world ocean review

Living with the oceans. 2024

8

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

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Published by
maribus in cooperation with

future ocean
KIEL MARINE SCIENCES

KDM
Konsortium Deutsche Meeresforschung
German Marine Research Consortium

mare

world ocean review

Living with the oceans. 2024

8
The Ocean – A Climate Champion? How to Boost Marine Carbon Dioxide Uptake

Preface

The more comprehensive our knowledge, the more we recognize its complexity. This is particularly the case for our oceans. Marine research is a relatively young science, and due to the numerous interconnections between physical, chemical and biological processes in an inaccessible and technologically inhospitable environment, our knowledge has developed more or less exponentially in step with modern research in recent decades. Half a century ago, the information that we gathered about the seas was primarily descriptive in nature, whereas today we are increasingly coming to understand the interactions between the oceans and the effects of the Anthropocene.

In the process, we must acknowledge that human activities are having a more serious impact on the marine ecosystem than we would have predicted half a century ago. Nothing poses a greater risk to the oceans and therefore to our planet than anthropogenic climate change. Our modern society's carbon dioxide emissions are causing acidification and warming of the seas, leading to major, practically irreversible changes. Never before in human history has our intervention in our ecosystem had such serious, indeed existential consequences as those currently resulting from our greenhouse gas emissions, and never before have we played God – omnipotent and absolute – on such a scale. If the warming of the Earth continues at the present rate, a collapse of nature and society is inevitable. However, in order to achieve the target of 1.5 degrees Celsius stipulated by science, we must once again resort to methods which are equally impactful and existential. The truth is that an immediate reduction of emissions to zero is no longer sufficient; the active removal of carbon dioxide and its secure storage on land or in the seas now appear to be necessary. We have only just begun to understand the devastating impacts of climate change on the marine environment, and yet here we are, intent once more on intervening in the ocean. And once again, the effects of this are difficult to predict.

If we apply the technologies that are needed and called for to actively store carbon dioxide in the seas, we will once again be acting like a higher power – often, as before, without the requisite knowledge.

I very much hope that this *World Ocean Review 8* will help to enhance understanding of the measures that will unfortunately be necessary and raise awareness of their impacts. Perhaps it will thus assist us to move towards the insight that "softer" biological methods are to be recommended, rather than those whose effects, yet again, are difficult to predict.

Our knowledge has increased, but so too has the complexity of our impact on the ocean. We should have learned by now that our main objective should be to achieve net zero emissions, rather than primarily aiming for a reversal of processes. We have waited too long; we have accepted climate change for too long, or have not recognized that it is happening at all. Our responses now must be all the more circumspect for that.

Nikolaus Gelpke
Managing Director of maribus gGmbH, mareverlag publisher and Patron of IOI

There is a prevailing consensus within the research community and broad sections of society that climate change will have increasingly dramatic consequences for humankind and the planet if we fail to reduce our annual global carbon dioxide emissions. The ocean plays a key role in this context, for it absorbs a substantial proportion of anthropogenic CO_2 emissions from the atmosphere. But for how much longer, and what will the effect of this be? The connection between the ocean and the climate is obvious, while the changes taking place on Earth are being felt more intensely from year to year.

A range of measures are therefore required in order to limit climate change and particularly to reduce CO_2 emissions to net zero. But how can this be done? In addition to achieving the required reduction, can any other effective measures be taken to boost the ocean system's capacity to sequester more carbon from the atmosphere? This future-focused issue is preoccupying researchers in Kiel, Germany, and across the world. In Kiel, the researchers' work transcends disciplinary boundaries and includes cooperation with natural and social scientists, the aim being to identify knowledge-based options for action that would enable sustainable management of the ocean and its resources.

Is active intervention in the marine carbon cycle feasible, effective, efficient and affordable? Which measures are acceptable to society? These bargaining processes and transformational decisions must always be based on sound, accessible and detailed knowledge. And this is provided in a concise form in this WOR 8. It offers an overview of the role of the seas in regulating our climate, with a focus on the marine carbon cycle. This new edition also identifies the options for intervention that are available to us, to humankind – from nature-based solutions to the storage of CO_2 in the deep sea or sea floor.

The themes addressed in WOR 8 will continue to preoccupy us for many years to come. At the international level, they are embedded in the UN Decade of Ocean Science for Sustainable Development, which started in 2021 and focuses on the interface between ocean and climate and on the necessary social transformation processes. Here, the ocean – a source of food for millions of people, a transport route but also a haven of dreams – is a beacon of hope. But for how much longer? There is the prospect of solutions but they are still in their infancy. Yet if we do take countermeasures, this raises the question of knock-on effects, such as ocean diseases, about which surprisingly little is known.

We would like to encourage people to remain positive, to work together and to embrace innovation for the sake of healthy marine ecosystems. The UN Decade of Ocean Science provides an important framework. And the *World Ocean Review* makes a valuable contribution, serving as a basis for a wide range of activities which include the climate negotiations.

Prof. Dr. Martin Visbeck
GEOMAR Helmholtz Centre for Ocean Research, Kiel, Co-Spokesperson of Future Ocean

Prof. Dr. Nele Matz-Lück
Kiel University (CAU)
Co-Spokesperson of Future Ocean

Prof. Dr. Ralph Schneider
Kiel University (CAU)
Co-Spokesperson of Future Ocean

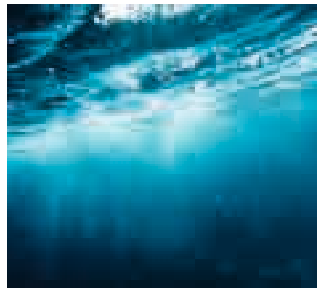
Can the ocean save us from the climate crisis? Surely not! But there are numerous options showing how processes in the oceans can help to enhance its capacity to absorb more climate-harming carbon dioxide (CO_2) from the atmosphere, giving us more time to develop alternatives for reducing our anthropogenic CO_2 emissions. The eighth *World Ocean Review* highlights this potential. The authors describe measures which can be or are already being implemented, as well as those which should be assessed as options in terms of their benefits and possible risks. All the German marine research institutions and organizations are involved in related projects, proving once again that collaboration among the various marine research disciplines is capable of making rapid, viable and sustainable contributions to solving a global problem.

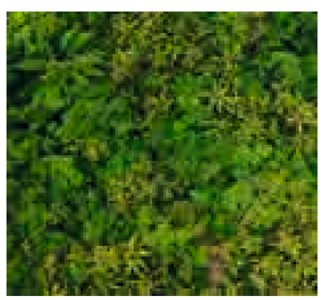
WOR 8 provides an impressive overview of current research in 2023 and also identifies where there are knowledge gaps so that even more robust recommendations can be made to executive agencies. These research projects are funded by the German Research Foundation, the Max Planck Society, the Leibniz Association, the universities and directly or indirectly by the German government and the (North German) federal states. In addition, the German Marine Research Alliance (DAM) has initiated a major research mission with more than 100 team members.

