are as yet unavailable. It is estimated that annually about 11 per cent (173 million tonnes) of the carbon taken up by macroalgae is stored in the seabed and in deep water masses
Loss of area	25 to 50 per cent of the original area; in industrialized and rapidly developing countries up to 60 per cent since the 1980s	35 to 50 per cent of the original area	approx. 29 per cent of original area since the 1940s, with large-scale losses in the USA, Australia, New Zealand and Europe	40 to 60 per cent of kelp forests have seen losses

The four vegetation-rich coastal ecosystems compared

	Salt marshes	Mangroves	Seagrass meadows	Kelp forests
Restoration potential	High; the maximum available area is 0.2 to 3.2 million hectares	High; the maximum area available is estimated to be between 9 and 13 million hectares	Medium; compared to mangroves and salt marshes, the restoration of seagrass beds is expensive and more rarely successful; the maximum area available is between 8.3 and 25.4 million hectares	Low, if too many grazers (sea urchins etc.) are on site; previous restoration projects to date have been rather small-scale
Main hazards and stressors	Changes in land use (agriculture, development), sea-level rise, introduced species, pollution	Deforestation, marine pollution, coastal development, extreme weather, sea-level rise	Sea-level rise, coastal development, rising air and water temperatures, eutrophication, bottom trawling, overfishing, boat traffic (especially anchorages), extreme storms	Ocean warming, ocean heatwaves, overfishing, marine pollution, overgrazing by sea urchins and fish, human harvesting of macroalgae, extreme storms

Estimated cost of additional carbon dioxide removal: 1 to 60 US dollars per tonne of carbon dioxide for mangrove forests and 100 to 1000 US dollars per tonne of carbon dioxide for salt marshes and seagrass beds

Estimated future emissions that can be avoided through effective protection of existing coastal ecosystems: 140 to 460 million tonnes of carbon dioxide equivalents per year

Potential additional carbon dioxide removal as a result of widespread restoration of degraded vegetation-rich coastal ecosystems: 0.621 to 1.064 billion tonnes of carbon dioxide equivalents per year from 2030. This amount would be equivalent to around 3 per cent of global carbon dioxide emissions from burning coal, gas and oil in 2020

for new plantings. One argument against such reclamation for nature restoration is that in many areas coastal land with high restoration potential is used by smallholder farmers whose entire income depends on precisely that land. If farming families had to give up their land, they would lose the resource base on which their livelihoods depend. For these and other reasons, some experts believe that in Southeast Asia, for example, the area on which mangrove forests could actually be restored or replanted is much smaller than generally held. Depending on the region, their proportion is a mere 5.5 to 34.2 per cent of the theoretically available coastal area, if all socioeconomic arguments against restoration are taken into account.

Other experts are more optimistic about the restoration potential.

In a global analysis of the status and restoration potential of mangrove forests, researchers concluded in 2018 that there are only two types of areas where mangroves cannot be replanted: locations that have been urbanized (0.2 per cent of the mangrove area lost in 1996 to 2016) and locations where former habitat has become permanent open water (16 per cent of the mangrove area lost in 1996 to 2016). According to the study, the restorable area of mangrove forests totals 8120 square kilometres, with 81 per cent of these areas being considered highly restorable.

Green, red and brown algae – part of the climate solution?

In 2020, coastal farmers worldwide harvested some 36 million tonnes of macroalgae, also known as seaweed or kelp; 97 per cent of these had grown in specially established algae farms. The seaweeds are used as food, animal feed or fertilizer, primarily in coastal countries. But their components are also traded worldwide because they are needed in the production of food, pharmaceuticals and cosmetics. And industrial companies are increasingly using algal biomass to produce biofuels – for instance in the People's Republic of China, which now produces 59.5 per cent of the world's traded macroalgae.

The term "macroalgae" covers organisms from three taxonomic groups: brown algae with some 2000 species, red algae with more than 7200 species and green algae with more than 1800 species. However, globally only 27 species were used for macroalgae farming in 2019, primarily red and brown algae.

