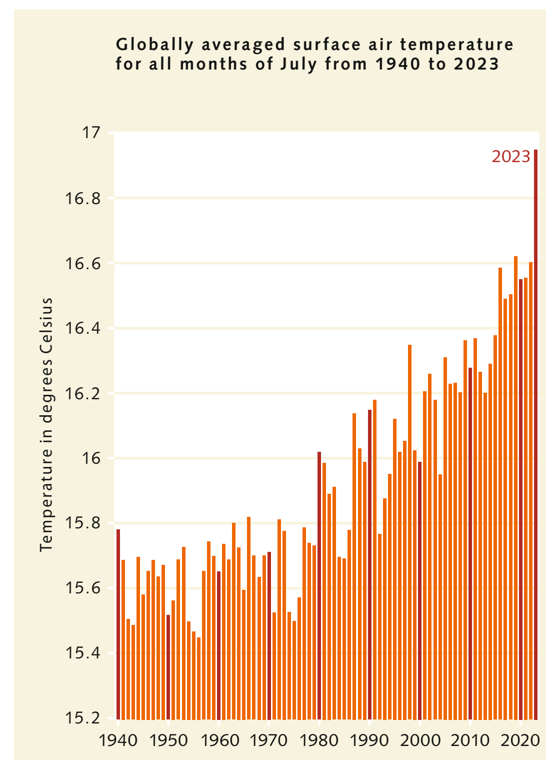
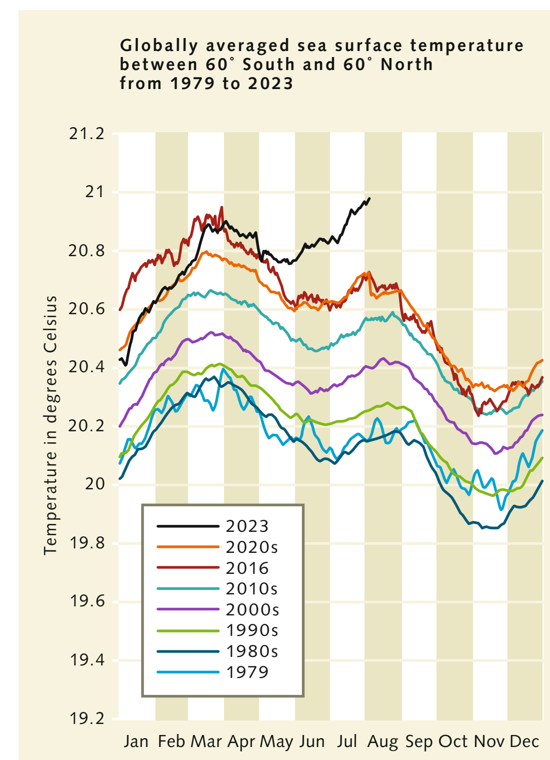
world ocean review
Living with the oceans. 2024

8

The Ocean – A Climate Champion? How to Boost Marine Carbon Dioxide Uptake

Summer 2023 in the northern hemisphere brought the alarming news and nightmare scenarios that climate researchers have been warning about for decades. With daytime temperatures climbing as high as 50 degrees Celsius and beyond, some regions of China and the southern United States resembled a giant hothouse where people and animals could only survive by seeking out cooler niches. Japan, China, South Korea and the north-western USA experienced extremely heavy rainfall, causing streams and rivers to burst their banks; many





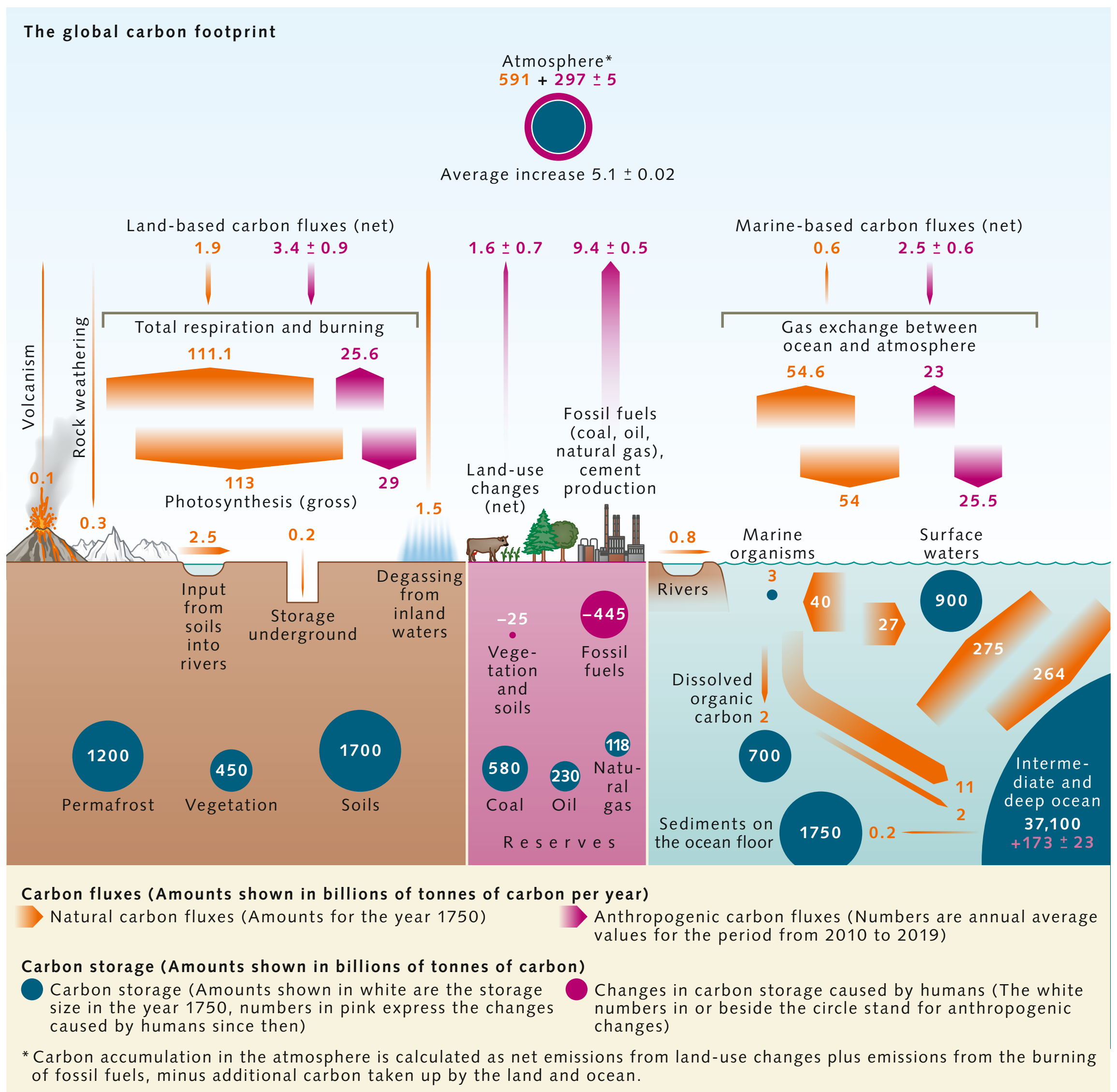
> July 2023 was the hottest month ever recorded (as of: autumn 2023). For the first time ever, the globally averaged surface air temperature exceeded 17 degrees Celsius. The month also set a new record for the highest global sea surface temperature outside the polar regions, at 20.96 degrees Celsius.