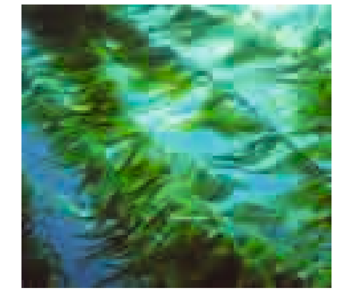
As well as materials, research vessels and other infrastructure, the projects particularly need creative and committed individuals. There is a correspondingly large demand for junior scientists and technical and support staff who are willing to take on these challenges, be it as staff members at our KDM institutes or elsewhere. In our scientific research, we present our findings in such a way as to provide the necessary level of detail for an expert readership. And in the KDM institutes and DAM, we produce information materials in diverse formats (e.g. print, digital, personalized) so that our key findings are available in a clear, concise and accessible form for a cross-section of society.

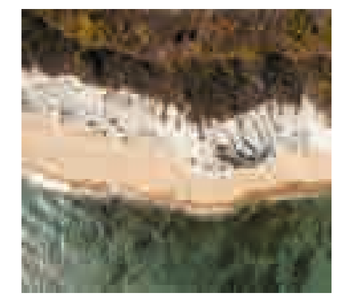
WOR 8 successfully complements this approach. There is a wealth of knowledge available. It is now time to take the action that is so urgently required.

Prof. Dr. Ulrich Bathmann
Director, Leibniz Institute for Baltic Sea Research (IOW), Warnemünde, and Chair of the German Marine Research Consortium (KDM)









1 Urgently sought – ways out of the climate crisis

> We have known for decades that the Earth's atmosphere is warming and the climate is changing, and that this is caused by our emissions of greenhouse gases. Our mindsets, however, have remained unchanged and precious time has been wasted. Only now, with dramatic impacts becoming increasingly obvious, are leaders starting to make serious efforts to find solutions. They are forced to recognize that merely reducing greenhouse gases is not enough to keep climate change within tolerable limits.

Code red for people and nature

> Climate change is now a daily reality. At least half the world's population is already suffering the direct effects of global warming. Wells are drying up, heat levels are becoming unbearable, storms and flood waters are sweeping away goods and property, and already ravaged ecosystems are increasingly failing to deliver their services. The climate and nature make no compromises. For humanity, therefore, everything is at stake, for the change that we ourselves have set in motion is proving to be a potentially lethal risk multiplier.

Our future is at stake

We have known for decades that the Earth's climate is warming, and that this is caused by our greenhouse gas emissions. However, the magnitude of the global climatic changes that have already occurred and the critical situation now facing life on Earth have rarely been described with such urgency as in the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change (IPCC).

On behalf of the IPCC, more than 750 climate scientists from around the world regularly review the current state of knowledge of global climate change. They analyse the findings of research on the causes and effects of climate change, collate information on the extent to which people and nature have the capacity to adapt to the new climatic conditions, and describe measures that may be effective in mitigating climate risks and limiting global warming.

The core message from the three volumes of the IPCC's *Sixth Assessment Report* is very clear: with its persistently high levels of greenhouse gas emissions, humankind is gambling away the prospects of a liveable future for present and future generations.

1.1 > Smoke rises from the chimneys of a Chinese steelworks in Inner Mongolia. Meanwhile, ore is smelted illegally by workers at a nearby camp. China is the world's largest emitter of carbon dioxide (accounting for around 30 per cent of global emissions in 2022), partly because coal is still the country's main energy source.

Rapid warming and its effects on the Earth's climate

According to data from the IPCC, the global surface temperature during the period from 2010 to 2022 was approximately 1.15 degrees Celsius higher than the reference figure for 1850 to 1900. There were much larger increases over land than over the ocean: mean temperatures over the continents rose by 1.65 degrees Celsius, while air masses over the ocean warmed by 0.93 degrees Celsius. Well-informed readers may wonder at these statistics, as the figure for global warming mentioned by other organizations and well-known news outlets since 2020 is 1.2 degrees Celsius. In light of this, it seems reasonable to ask: is the IPCC working with obsolete data? By no means.

Global climate reports such as those produced by the IPCC or the analyses published regularly by the World Meteorological Organization (WMO) focus on long-term changes in climate parameters. In order to determine global surface temperature, therefore, they do not simply analyse the temperature data for a specific year, as these figures may be influenced by short-term natural temperature fluctuations. Instead, the IPCC authors use monitoring data from the previous 20 years as baseline figures. They are thus able to detect the real long-term trend.

And the fact is that global warming is accelerating: in the past 50 years (1970 to 2020), global surface temperature has increased faster than in any other 50-year period over the last 2000 years. A detailed look at the last four decades (1980 to 2020) reveals that each one of these four decades has been successively warmer than the decade that preceded it.

This development means that many of the Earth's climate system components are changing at a speed not experienced by our planet for many hundreds or even thousands of years. However, the magnitude of these changes is not uniform everywhere. Some regions are more severely affected than others. What's more, with every additional tenth of a degree of warming, the changes under way are amplified. This means that the magnitude and extreme speed of the changes, but also the associated risks, will increase with each additional increment of warming, no matter how small. This applies particularly to ocean warming, acidification and deoxygenation; the continued rise in hot extremes over land and in the oceans; the melting of the ice sheets; sea-level rise; and shifts in the Earth's water cycle.

The oceans and seas – more warming, acidification and oxygen depletion

CURRENT STATUS: The oceans and seas are our planet's largest storehouse for heat. This storehouse is being recharged continuously by climate change and the associated warming of the atmosphere. Over the last 60 years, around 90 per cent of the excess heat retained in the Earth's atmosphere due to the greenhouse effect has been absorbed by the oceans and seas and stored in their depths. As a result, ocean heat content has increased significantly and water temperatures are rising more rapidly than at any time since the last glacial period. Sea surface temperature alone has risen by an average of 0.93 degrees Celsius in the period from 1850 to 1900 to 2022. Researchers describe the increase in ocean temperatures as the clearest indicator of human-induced climate change – firstly, because the ocean absorbs the largest proportion of the excess heat, and secondly, because its surface temperatures are subject to less year-to-year fluctuation than the atmosphere, for example. The warming trend is therefore easier to detect.