Macroalgae are highly productive organisms. They grow quickly and sequester between 91 and 522 grams of carbon per square metre of sea surface, filtering the nutrients (nitrogen and phosphorus) they need to grow from the seawater. They thus not only clean the water and help combat the eutrophication of coastal waters, but they also locally reduce seawater acidification as they absorb carbon dioxide from the water for their photosynthesis and store the carbon in their tissue.

These climate-friendly properties and their comparatively simple cultivation gave experts the idea of taking more carbon dioxide out of the atmosphere by creating huge algae farms in which macroalgae photosynthesize and grow – both near the coast and in the open ocean. The resulting algae forests or mats could then be put to three climate-friendly uses:

- as feedstock for bioenergy production with subsequent carbon dioxide capture and storage (BECCS),
- as feedstock for the production of biochar, which could subsequently be used, among other things, to increase the soil carbon content and water retention capacity of agricultural lands, and
- as biomass to be used for rapid intentional deep-ocean sinking.

The rapid sinking of large amounts of biomass could accelerate the organic biological carbon pump (see Chapter 2), giving marine organisms in the water column less time to consume or decompose the macroalgal biomass. Significantly greater quantities of biomass could reach depths of more than 1000 metres or even the seabed and be decomposed there or permanently stored in the sediment. In both cases, the carbon contained in the macroalgal biomass would be locked away at depth for a long time. For comparison: If biomass sinks to a depth of 500 to 3000 metres, it takes more than 50 years, depending on the ocean region, for the carbon it contains or possible degradation products to rise back to the sea surface.

A rapid expansion of large-scale algae farming is currently not taking place because seaweed farms have so far mainly been operated in coastal waters, where both space and nutrient availability are limited. In addition, coastal waters are warming up with climate change, which makes algae farming even more difficult. Scientists and enterprises in the field are therefore trying to develop cultivation methods for open-ocean macroalgae farming that could be used over thousands of square kilometres. There's no shortage of ideas. These include, among others:

- free-floating *(Sargassum)* macroalgae cages that are towed from one nutrient-rich marine region to the next by remote-controlled tug boats to achieve maximum growth rates;
- macroalgae cultivation platforms that float nine metres below the sea surface during the day and are towed down into nutrient-rich deep water at night;
- cultivation platforms that are sunk and unloaded as soon as they are completely covered in macroalgae. The aim here would be to transport the algal biomass to great depths as quickly as possible.

5.15 > Research is currently underway to determine whether the ocean's CO_2 uptake could be increased by sinking floating *Sargassum* algae.

Limits and risks of macroalgae farming

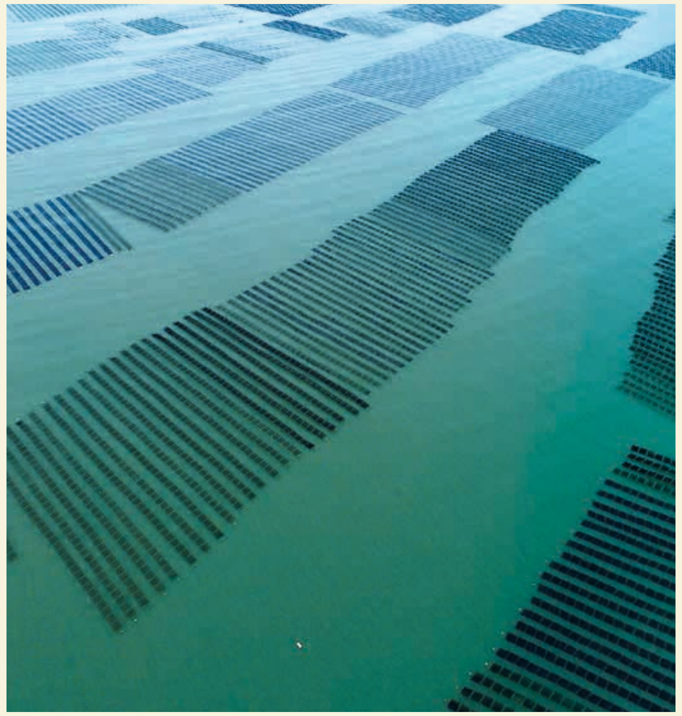
Even though large-scale algae cultivation is one of the so-called nature-based climate solutions, it has disadvantages for both humans and the environment: Where many macroalgae grow, an ecosystem-wide competition for the nutrients dissolved in the ocean water begins. If the algae are harvested and thus removed from the sea, the marine biocoenoses will not only lack an important nutritional basis, but in the long term the ocean's material cycle will also lack the nutrients contained in the algal biomass. This deficiency applies first and foremost to coastal waters that are not over-fertilized and as a consequence means that the productivity of the marine region in question decreases.