Overall-Conclusion

people were swept to their deaths by the floodwaters. Meanwhile, in some areas of the Mediterranean where summer temperatures soared to life-threatening levels, fire services and volunteers battled recurrent forest fires which forced thousands of locals and holiday-makers out of their homes.

A succession of extreme weather events that occurred not as one-offs but in parallel in numerous regions of the northern hemisphere: by mid-July 2023, the World Meteorological Organization (WMO) was describing this striking concurrence as a summer of extremes. A far more telling comment from the weather experts appeared as an aside in the WMO's statement, however: in a world impacted by climate change, extreme weather on the scale observed will become the new normal.

Climate change is now a feature of everyone's daily lives and has long been harsh reality. At least half the world's population is already suffering the direct effects of global warming, particularly population groups which lack the financial resources, technical capacities and political support that would enable them to take the necessary precautionary measures. Simultaneously, already ravaged ecosystems are increasingly failing to deliver their services. This much is clear: the climate and nature make no compromises. For humankind, combating climate change is thus a matter of survival. Climate change is proving to be a potentially lethal risk multiplier – and its destructive potential, as everyone is surely aware, increases with every additional tenth of a degree of warming.



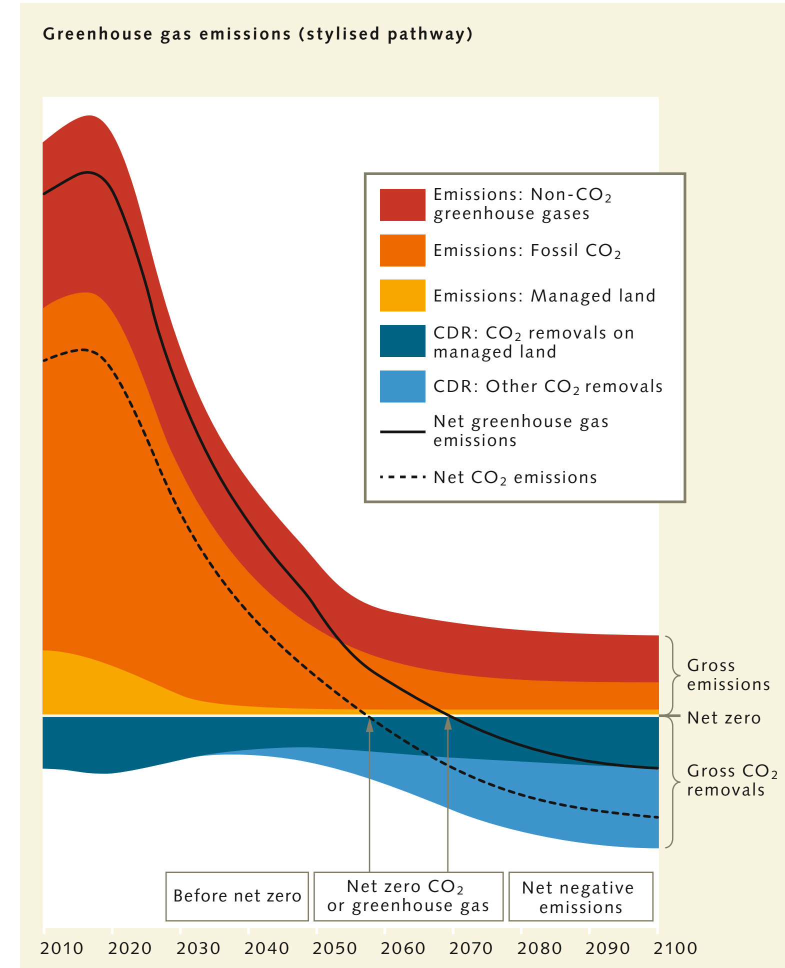
> Figures for the global carbon footprint: Anthropogenic carbon dioxide fluxes are shown in pink. They are the reason that carbon dioxide is being enriched in the atmosphere and why the Earth's temperatures are rising.

The only way out – a greenhouse gas-neutral future

Stopping all anthropogenic greenhouse gas emissions is the only way out of this self-induced climate crisis. This applies particularly to emissions of climate-impacting gases, namely carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). They are released into the atmosphere when we extract fossil resources such as oil, natural gas and coal and burn these fuels to generate energy; when we engage in intensive arable and livestock farming; when we send our waste to garbage dumps; when we slash and burn the forests; and when we drain wetlands or perform industrial processes such as cement production. If global warming is to be kept to 1.5 degrees Celsius by 2100 relative to preindustrial levels – the best-case scenario – carbon dioxide emissions must be reduced to net zero by the year 2050. All other greenhouse gas emissions must decrease drastically at the same time – ideally also to net zero. In this scenario, the global goal of greenhouse gas neutrality would be achieved by 2050.

There is an abundance of suggestions for how we can avoid a significant proportion of our emissions. However, these suggestions are not being implemented consistently or on the required scale. At the same time, experts now agree that it will certainly not be possible for humankind to eliminate all greenhouse gas emissions on time and in an equitable and sustainable manner, even if great effort is invested in achieving that goal. Some human activities will continue to produce substantial residual amounts of carbon dioxide, methane, nitrous oxide and other greenhouse gases beyond 2050. These residual emissions will have to be offset; in other words, we will have to remove an equivalent amount of climate-impacting carbon dioxide from the atmosphere and store it securely for time periods ranging from decades to thousands of years. Experts are predicting that the targeted removal of hundreds of billions of tonnes of carbon dioxide from the atmosphere will be necessary by the end of this century if global warming is to be kept to well below 2 degrees Celsius. This is a challenge of such magnitude that it is almost impossible to convey it in words.

It is important to note that the term "carbon dioxide removal" (CDR) should only be applied to methods involving the capture of carbon dioxide from the



> The active removal of carbon dioxide from the atmosphere will be necessary to reduce net anthropogenic emissions in the short term, to achieve the goals of carbon-dioxide and greenhouse gas neutrality in the intermediate term, and in the long term to reduce the carbon dioxide concentration in the atmosphere by negative emissions.