As the ocean has warmed, stratification of the water masses in the upper 200 metres of the water column has increased. Concurrently, due to increased evapotranspiration from the sea surface, the surface water at evapotranspiration sites, which already has a higher salt content, has become even more saline.

By contrast, in areas of the sea with heavy precipitation or high meltwater inflow, freshwater influx has increased, further reducing the already low levels of near-surface salinity here.

Both these trends – increased stratification of the water masses, and changes in salinity – have, since the 1950s, reduced the density-dependent mixing of surface water with the underlying water masses, thereby amplifying ocean deoxygenation. Oxygen depletion is particularly noticeable in the oxygen minimum zones which are forming in the Western Pacific, the Indian Ocean and off the west coast of Southern Africa below the surface layer, i.e. in water depths between 100 and 200 metres. In these zones, the seawater contains less than 70 micromoles of oxygen per kilogram (µmol/kg), which means that marine fauna such as sharks and tuna, which rely on a plentiful supply of oxygen, have no chance of survival here.

The oceans and seas do not just absorb heat, however; they also take up around a quarter of the carbon dioxide generated by human activity. But unlike oxygen, carbon dioxide does not simply dissolve in seawater: it undergoes a chemical chain reaction which increases the water's acidity. This process of ocean acidification has highly detrimental effects on the habitat conditions of many marine organisms. Experts refer to a reduction in pH as the measure of the ocean's acidity. According to the IPCC, in the last 40 years, ocean surface pH has decreased in almost all areas of the sea – to such an extent that oceanic acidity is now at its highest level for at least 26,000 years. What's more, ocean acidification appears to be taking place with record-breaking speed at present. Making matters worse, acidification is no longer affecting surface water alone; in the last 30 years, it has been detected with increasing frequency in the deeper ocean as well.

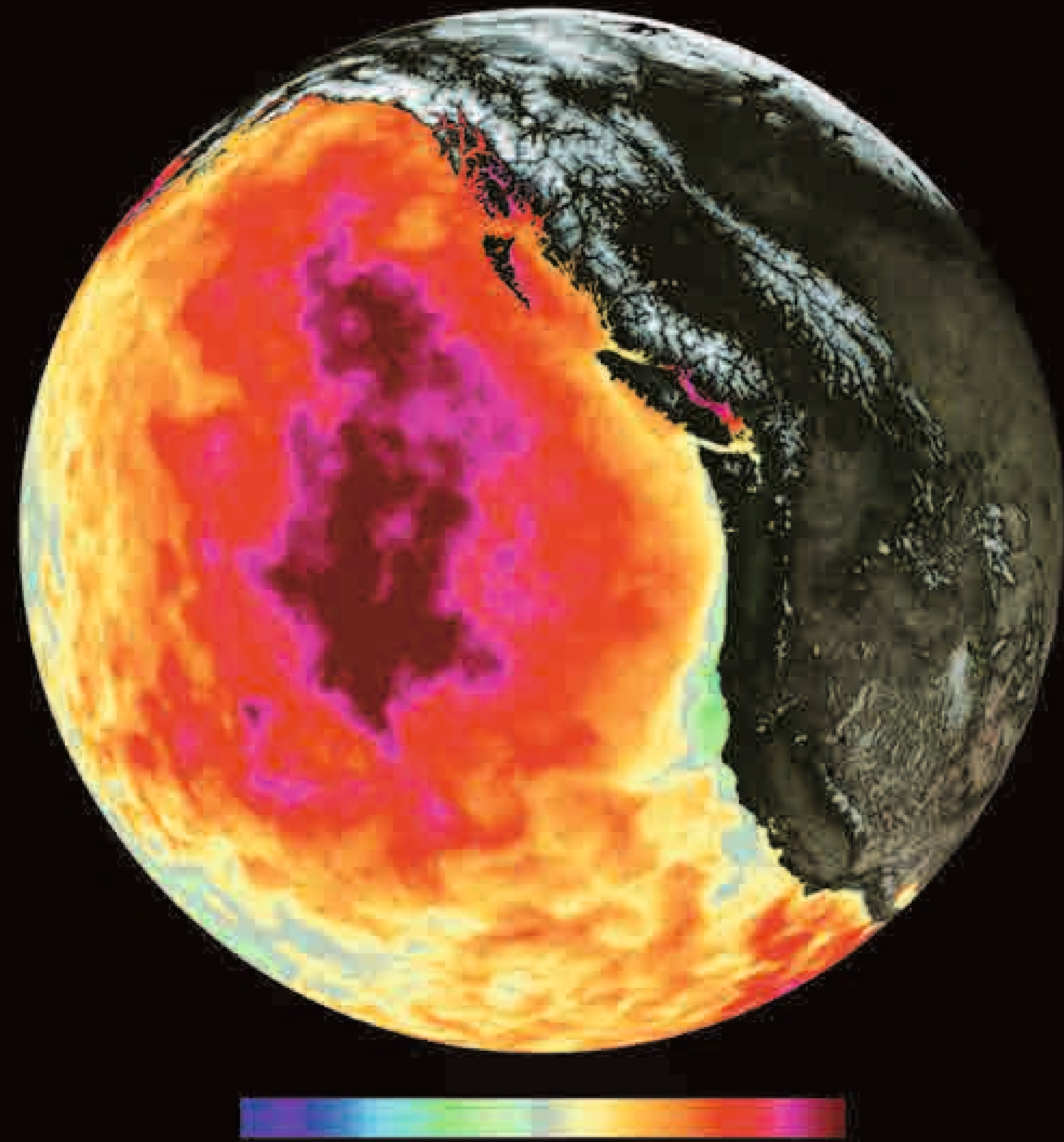
OUTLOOK: The temperature of the oceans and seas will continue to increase even if humankind succeeds in limiting global warming to 1.5 degrees Celsius. This can be explained by the inertia of the ocean system: key processes take place so slowly that the effects of any initiated changes are felt over hundreds, if not thousands of years and take just as long to reverse. Even so, we have the solution in our hands: the rate of ocean warming from 2050 will depend entirely on whether we can curb climate change. And it is the future water temperature which will determine how much oxygen the oceans will still contain. The warmer the sea, the less oxygen can be dissolved.

An increase in hot extremes in all regions of the world

CURRENT STATUS: Meteorologists have observed an increase in the frequency and intensity of hot extremes since the 1950s, as well as an increase in heatwave intensity and duration over land. What is new is that these weather extremes are now reaching record temperatures which would have been impossible without human-induced climate change. The extreme heatwave which struck north-west areas of the USA and Canada in late June 2021 is an example: in some localities, temperatures rose to 49.6 degrees Celsius, with highs at some weather stations breaking historically observed heat records by as much as 4.6 degrees Celsius. The research now confirms that temperatures during this heatwave would have been around two degrees Celsius lower without human-induced climate change. In a world with global warming of two degrees Celsius, however, maximum temperatures during this heatwave would have exceeded 50 degrees Celsius. Global warming further increases not only the scale but also the likelihood of another similar heatwave in the North American west. The probability of such a heatwave in June 2021 was estimated at around one in 1000 years, but in a world with two degrees Celsius of global warming, this type of extreme event would occur every five to ten years.