Initially, this dangerous chain reaction would result in less phytoplankton and fewer macroalgae, followed by fewer animals surviving not long after, as they run out of food. In China's macroalgae-farming areas, experts have been trying to solve this nutrient problem for years. So far, however, every promising approach ultimately resulted in further difficulties in macroalgae cultivation. So there is still no real solution to date.

The natural nutrient deficiency in marine regions such as the subtropical gyres also means that large-scale open-ocean macroalgae farming could not be extended to the entire ocean. It would probably only be promising in the upwelling areas, i.e. those marine regions where nutrient-rich deep water rises to the sea surface, as well as everywhere where humans either succeed in pumping deep water to the sea surface or regularly pull the growth platforms down from the light-filled sea surface layer into nutrient-rich deep water.

When researchers recently simulated the effects of large-scale open-ocean macroalgae mariculture and deep-sea sinking in an Earth system model, further consequences and risks for the ocean system became apparent.

The rapid sinking of biomass into water depths of more than 3000 metres and the thus reduced natural decomposition of organic material at medium water depths would decrease the oxygen deficiency zones in this part of the water column. At the same time, however, oxygen consumption would increase at greater depths and on the seabed. There, marine organisms would decompose a large proportion of the algal biomass, resulting in the formation of large oxygen deficient zones in the deep sea; at the same time the deep water would acidify due to the microbial release of carbon dioxide. But that's not all: as more biomass would also be stored in the seabed, the ocean would lack the nutrients it contains in the long term. This, in turn, would further reduce phytoplankton growth and thus result in less marine life.



5.16 > In November, the macroalgae farms in the Chinese province of Fujian can already be spotted from a distance. By this time of year, the red and brown algae cultivated here have grown sufficiently and are being hauled in by the fishermen, rope-by-rope.

In consequence, it is already foreseeable that macroalgae farming will by no means be the sole solution to our climate problem. Instead, it is one of a multitude of methods that we can use to increase the ocean's carbon dioxide uptake. Its large-scale deployment, however, has drawbacks that first must be thoroughly weighed against potential benefits.

Not a panacea, but a useful tool in the right place

Blue carbon experts are still arguing about what conclusions should be drawn from the uncertainties mentioned above regarding the feasibility and long-term effectiveness of the large-scale restoration and expansion of vegetation-rich coastal ecosystems. Sceptics describe the existing blue carbon approaches as too immature to be used as a basis for national removal targets or to be included in carbon offset trading.

In support of their position, they point to the comparatively wide range of additional carbon dioxide removal potential of marine meadows and forests. The wider that range, the more uncertain the actual potential for carbon removal.

Other experts, however, are encouraged by that range to take a closer look. Studies indicate that protected and restored coastal ecosystems could remove an additional 0.06 to 2.1 gigatonnes of carbon dioxide per annum from the atmosphere.

This removal quantity is roughly equivalent to 0.02 to 6.6 per cent of global carbon dioxide emissions in 2020 and would be far from sufficient to offset the projected residual emissions of several billion tonnes of carbon dioxide and other greenhouse gases.

Blue carbon approaches alone would therefore not achieve the goal of global greenhouse gas neutrality even if all known measures that could prevent man-made greenhouse gas emissions were implemented in parallel.

However, current research on the carbon uptake and storage by tidal marshes, seagrass meadows, mangrove and kelp forests also proves that there are indeed coastal areas where marine meadows and forests store a great deal of carbon and in this way contribute significantly to reducing greenhouse gas concentrations in the Earth's atmosphere.

The size of this contribution, however, is determined by local environmental conditions, which vary greatly from site to site and explain the major differences in carbon dioxide removal potential. It would therefore be wrong to dismiss the ability of coastal ecosystems to absorb significant amounts of additional carbon dioxide, the experts argue. Instead, research is tasked with investigating the extent to which each individual coastal ecosystem absorbs, stores and, if necessary, releases carbon and to what extent it would also be able to fulfil this removal and storage function in a warmer world.