Overall-Conclusion

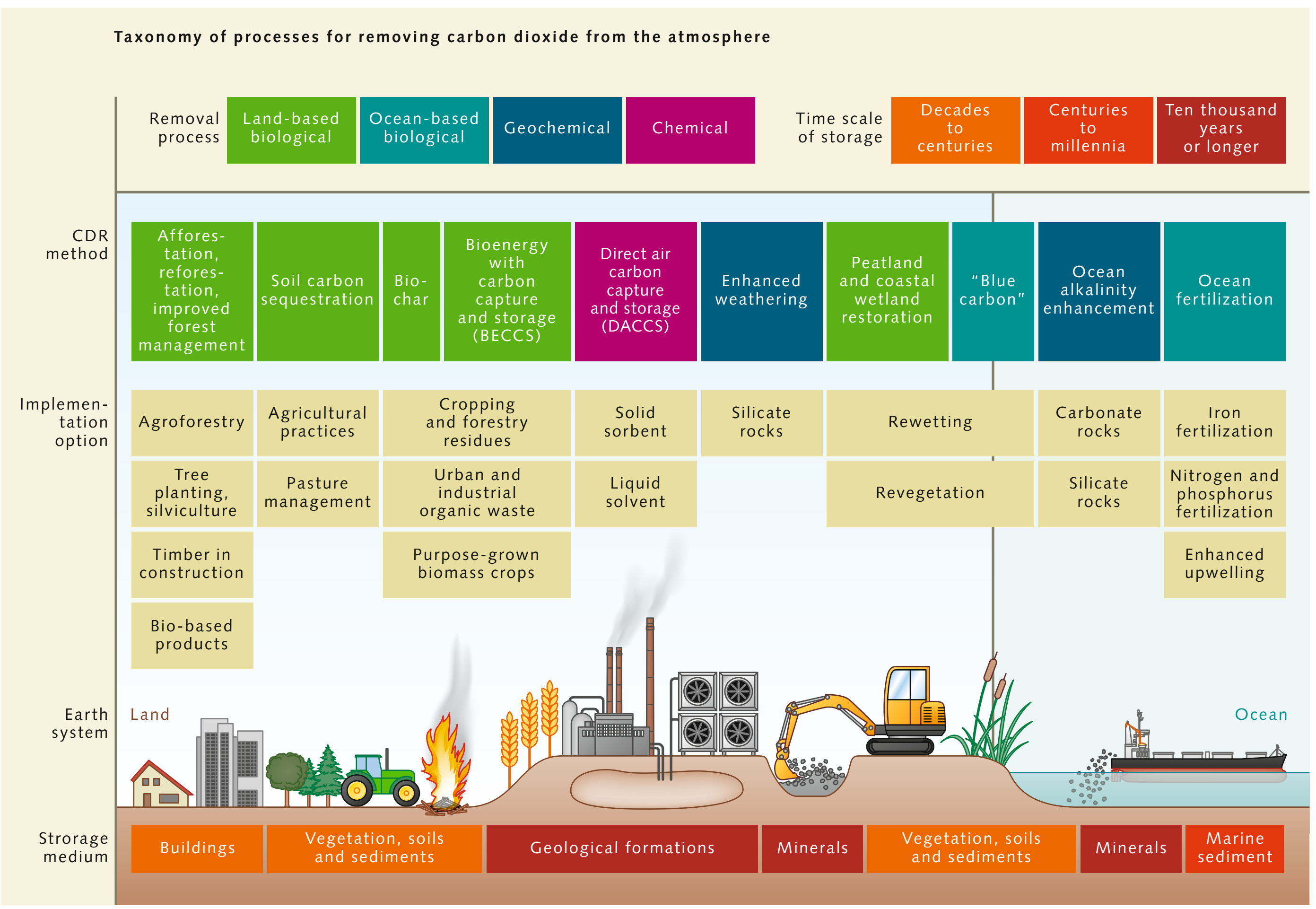
atmosphere and its subsequent permanent storage; such removal must also result from human efforts and be additional to natural CO_2 uptake processes.

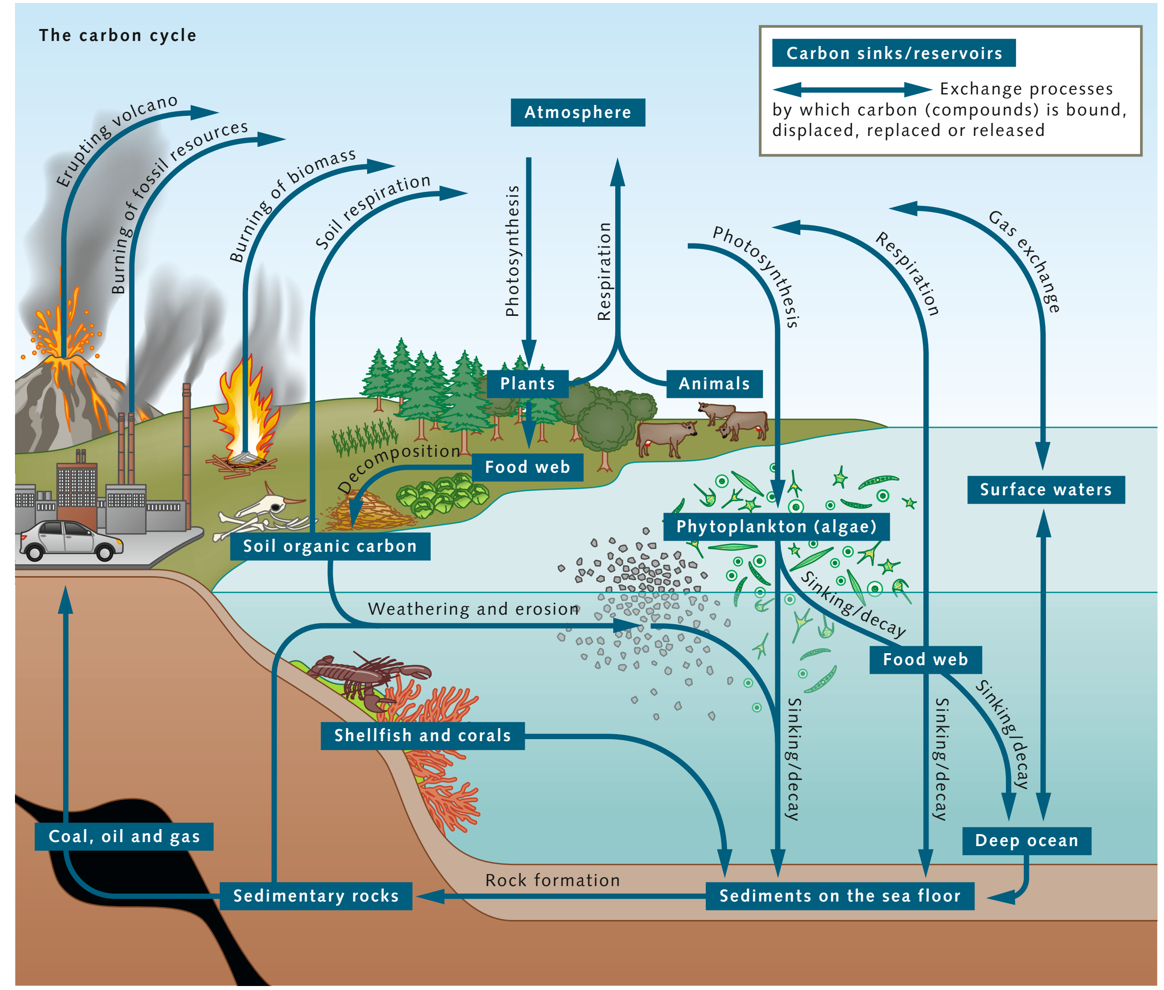
The ocean – a carbon dioxide uptake champion

The Earth's climate system uses physical, chemical and biological processes to extract carbon dioxide from the atmosphere and store it on land, in the seas or in the geological subsurface. The world ocean employs these processes so extensively that it has been able to moderate major changes in atmospheric CO_2 concentration throughout the course of the planet's history. These equilibration processes, however, occur over time spans of millions of years. Because of its natural ability to absorb carbon dioxide, the ocean is pivotal to the global carbon cycle. It contains around 40,000 billion tonnes of carbon, the largest proportion of which is dissolved in the seawater. The ocean is thus the second largest reservoir of carbon on the planet.