The frequency, intensity and duration of marine heatwaves are also increasing. Marine heatwaves have approximately doubled in frequency since the 1980s and cause major damage to marine biological communities. Here too, researchers can now clearly identify human influence as a factor. Without climate change, the marine heatwave which devastated life in the Northeast Pacific in the years from 2013 to 2015 and has gone down in history as "the Blob" would, in all probability, not have occurred. Among other things, the heatwave caused mass die-offs of the common murre *(Uria aalge)*, with as many as one million of these seabirds dying of starvation because the unusually warm water temperatures greatly reduced populations of their prey species compared with normal levels. As a result, there was a thousand-fold increase in the common murre's mortality rate.

1.2 > In some marine regions of the North Pacific (shown here in dark red), the water temperature in May 2015 was up to 3 degrees Celsius higher than average. The marine heatwave – now known as "the Blob" – which caused this rise in temperature lasted for more than 250 days and killed thousands of fish, seabirds and marine mammals.



1.3 > Weakened by the heat: members of the public seek refuge in the air-conditioned rooms of a convention centre in Portland in the US state of Oregon. The rooms were opened to the public during an extreme heatwave in early summer 2021, providing an opportunity to rest and cool down.

OUTLOOK: The intensity and duration of heatwaves over land will continue to increase even if humankind succeeds in limiting global warming to 1.5 degrees Celsius. Marine heatwaves will also occur more frequently. If the world warms by an average of 1.8 degrees Celsius by the year 2100, there will be a two- to ninefold increase in the number of marine heatwaves over the next 60 to 80 years. If the global mean temperature rises by around 4.4 degrees Celsius relative to preindustrial levels, there will be a three- to 15-fold increase in the frequency of marine heatwaves in the final two decades of this century relative to 1995 to 2014, with the greatest changes predicted for tropical waters and the Arctic Ocean.

Global mountain glacier retreat

CURRENT STATUS: The world's glaciers currently contain less ice than at any time in the last 2000 years. Global retreat of mountain glaciers has been accelerating since the 1990s because air temperatures are increasing at higher altitudes as well. Due to the temperature increase, less snow survives on the glacier's surface until the end of summer, which means that there is less snow available for conversion into ice in subsequent years. Surface melting of mountain glaciers is also increasing. Their meltwater has contributed around 6.72 centimetres of mean sea-level rise in the last 120 years.

OUTLOOK: A further decrease is projected in snow cover and glacial ice mass in the world's mountain ranges in the coming decades, along with permafrost thawing in many high mountain regions. As there will be more heavy rainfall instead of continuous snowfall at the same time, researchers are predicting a growing risk of floods and landslides for many mountain regions. The loss of glacier ice will also adversely affect the vital water resources of millions of people who live along rivers that are fed from glacial meltwater.

A clear decline in Arctic sea ice

CURRENT STATUS: On average, the Arctic has been warming at least twice as fast as anywhere else on Earth in recent years. As a result, the Arctic minimum sea ice extent – when the ice shrinks to its minimum size at the end of summer – has decreased by around 40 per cent since the satellite record began in 1979. The remaining ice is also noticeably thinner than before, which means that it drifts across the Arctic Ocean more rapidly and rarely survives for more than two years before melting.

OUTLOOK: Arctic sea ice will melt at an accelerated rate in summer, while less ice will form in winter. Both these developments mean that the Arctic Ocean will be ice-free at the end of summer at least once by 2050, apart from small residual areas of ice, totalling less than a million square kilometres, in sheltered bays and fjords.

Continued ice-mass loss for the Greenland and Antarctic Ice Sheets

CURRENT STATUS: From 1992 to 2020, an estimated 4890 gigatonnes of ice were lost from the Greenland Ice Sheet; the resulting meltwater added 1.35 centimetres to global sea-level rise. The Antarctic Ice Sheet lost 2670 gigatonnes of ice during the same period, with West Antarctica suffering the most significant ice loss. Both here and on the Antarctic Peninsula, glacier flow velocity has clearly increased in the last two decades. This means that relative to 2000, the glaciers are transporting far more ice from land into the sea today.

OUTLOOK: With further warming, the world's two major ice sheets will lose more ice and their contributions to global sea-level rise will increase. If the world warms by more than two degrees Celsius, the West Antarctic Ice Sheet will very likely collapse and its ice masses will slide into the sea. However, the timing, speed and magnitude of this potential collapse are very difficult to predict with any degree of certainty.

Accelerated sea-level rise

CURRENT STATUS: Between 1901 and 2018, global mean sea level rose by 20 centimetres; moreover, the rate of global mean sea-level rise has increased continuously since the 1960s. In other words, sea-level rise is accelerating. Between 2006 and 2018, sea levels were already rising by 3.7 millimetres per year, and according to the WMO, the figure for 2013 to 2022 reached 4.62 millimetres. This means that global mean sea level has risen faster than at any time in at least the last 3000 years. However, levels may have risen even more sharply in some localities and regions. This can be due to the simultaneous occurrence of coastal subsidence or because the action of wind and ocean currents has caused a localized build-up of water along the coast.

OUTLOOK: The development of the global sea level is determined by two factors: seawater temperature (the warmer the water, the more it expands and takes up more space); and changes in water storage by terrestrial water systems (ice masses, groundwater, rivers, lakes). If more terrestrial water enters the ocean, sea levels will rise. A further aspect of relevance to every local stretch of coastline is whether the coastal area itself has undergone any changes in elevation; this can occur, for example, if large quantities of groundwater are extracted, resulting in underground subsidence, or if geological processes cause the land surface to rise or sink. Localized sea-level changes may therefore be significantly higher or, indeed, lower than the global trend.

According to the IPCC's projections, global mean sea level will continue to rise even if humankind succeeds in reducing its greenhouse gas emissions to zero within a short time frame. Possible scenarios range between an additional 18 centimetres and 23 centimetres by 2050. A 38 to 77 centimetre rise is expected by the end of the century.