Only when sufficient data on the carbon cycle of local tidal marshes, seagrass meadows, mangroves and kelp forests are available could a decision be made as to whether new plantings for the restoration or expansion of marine meadows and forests in these areas would be socially equitable and actually promising from an emissions perspective, i.e. whether they would result in additional carbon dioxide removal. Optimistic estimates indicate that this would be the case in so many coastal areas that, in a best-case scenario, the current area of marine meadows and forests worldwide could be expanded by 30 to 50 per cent by 2050.

Should this hope not be fulfilled and the vegetated areas gained ultimately prove to be smaller, both humans and nature would still benefit from healthy and productive coastal ecosystems in many different ways.

Their many co-benefits make tidal marshes, seagrass meadows, mangroves and kelp forests an invaluable guarantor of survival for millions and millions of people and even more marine organisms. Protection and restoration measures therefore tend to enjoy broad societal support.

The scientific community refers to blue carbon approaches as measures with very few downsides which therefore give rise to few concerns (low-regret measures). Moreover, the restoration methods at least for mangroves and tidal marshes are technically mature enough that their use would be theoretically feasible and could be well controlled by local administrations and political institutions.

Investments in effective and science-based conservation and restoration projects for tidal marshes, seagrass meadows, mangroves and kelp forests are therefore already paying off today. Measures of this kind are needed more urgently than ever in a warming world.

Conclusion

Coastal ecosystems – marine carbon sinks providing indispensable additional services

Vegetation-rich coastal ecosystems such as tidal marshes, seagrass meadows, mangrove forests and kelp forests are key players in the marine carbon cycle. Taken together, plant communities are responsible for at least 30 per cent of the organic carbon stored in the seabed.

Carbon storage by these ecosystem types follows a fixed pattern: plants take up carbon dioxide and convert the carbon it contains into biomass. This is then stored in the root system (except in the case of kelp) or accumulates over time on the seabed in the form of dead branches, leaves and stalks. Sinking sediment subsequently buries the dead plant matter and much other organic material, cutting it off from oxygen. Under these conditions, the animal and plant remains cannot decompose. Instead, they form carbon reservoirs in the seabed that are in fact larger than the soil carbon stores of terrestrial forests and will remain as long as the salt marshes, seagrass meadows and mangrove forests thrive – which, ideally, can be for periods of many thousands of years.

This climate-relevant characteristic of marine meadows and forests allows for two conclusions to be drawn. Firstly, agencies and communities which protect existing marine meadows and forests effectively prevent the degradation of their carbon stocks and thus the release of large quantities of greenhouse gases. Secondly, by planting new vegetation-rich ecosytems or restoring damaged coastal ecosystems, there are hopes of enhancing their natural carbon uptake in such a way that unavoidable anthropogenic greenhouse gas emissions can be offset.

The size of the carbon dioxide removal potential of coastal ecosystems is a matter of some debate in the scientific community, as key basic knowledge is still lacking, such as the level of carbon storage in the individual coastal ecosystems. There is much evidence to suggest that there are major differences in carbon storage between locations, primarily due to local site conditions. New plantings which are designed to achieve additional carbon dioxide removal therefore only make sense in those regions where optimal growth and storage conditions prevail.

However, it would be wrong to make decisions on the restoration or possible expansion of vegetation-rich coastal ecosystems solely on the basis of their carbon removal potential. Tidal marshes, seagrass meadows, mangrove forests and kelp forests offer a long list of existential co-benefits. For instance, they produce oxygen, purify water, provide habitat and food for animals and plants, slow down waves and currents, protect the coasts from erosion and provide many millions of people all around the world with food, wood and an array of income opportunities.

Investments in their protection and in the restoration of destroyed marine meadows and forests therefore generate dual benefits. They help to offset emissions while simultaneously improving conditions for human communities as well as marine organisms. However, the success of planned projects depends not only on whether they are professionally designed and implemented. It is similarly critical to involve the local communities in project planning and all-important decision-making processes. Without their support, as experience from many parts of the world has shown, restoration projects on land and at sea are doomed to fail.