There is a continuous exchange of carbon between the ocean and the atmosphere. Every year, more than 150 billion tonnes of carbon pass back and forth in the form of the greenhouse gas CO_2. Because CO_2 concentrations in the atmosphere are increasing due to anthropogenic emissions, the oceans are absorbing more CO_2. In recent decades, the world ocean has absorbed around 25 per cent of the anthropogenic carbon dioxide emissions from the atmosphere, thus significantly inhibiting the progress of global warming. However, this carbon dioxide uptake has resulted in large-scale acidification of its water masses.

> Processes of carbon dioxide removal from the atmosphere could be employed both on land and in the ocean. This figure shows the different approaches, sorted by type of removal and by subsequent storage medium.





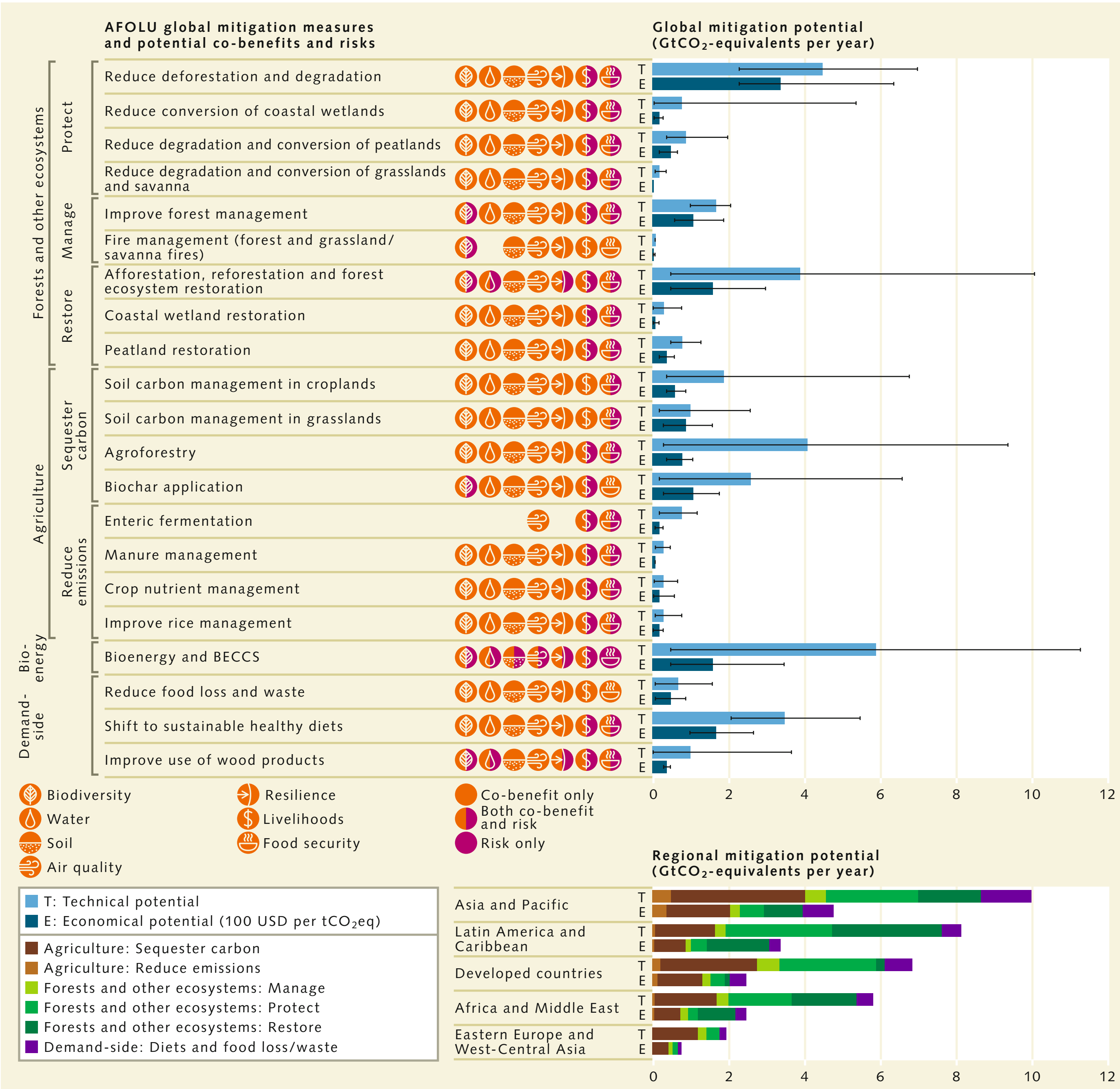
> The Earth's natural carbon cycle: Carbon sinks, or reservoirs, in which carbon or one of its many compounds are stored, are shaded in blue. The arrows represent exchange processes through which carbon or one of its many compounds are bound, stored, exchanged or released.

The untapped potential of soils and terrestrial vegetation

Only in the last ten years or so has targeted action to enhance the ocean's natural carbon uptake been the subject of more intensive debate. Previously, all hopes rested on the carbon dioxide uptake capacity of soils and terrestrial vegetation. These terrestrial carbon stores are much smaller than the oceanic carbon stores. Even so, their carbon fluxes play a key role in the current climate crisis. Firstly, humans have always contributed to the depletion of natural terrestrial carbon stocks through land-use change. This depletion occurs wherever forests are cleared (slash-and-burn), wetlands are drained, natural grasslands are converted to arable land and soils are depleted by intensive agriculture. Each of these activities involves the burning or decomposition of organic matter, thus creating and releasing greenhouse gases. And secondly, the world's terrestrial vegetation and soils still function as a carbon sink, i.e. they continue to absorb more atmospheric carbon dioxide and store the carbon it contains than they release through counteracting processes.

Based on this knowledge, various solutions have been developed that can largely prevent further greenhouse gas emissions from land-use change, increase the size of the carbon sinks formed by soils and terrestrial vegetation, and offset any residual emissions from human activities. Not all these measures are without risk, and competition

Overall-Conclusion



> Sustainable land use and the proper use of land-based carbon removal techniques would yield benefits for climate, people and nature. This overview shows the extent to which greenhouse gas emissions could be prevented or compensated for by means of 21 selected land-based methods. It also shows the estimated annual mitigation potential at a carbon price of 100 US dollars per tonne of carbon dioxide equivalents. Potential co-benefits and trade-offs arising from the implementation of the mitigation measures are summarized in the round icons for each of the 21 measures. What is striking is that the mitigation potential is greatest in Asia and the developing Pacific region.

for the required land and water resources is fierce in some places. Properly implemented, however, known land-use methods could achieve roughly 20 to 30 per cent of the emissions reductions and carbon dioxide removal needed by 2050 to keep global warming to below two degrees Celsius in the long term. But thus far these measures have been implemented on far too small a scale.

Research under time constraints and massive expectations

Given that far too little progress has been made on emissions avoidance and land-based carbon dioxide removal, the scientific community, policy-makers and the private sector are now searching for ocean-based solutions – while facing ever more time constraints and expectations. As many of the stakeholders involved in this research are pursuing commercial interests, a code of conduct has been produced for these scientific activities. Its purpose is to guarantee transparency and prevent unintended negative developments. As another new feature, major research projects on marine CDR procedures now apply an interdisciplinary approach from the start.