Changes in the water cycle

CURRENT STATUS: Global warming is increasing evapotranspiration from both land and sea worldwide. This in turn increases the amount of water vapour in the atmosphere, making it more likely that rain droplets will form. A further effect of evapotranspiration is loss of soil moisture, which is vital for plant growth. These two physical processes cause permanent changes in the weather and climate: an increase in the frequency and intensity of

1.4 > This iceberg has broken off the Greenland Ice Sheet. Since 1996, the Greenland Ice Sheet has lost more ice due to surface melting and iceberg calving than can be formed through the compression of fresh snow.

heavy precipitation events has been observed since the 1950s, at least in those regions of the world with continuous weather records. Concurrently, climate change heightens the risk of drought in some regions due to a lack of precipitation, especially during the driest months, although there may be heavy rainfall at other times of the year in such torrential amounts that it causes surface runoff, with very little water penetrating the soil. Reduced snow cover is also a significant problem. Winter snowfall has become a less common occurrence since the 1950s, with the result that snow cover is no longer forming in many localities. In the past, meltwater from snow provided a water supply for people and nature in spring, but is now largely unavailable in many areas, particularly in mountain regions and the tundra.

OUTLOOK: Heavy precipitation is projected to intensify and be more frequent in many localities. As a result, the high-water and flood risk will also increase. There will also be a higher risk of drought, with more regions affected by drought more frequently and for longer periods in future. Snow cover will continue to decrease, mainly in the northern hemisphere, with earlier temperature-related onset of spring snowmelt and potentially smaller volumes of water in rivers and streams.

More typhoons and hurricanes

CURRENT STATUS: The global proportion of tropical cyclone occurrence in Category 3 to 5 on the Saffir-Simpson Hurricane Wind Scale (wind speeds from 178 kilometres per hour) has increased in the last four decades, as has the frequency with which a fairly weak storm rapidly develops to hurricane strength. In the West Atlantic, tropical cyclones are now moving more slowly landward from the open sea; when they make landfall, they linger for longer, often resulting in increased damage. In the North Pacific, extratropical cyclones have shifted their tracks northward and now make landfall at different locations relative to 40 years ago.

OUTLOOK: Researchers are predicting very little change in the number of cyclones overall. In the tropical regions, however, the proportion of very strong – and therefore destructive – storms will continue to increase.

When extremes collide

As well as warming up the world, climate change is exposing people and nature much more frequently to weather and climate extremes. They include heatwaves, heavy rainfall, severe storms, droughts and floods, as well as storm surge due to sea-level rise, which can cause extensive flooding in coastal areas. The frequency with which two or three weather extremes occur concurrently is also increasing. In the last 100 years, for example, more heatwaves have been observed in regions already affected by drought.

When such extremes collide, the climate impacts on people and nature are amplified. For example, a heatwave

Climate change in figures – the WMO's seven Global Climate Indicators

The increase in global mean surface temperature is the parameter generally used by the media and policy-makers to convey the magnitude of the changes occurring across the climate system. On its own, however, this single parameter is insufficient to provide a detailed picture of the overall state of the Earth's climate and any changes that may have occurred. In 2018, the World Meteorological Organization (WMO) therefore identified seven key indicators which it has used since then to describe the global changes in the climate system to the general public and decision-makers. These indicators are:

(1) global mean surface temperature,
(2) ocean heat content,
(3) global mean sea-level change,
(4) Arctic and Antarctic sea-ice extent,
(5) changes in the mass balance of the Greenland and Antarctic Ice Sheets,
(6) global mean ocean pH (ocean acidification) and
(7) mean atmospheric carbon dioxide concentrations.

Each of these indicators is scientifically assessed at least once a year, with monitoring data collected using a standardized global methodology. Together, they capture changes in the Earth's atmosphere and energy balance and provide an initial insight into the current state of the global climate. All seven indicators can be described in simple numerical terms. The latest figures for the seven indicators are published by the WMO in its *State of the Climate* report, which is produced annually. In 2021/2022, four of the seven indicators set new records. This means that in 2021 and 2022, atmospheric carbon dioxide concentrations, sea-level rise, ocean acidification and ocean heat content were higher than at any time since weather and climate records began.

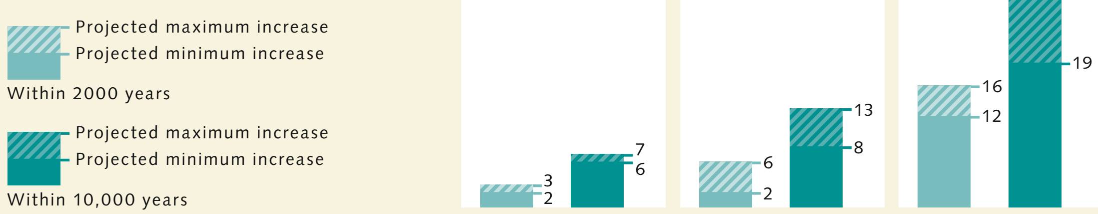
combined with drought causes far more extensive damage than would result from just one of these extreme events. This applies not only to heatwave-drought compounds but also to cases in which coastal regions are affected by severe storms involving both storm surge (marine flooding) and heavy rainfall (flooding on land, river floods). In combination, a storm, storm surge and heavy rainfall cause flooding on a much wider scale than would be induced by just one of these weather extremes.

The risk that extreme events will occur concurrently and that their respective impacts will be amplified is increasing as a result of climate change. Low-lying coastal regions which are regularly affected by cyclones are especially at risk.

Response of the climate system relative to 1850 to 1900
(Figures in brackets indicate the minimum to maximum range)