They investigate not only key aspects of natural science but also relevant economic, legal, social and political issues and processes and the interactions between them. It is already clear that if the ocean is to make a significant contribution to offsetting residual emissions, small-scale CDR measures will not be sufficient. Instead, a new carbon dioxide removal industry will need to be established, which will change the appearance of the landscape in affected marine and coastal regions accordingly. It will also require massive human intervention in the ocean's natural processes across large areas and for a long period of time.

Three categories of ocean-based CDR methods

There is scope to enhance carbon dioxide uptake by the ocean using a variety of CDR methods. Biological methods are based on photosynthesis: here, algae and marine or coastal plants break down carbon dioxide, convert the carbon that it contains into organic compounds and store it in the form of biomass. Chemical methods rely on a chemical equilibrium reaction which starts when carbon dioxide dissolves in seawater. In the process, the carbon it contains is bound chemically so that in the best case, it stays in the ocean for many thousands of years. With geochemical methods, by contrast, carbon dioxide is liquefied or dissolved in water and then injected into geological formations deep under the ocean floor. However, this form of carbon dioxide storage only qualifies as a removal method if the stored CO_2 has been extracted from the atmosphere – which is rarely the case at present. In current subsea carbon dioxide storage projects, almost all the sequestered carbon dioxide comes from fossil sources, having been captured during the extraction of natural gas, in industrial or combustion processes such as cement or steel production, or in waste incineration. Storing this carbon dioxide merely prevents its release; it does not allow for any offsetting of residual emissions.

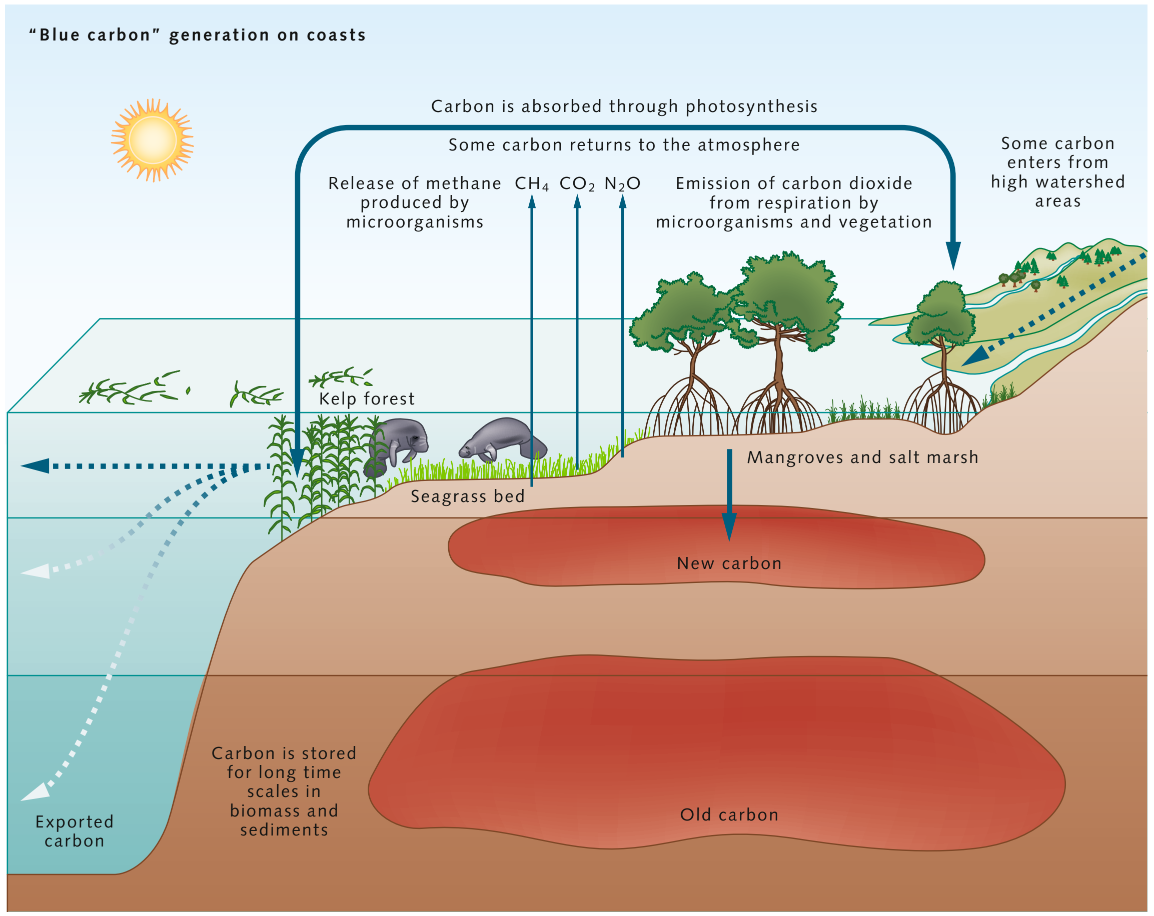
Coastal ecosystems – marine carbon sinks providing indispensable additional services

The world's tidal marshes, seagrass meadows, mangroves and kelp forests make a significant contribution to natural capture and storage of carbon dioxide by the ocean. Many coastal ecosystems store far more carbon underground than terrestrial forests. However, marine forests and meadows can only lock away the carbon securely as long as they continue to thrive. By conserving coastal ecosystems, we prevent the degradation of their carbon stocks and thus the release of large quantities of greenhouse gases. At the same time, planting new marine meadows and forests or restoring damaged ecosystems offers hope of enhancing their natural carbon dioxide uptake in such a way that residual emissions can be offset.

The size of the carbon dioxide removal potential of coastal ecosystems is a matter of debate. One unanswered question, for example, is the level of carbon storage in individual marine meadows and forests. There is much evidence to suggest that carbon storage depends on local environmental factors and varies greatly from place

Overall-Conclusion

> 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.

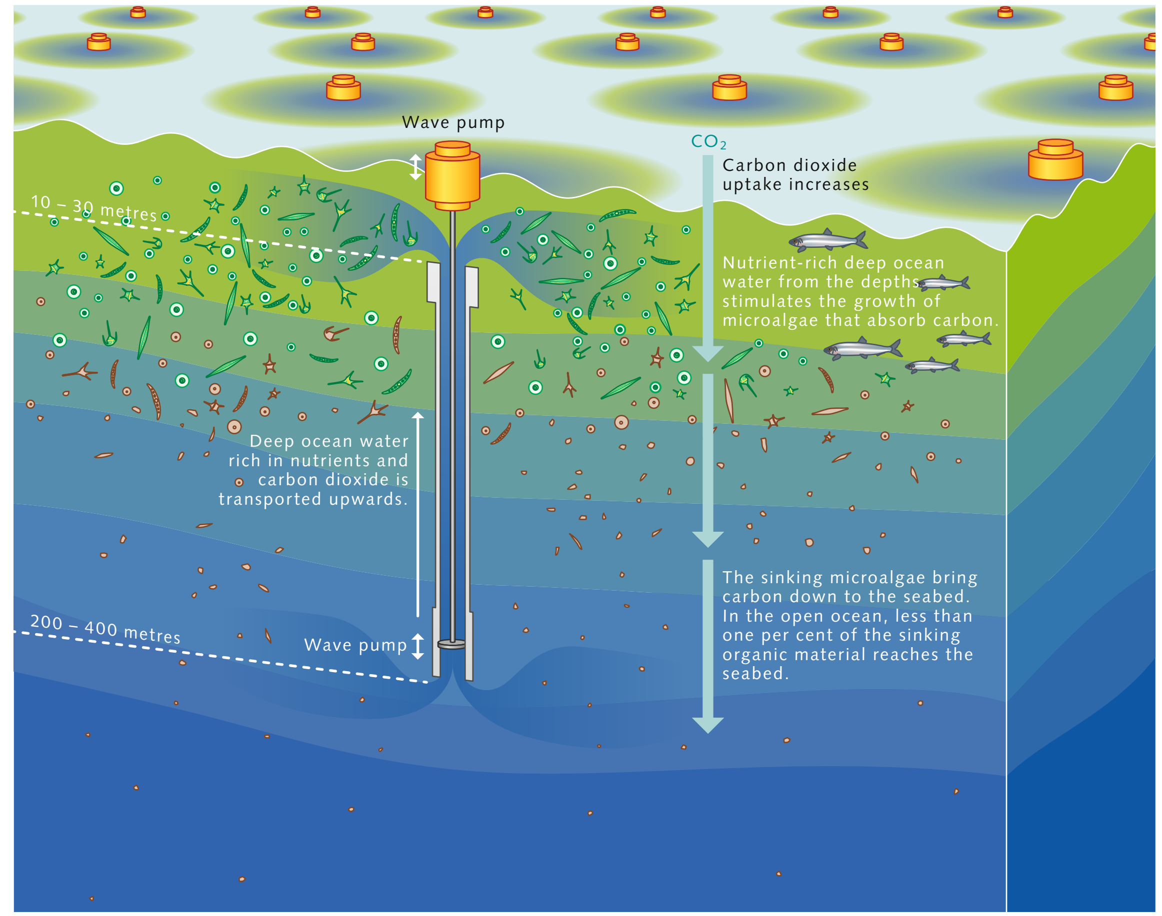


to place. New plantings aimed at removing additional carbon dioxide from the atmosphere therefore only make sense in locations with optimal growth and storage conditions.

Nevertheless, it is essential to invest in the conservation and restoration of destroyed coastal ecosystems in other locations as well, for a multitude of reasons. Many of their co-benefits are vital for humankind's survival. Tidal marshes, seagrass meadows, mangroves and kelp forests produce oxygen, clean water, provide habitat and food for animals and plants, protect the coasts from erosion and provide millions of people with food, wood and an array of income-generating opportunities. Wherever coastal ecosystems are restored or expanded, there is potential to generate dual benefits for society – from additional carbon dioxide removal and from renewed availability of ecosystem services. However, the success of planned restoration and expan-sion projects depends in part on how local communities are involved in all the relevant decision-making pro-cesses. Without their support, these project are doomed to fail.

Artificial upwelling – of limited utility

"Artificial upwelling" is the term used to describe processes that aim to transport nutrient-rich deep ocean water to the sea surface in order to boost the growth of microscopic algae and thus the ocean's biological carbon pump. However, to function as a negative emission technology the boosted food web must bind and sequester more carbon in the depths of the ocean than outgasses at the surface from the mostly carbon dioxide-rich deep ocean water upwelled to the surface – a requirement that can presumably only



> A variety of methods can be used to generate artificial upwelling. One idea is to deploy tube-like wave pumps in the ocean. They have a surface buoy at the upper end that rises and falls, following the wave motion. The motion transfers to a pump in the upwelling tube which then lifts the deep ocean water to the surface.

be met under very specific conditions, which is why the potential for additional carbon dioxide removal via these processes is considered to be quite limited.

There is also continued uncertainty as to the technical means by which artificial upwelling can be generated on a climate-relevant scale, what risks the processes entail for the marine environment and what kind of regulatory framework would be required for large-scale deployment in future. The operation of thousands of pumps would presumably severely restrict other forms of marine use.

So far, the use of artificial upwelling would appear to only make sense and be economically worthwhile as an aid in kelp farming. The harvested algae are currently used mainly as a food- or feedstuff and as an additive in the manufacturing of various products, however. Techniques for targeted carbon dioxide removal through increased kelp farming are still at the research and development stage.

Alkalinity enhancement – understood in theory but insufficiently tested in the field

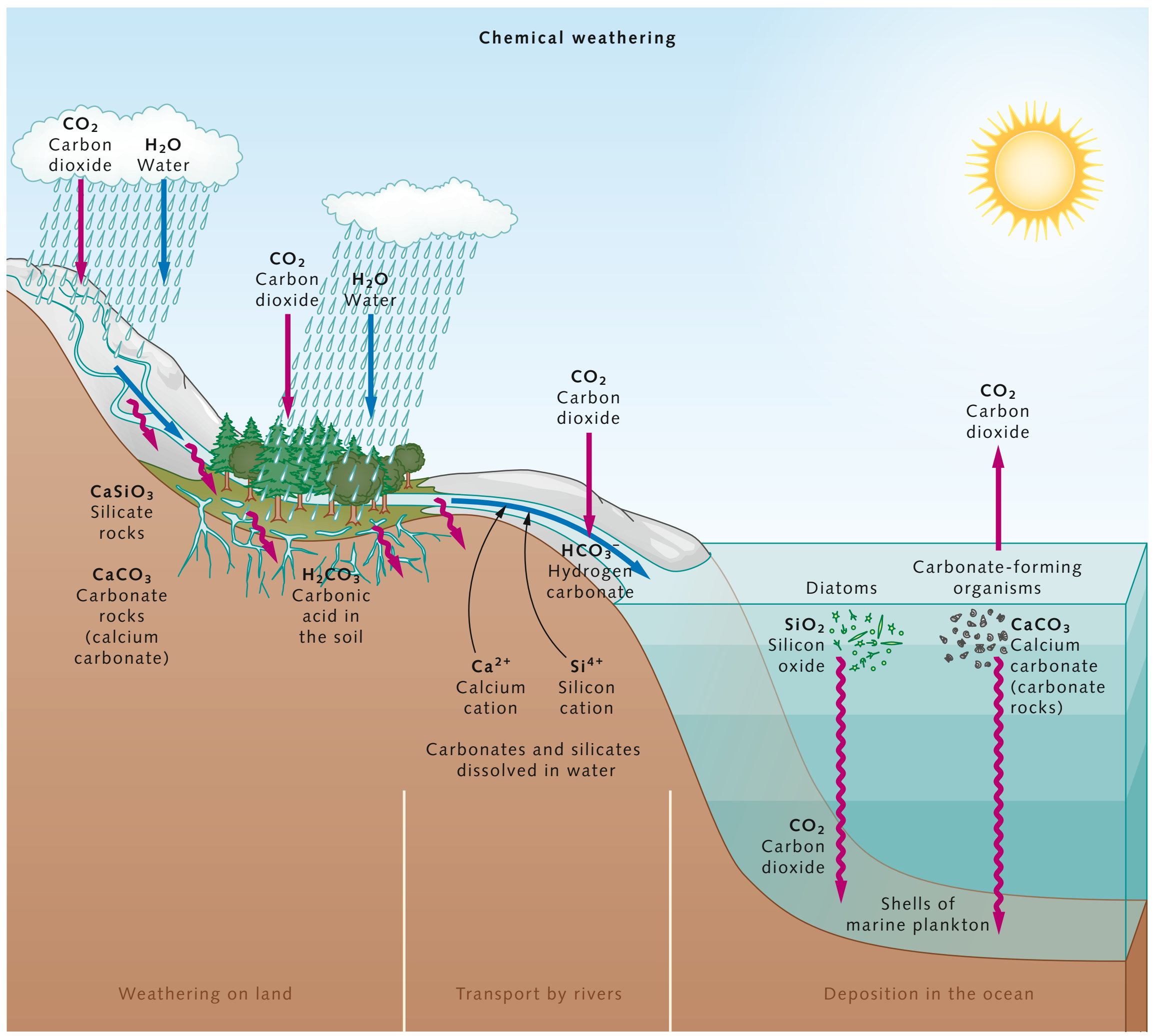
Dissolution products from the natural weathering of rocks increase the ocean's acid-binding capacity (alkalinity). They thus enable chemical bonding of dissolved carbon dioxide in the ocean and the subsequent absorption of new carbon dioxide from the atmosphere. This natural process of climate regulation could be selectively accelerated if large amounts of limestone and silicate rocks were mined and distributed in the sea in the form of rock flour or alkaline solutions. Such alkalinity-enhancing