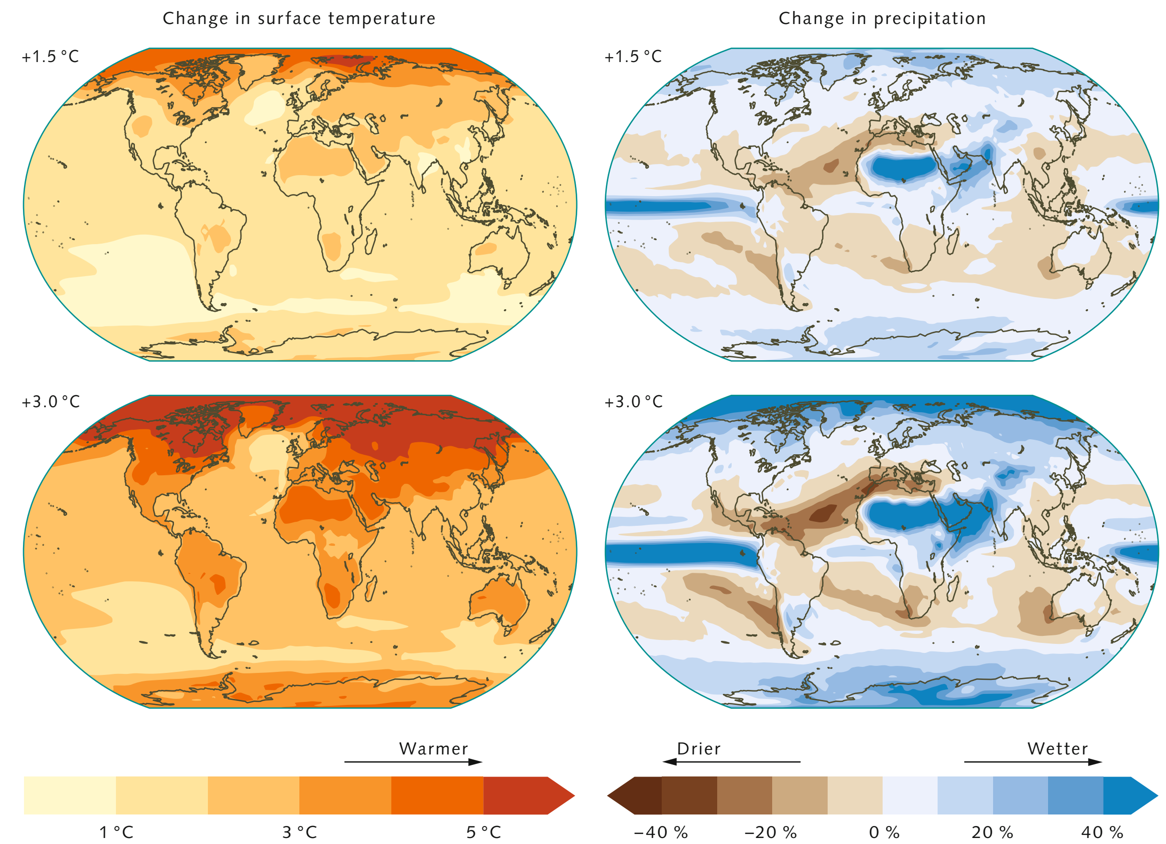
	Today: Response to +1.1 °C	Response to +1.5 °C	Response to +2 °C	Response to +4 °C
Temperature Hottest day in a decade (+ °C)	+1.2 °C (+0.7 to +1.5 °C)	+1.9 °C (+1.3 to +2.3 °C)	+2.6 °C (+1.8 to +3.1 °C)	+5.1 °C (+4.3 to +5.8 °C)
Drought A drought that used to occur once in a decade now happens x times more	x1.7 (x0.7 to x4.1)	x2.0 (x1.0 to x5.1)	x2.4 (x1.3 to x5.8)	x4.1 (x1.7 to x7.2)
Precipitation What used to be a wettest day in a decade now happens x times more	x1.3 (x1.2 to x1.4)	x1.5 (x1.4 to x1.7)	x1.7 (x1.6 to x2.0)	x2.7 (x2.3 to x3.6)
Snow Snow cover extent change (%)	–1 % (–3 to 1)	–5 % (–7 to 2)	–9 % (–13 to 2)	–26 % (–35 to –15)
Tropical cyclones Proportion of intense tropical cyclones (%)		+10 %	+13 %	+30 %

Long-term consequences: Sea level rise
Today, sea level has already increased by 20 cm and will increase an additional 30 cm to 1 m or more by 2100, depending on future emissions. Sea level reacts very slowly to global warming so, once started, the rise continues for thousands of years.



1.5 > Many climate system components react swiftly to global warming – and the higher the temperature increase, the greater the changes. Other climate impacts have a slower onset but become locked in and cannot be reversed in the short term once they have begun. Sea-level rise is the most striking example.

Climate change and regional impacts



1.6 > Climate change is not uniform in all parts of the world. Instead, there are regional differences which will become more apparent as global warming continues. For example, precipitation will increase in high latitudes, the tropics and monsoon regions and decrease in the subtropics.

The impacts – extensive damage to people and nature

The physical climate parameters determine the broad framework within which life on Earth can exist. Any change in these parameters affects the survival conditions not only for people and nature, but also for our built environment. Buildings, roads, power grids, bridges and other key infrastructures are, after all, designed to withstand specific environmental conditions. Global warming of 1.15 degrees Celsius has already led to wide-scale loss and damage for people and nature, and every additional tenth of a degree of warming will further increase the risk of harm.

The IPCC's conclusions on the observed and future impacts of climate change on the various forms of life on Earth can be summarized as follows:

Reorganization of natural biological communities

Global warming is causing drastic and ever-increasing changes in the natural world. These changes affect species composition in natural biological communities on land and in lakes, rivers and seas, weakening their functionality and resilience. Slow onset changes (sea-level rise, ocean acidification) are as problematical as the increased frequency and intensity of extreme events.

In all regions of the world, rising temperatures and weather extremes such as droughts, heatwaves, storms, heavy rainfall and floods are creating climatic conditions that animal and plant species have not experienced for thousands of years. In many cases, the record-breaking temperatures measured already exceed living organisms' tolerance limits. Furthermore, weather extremes are now occurring so frequently that ecosystems have little or no time to recover from one heat shock before the next one follows.