Overall-Conclusion

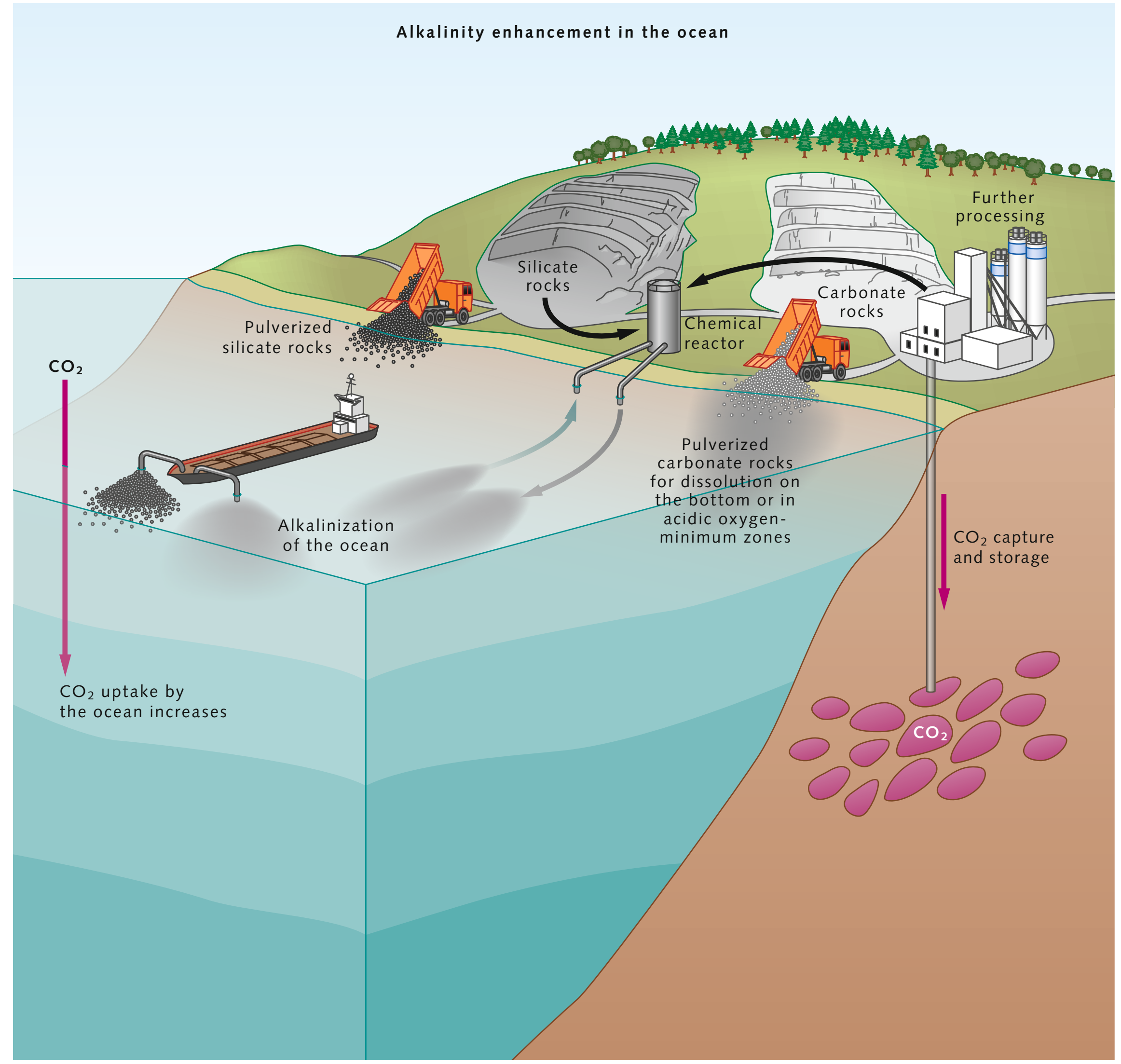
processes would also have the benefit of reducing acidification in the treated water masses and improving the living conditions for many marine organisms.

The chemical processes involved in a targeted programme of alkalinity enhancement of the ocean are now well understood. Its technical feasibility, however, is difficult to assess because most of our knowledge comes from computer simulations and small-scale laboratory experiments. Large-scale field experiments are still lacking. In the laboratory, researchers are now testing various naturally occurring and artificially produced minerals for their suitability and weathering properties. At the same time, studies are being carried out on the possible environmental impacts and risks, about which very little is currently known. Specialists are also working on electrochemical methods of alkalinity enhancement. While these methods require a substantial amount of energy – which should of course come from renewable sources – they could be applied without rock material.

If the currently known chemical methods of alkalinity enhancement were applied worldwide, it is estimated that an additional 100 million to more than a billion tonnes of carbon dioxide could be removed from the atmosphere annually. However, this would be countered by new greenhouse gas emissions generated in the quarrying, transporting and processing of the rocks.



> The alkalinity of seawater is determined by two fundamental processes: first, by the introduction of dissolved, acid-binding dissolution products of rock weathering; and secondly, by the natural uptake and further processing of these dissolution products by marine creatures such as calcareous organisms (carbonates) or diatoms (silicates). In the formation of carbonate minerals ($CaCO_3$) a portion of the bound carbon dioxide (CO_2) is released again.



> For two of the promising methods for enhancing the alkalinity of the ocean, limestones or silicate rocks must be mined on land and ground into rock powder. The carbon dioxide emissions from these processes would have to be captured and stored. Otherwise, the methods would not have a meaningful positive impact on climate.

Subsea carbon dioxide storage – an up-and-coming but controversial method

Carbon capture and storage (CCS) technologies will have a vital role to play if the goal of global greenhouse gas neutrality is to be reached by 2050. Firstly, they prevent the release of carbon dioxide from fossil sources. Secondly, CO_2 removal methods such as the much-discussed Bioenergy with Carbon Capture and Storage (BECCS) process can only help to offset residual emissions if it captures carbon dioxide produced during combustion. The CO_2 must then be processed into long-lived products such as carbon fibre or be securely stored.

The number of carbon capture facilities in operation worldwide is increasing; the majority of them capture carbon dioxide from fossil sources. The question, however, is where the captured CO_2 should be stored over the long term. Experts assume that most of the gas will have to be stored underground. This is only technically feasible in rock strata that are sealed by an impermeable surface layer, preventing the carbon dioxide from escaping from these deep formations.

Overall-Conclusion

Onshore, geological carbon dioxide storage projects often encounter local opposition. Experts are therefore searching for geological formations that would be suitable as deep subsea storage sites. Sandstone formations and the porous upper basalt layer of the oceanic crust can potentially be considered here. Technologies for carbon dioxide storage in sandstone formations have been deployed successfully since 1996. At present, the only place where carbon dioxide is injected into the upper oceanic crust is Iceland, where the basalt protrudes above the surface of the sea and is within easy reach. By contrast, relatively little is known about the storage potential of basalt formations in the ocean floor. This is currently being studied in various research projects.

A key difference can already be discerned, however: carbon dioxide that is injected into sandstone may, under certain conditions, remain in the rock's pore water for many thousands of years before mineralization takes place, securely binding the carbon dioxide in solid form. In highly reactive basalt, by contrast, mineralization occurs far more rapidly.

Nevertheless, CO_2 storage in the ocean floor is not without risk. Storage sites must be extensively surveyed, selected with care and then monitored over long periods using technologies that are as eco-friendly as possible (keyword: noise pollution). Furthermore, carbon dioxide injection in one area of the sea may restrict other forms of marine use throughout the affected region. Cross-sectoral coordination of these storage projects is therefore essential.

Mechanisms for storing carbon dioxide in the deep subsurface

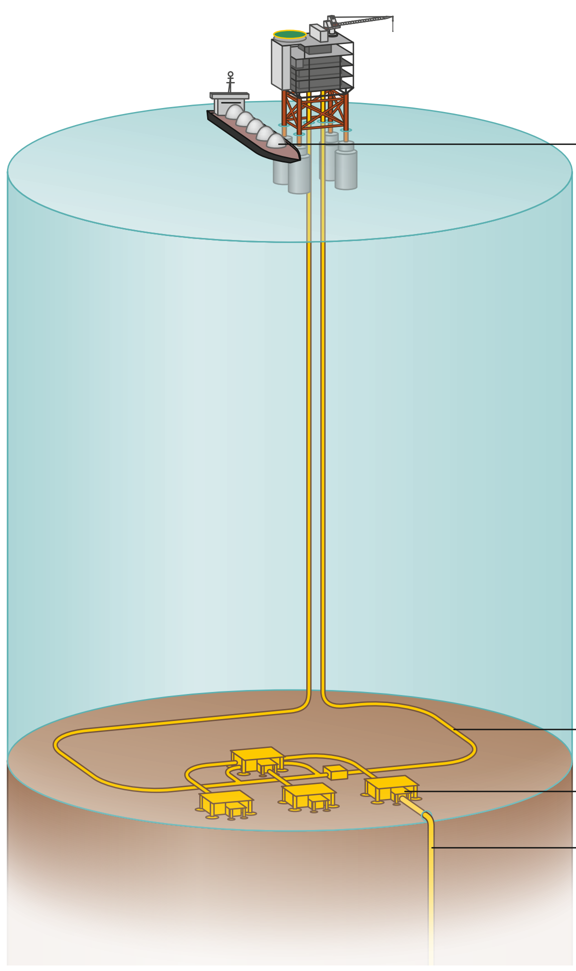
Structural trapping
An impermeable cap rock prevents the carbon dioxide from escaping upward from the reservoir rock.

Capillary/residual trapping
A large part of the CO_2 is trapped in the pore spaces between sand grains.

CO_2 dissolution
Over time, the injected CO_2 dissolves in the salty pore waters of the reservoir rock. The CO_2-rich water becomes heavier and sinks downwards.

Mineralization
The carbon dioxide dissolved in water reacts with minerals contained in the reservoir rocks, is transformed to dissolved bicarbonate, and is finally precipitated in the form of carbonate minerals. The former carbon dioxide is then firmly bound within these.

The stored CO_2 must be monitored using a variety of technologies during and after injection.



> Four mechanisms contribute to the feasibility of carbon dioxide being stored in deep-seated rock formations. The gas is not truly safely stored, however, until it dissolves in the pore waters and is ultimately mineralized.

Key principles for the governance and regulation of possible CDR
In view of the increasingly dramatic impacts of climate change, we must do our utmost to keep global warming to a minimum. Emissions avoidance must take the highest priority, but the use of promising ocean-based CDR methods is likely to have a role to play in the long term as well. They are not the only solution to the climate crisis, however, but must form part of a broader plan on managing residual emissions.

If ocean-based CDR methods are used, this will impact an ocean that is already subjected to diverse forms of human use and exploitation. In order to protect the ocean and guarantee fair burden-sharing, carefully considered national and international CDR strategies are therefore required, with clear targets and rules for all stakeholders. Experts have developed initial principles for the governance and regulation of land- and ocean-based CDR methods. In their view, in addition to prioritizing emissions avoidance, it is important to ensure prior to deployment that, firstly, the carbon dioxide removal is permanent and the interventions will not emit more new greenhouse gases than the quantity of carbon dioxide removed from the atmosphere. And secondly, the methods must be comprehensively assessed in advance from a climate, environmental and social perspective and possible goal conflicts avoided or resolved; this must be achieved in a sustainable and equitable manner.

Depending on the CDR method used, an array of technical installations and infrastructures would also be required, such as CO_2 pipelines, transport ships and storage sites for injection into deep subsea formations, as well as reactors for accelerated weathering of rock and capture systems for the direct removal of carbon dioxide from ambient air. These infrastructures may well take years to construct. In reality, however, their construction would need to be completed swiftly if CDR methods are to be used to remove carbon dioxide from the atmosphere by 2050 in the very large quantities required under the climate scenarios in which we reach our climate targets.

As all the regions of the oceans are connected by currents, a harmonised regulatory framework for ocean-based CDR deployments would be required at the international level. In the experts' opinion, there is little sign at present that the international community will agree on a common, overarching regulatory framework for all forms of CDR. The numerous land- and ocean-based CDR methods vary too much for that. Proposals on separate regulation of ocean-based CDR methods appear more promising. The London Protocol shows how this might work. This legislation has been extended in recent years to include "marine geoengineering". Provisions on ocean fertilization and carbon dioxide storage in sub-seabed formations have already been integrated into the Protocol as well. There is scope for similar integration of regulations on other CDR methods involving the introduction of substances or technologies in the sea.

Harmonized procedures for accurately monitoring, documenting and verifying carbon dioxide fluxes in land- and ocean-based removal projects are also urgently required. Monitoring can reduce legal uncertainties and prevent abuse while offering scope for certification of permanent carbon dioxide removals. If certification comes with economic benefits, this would encourage companies and other stakeholders to invest in ocean-based CDR projects.

At the same time, we need a broad public debate about the possible use of marine CDR procedures. So far, this debate has merely involved scientists, some sectors of the economy and a small number of political institutions. For a multitude of reasons, strong public engagement is a key prerequisite for successful climate change mitigation, however. In the case of ocean-based CDR methods, this applies particularly to the coastal population in whose immediate vicinity CDR methods would be deployed or in whose neighbourhoods some of the required technical installations would be established.

It is already certain that these deployments will not be entirely without risks or consequences. For that reason, careful consideration of trade-offs is required in all decision-making, with due regard for the needs of people, climate and nature alike. This is an immensely challenging task. However, the time for simple solutions is long gone, due to our failure to take action on climate change.