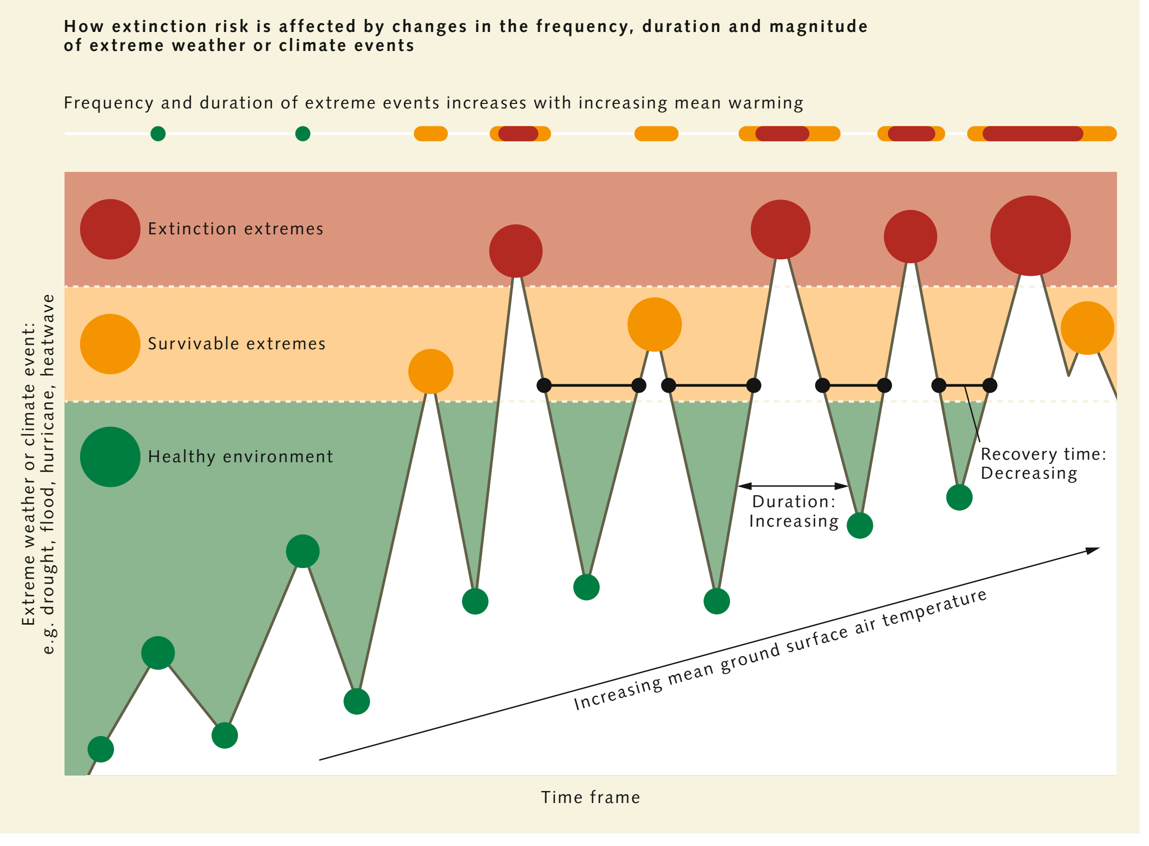
For example, the time needed for tropical coral reefs to recover from temperature-induced coral bleaching is at least ten years. However, in Australia, the Great Barrier Reef has experienced a total of six mass bleaching events since 2000, four of which occurred between 2016 and 2022. It is important to note that the coral bleaching event during the Australian summer of 2021/2022 was the first to occur under La Niña conditions, when cooler water temperatures would normally be expected off the east coast of Australia. And yet 91 per cent of corals on the Great Barrier Reef showed signs of significant heat stress.

Approximately 14 per cent of the world's corals – equal to 11,700 square kilometres of reef – has been lost since 2009, mainly as a result of marine heatwaves. However, scientists are also documenting mass mortality of trees, e.g. in boreal forests and mixed forests in western regions of North America. Stressed by drought and heat, they succumb to diseases or pests, fall victim to forest fires or dry out.

In light of recent studies on the impacts of climate change, combined with a better understanding of natural processes, the IPCC also concludes that the extent and magnitude of climate change impacts on nature are far greater than previously assumed. Most of the climate-induced changes that we are already seeing today are occurring more rapidly than was predicted 20 years ago. They also cause far more damage and affect much larger areas.

For example, as a result of climate change, many biotic communities' biological clocks are changing, disrupting the synchronization of once finely coordinated events or processes. In the ocean, algal blooms are now occurring earlier, before the fish larvae which feed on them start to hatch. By the time the juvenile fish have developed to the

1.7 > The increasing frequency and intensity of extreme events pose a genuine threat to plants and animals. The more frequently an individual species or entire ecosystem is affected by an extreme event and the less time organisms have to recover from the shock, the greater the risk that they will die out locally.



stage where they are able to forage for food, the algal blooms have long gone. On land, hibernating animals are waking too early from their winter sleep, only to search in vain for food. Trees and flowers are coming into bloom before any pollinators appear, and when hungry chicks open their beaks for food, parent birds struggle to find enough insects with which to feed them.

In order to escape the rising temperatures, flora and fauna around the world are abandoning their established habitats or dying out locally. Around half of the many thousands of species assessed appear to be reacting in this way. Marine species are shifting polewards or into greater depths in search of the ambient temperatures to which they are habituated. The current rate of their habitat shift averages around 59 kilometres per decade. However, ocean warming is not the only stress factor affecting flora and fauna. Habitat conditions are also worsening due to increasing ocean acidification and oxygen depletion. Collectively, all three factors have resulted in a reorganization of life in the ocean, particularly near the surface, in the last 50 years.

Terrestrial organisms are also shifting polewards or migrating to higher elevations. Organisms which are only able to move slowly, if at all, run the risk of extinction, at least at local scale. This applies to terrestrial and marine biological communities alike. The prospects of survival are particularly bleak for organisms which live in geographically restricted habitats such as ponds and lakes, meaning that they have no chance of migrating, and for species which are adapted to cold habitat conditions in polar and mountain regions. Very few suitable refuge areas will be available globally for these cold-climate specialists in future.

Making matters worse, the impacts of climate change on nature and species diversity are compounded by other human-induced stress factors – first and foremost the wide-scale destruction of natural habitats through de-

1.8 > A coral colony before bleaching (right) and afterwards (left). If the water is too warm, the corals expel the symbiotic algae that supply them with food, consequently losing their colour. If these conditions persist, coral starvation occurs.

forestation, drainage of wetlands, coastal construction and development, overfishing of the seas, and resource extraction. Environmental pollution also plays a major role, as do uncontrolled soil sealing and the spread of invasive species. Wherever these stress factors overlap, their effects are mutually reinforcing, weakening the resilience of natural ecosystems. For many biological communities, climate change is thus a risk multiplier – and as warming continues, it will become a lethal threat for many. One fact stands out: with each tenth of a degree of warming, the impacts and climate risks for terrestrial and marine ecosystems will increase.

Mass extinction
A mass extinction is defined by scientists as an event in which more than 75 per cent of species of flora and fauna die out, usually within a time span of less than two million years, and their roles in the ecosystem are not filled soon afterwards by new or different species. There is evidence that this has already occurred five times in the last 540 million years; however, these individual events took place over timespans up to several million years.

The world's oceans, for example, face the prospect of a mass extinction due to the combined effects of climate change and human overexploitation of the marine environment. This would be the sixth mass extinction in Earth's recent history. New research shows that if atmospheric and ocean temperatures continue to rise, the loss of marine species due to heat stress and oxygen depletion over the next 75 years will equal the losses from overfishing, pollution and habitat destruction. In sum, global warming of up to 4.9 degrees Celsius by the end of this century would cause so many marine species to die out that this would qualify for definition as mass extinction.

The extinction rate would be particularly high in the polar regions, where cold-climate specialists are struggling to adapt due to the speed of the changes. However, the greatest decline in diversity would be observed in the currently still species-rich tropics, where biological communities have already reached their maximum temperature tolerance limit. But the research also shows that if global warming can be held below two degrees Celsius, the risk of a mass extinction decreases significantly.

Climate change – a risk multiplier

The upheavals in the natural world have far-reaching implications for humankind. One by one, ecosystems are denying us their vital services. Cereals, fruit trees and other crops are no longer being adequately pollinated; grazing for livestock – cattle, sheep and goats – is proving increasingly difficult to find; more and more often, coastal fisherfolk are pulling in empty nets, particularly in the warm, tropical regions, because fish populations are migrating to cooler waters. There is less air and water purification, less effective protection of coasts from erosion, and popular holiday destinations are losing their main attractions – forests, snow-capped mountains and coral reefs. In parallel, many people who enjoy woodland walks or relaxing by the sea are finding that their mental health is suffering. In short, the more the ecosystems change, the more we lose our vital natural resources.

Water – too much or too little

Climate change also directly affects human communities and our built environment. For example, more frequent heavy rainfall increases the risk of river floods in some regions of the world. The potential damage induced by this type of natural disaster is estimated to be four to five times greater in a world with four degrees Celsius of warming than if global warming were limited to 1.5 degrees Celsius. However, even with warming of 1.5 degrees Celsius, more people will lose their lives and property to floods than at present. In Colombia, Brazil and Argentina, for example, the number of people affected by river floods would increase by 100 to 200 per cent, with an increase of 300 per cent in Ecuador and even 400 per cent in Peru.

Rising spring and winter temperatures, in turn, cause earlier snowmelt at high altitudes, resulting in changes in average water levels in mountain streams and rivers. For human communities, this development means that the rivers may carry a large volume of water during periods when it is scarcely needed, while later in the year, water levels are too low to allow extraction of the required quantities.

Already, more than half the global population lives under conditions of severe water scarcity, at least partly induced by climate change, for at least one month of the year; this may be due to extreme aridity, but also to floods, storms and heavy rainfall events whose impacts also put the drinking water supply at risk in many localities. The effects are felt particularly by cities, municipalities and villages whose residents rely on meltwater from the shrinking mountain glaciers, as well as by people living in areas without a central water supply. If rivers burst their banks here or if a natural spring dries up due to drought, many thousands of people are often left without access to clean water.

Alongside agriculture, which is the world's largest consumer of freshwater, the energy sector is also affected by water scarcity: since the 1980s, the amount of power generated in hydroelectric plants has decreased by four to five per cent worldwide due to falling water levels and reduced flow rates. Indeed, in some localities, hydropower plants are threatened with closure due to water scarcity. Conditions at Lake Powell, the second largest artificial reservoir in the USA, illustrate the gravity of the situation until the winter of 2022/2023. The Lake is located on the border between Utah and Arizona. It is fed by the Colorado River and together with the Lake Mead reservoir further downstream, supplies around 40 million people with drinking water. Farms along the length of the river also extract water to irrigate their fields and crops. After 22 years of drought in the western USA and persistently excessive water extraction from the Colorado River, the reservoir was filled to just 24 per cent of its capacity at the end of March 2022. Between 2019 and 2022 alone, the water level dropped by more than 30 metres, coming close to the critical threshold below which the lake's hydroelectric dam is unable to generate power. The federal agency responsible for the reservoir therefore decided to release less water than usual from the lake during the rest of the year and to open the dam gates of another reservoir further upstream in order to provide an additional water inflow into Lake Powell. The drought in the American West has stretched over 22 years (2000 to 2022/2023) and is now classed as the driest period in 800 years.

Food – hard times for arable farming, livestock husbandry and aquaculture

Wherever there is too much rainfall, or it rains at the wrong time of the year, arable and livestock farming becomes more challenging. According to the IPCC, farmers and foresters, fishers and aquaculturists around the world are already adversely affected by climate change to such an extent that they are no longer able to produce sufficient staple crops and timber to meet the global population's needs.

With higher temperatures and increased aridity, cereals and fodder crops wilt in the fields and diseases spread. Due to ocean acidification, rising water temperatures and multiple algal blooms (eutrophication), fish farmers are finding it increasingly difficult to bring mussels and other shellfish to maturity. Global warming also increases the complexities – and therefore the costs – of transporting, storing and selling perishable foods such as fruit and vegetables safely so that once purchased, they stay fresh for a few days at home. Climate change thus affects not only the producers but the entire supply chain up to and including the consumer, posing a threat to food security throughout the world.

The losses are particularly severe when regions are affected by extreme events such as droughts, floods and heatwaves. The frequency of these sudden harvest or production losses on land and in the sea has steadily increased since the 1950s and often has a domino effect. For farming families, crop failure means the loss of their food supply and livelihoods. Concurrently, the availability of basic foodstuffs is reduced, pushing up prices and making staple foods unaffordable, especially for low-income families. The resulting hunger and malnutrition have particularly negative effects on child health. These developments can be observed in Asia, Central America, the sub-Saharan regions, the Arctic, the small island states and elsewhere – and once again, it is the smallholder farmers and artisanal fisherfolk who are impacted most severely by climate change.

The situation will worsen as warming continues – in part because higher temperatures mean that more water is lost through evapotranspiration from foliage and soil. Water demand from agriculture will therefore increase. This situation will be compounded by the substantially reduced availability of water during the growing season in many regions, multiplying the risks. To take just three examples:

- With global warming of two degrees Celsius by 2100, the probability of extreme droughts occurring across wide areas in Northern South America, the Mediterranean region, Western China and at high latitudes in Europe and North America will increase by 150 to 200 per cent.

- Whereas around 40 per cent of total croplands (approximately 3.8 million square kilometres) experienced water scarcity in the period from 1981 to 2005, a new study shows that agricultural water scarcity will intensify in more than 80 per cent of global croplands by 2050 – even if the world warms by just 1.6 degrees Celsius by 2050 relative to preindustrial levels.
- During the same period, the impacts of climate change alone will mean that an estimated eight to 80 million people in South Asia, Central America and sub-Saharan Africa will no longer have access to adequate food and will therefore suffer from hunger. The precise figure will depend on the degree of warming and hence the magnitude of future climate change.

Health – the limit of human tolerance

Climate change adversely affects both the physical and the mental health of people in all regions of the world. Severe mental health challenges are reported mainly by people who have been exposed to extreme weather events or by rescue workers deployed during such events, and by people who have suffered loss of livelihoods or even their homes, communities or culture as a result of climate change. Physical health is adversely affected primarily by extreme heat. Rising air temperatures and longer and more intense heatwaves have increased the occurrence of diseases and led to higher mortality worldwide, including in the middle latitudes. The elderly, people with medical conditions and outdoor workers are particularly impacted. Additionally, for this latter group, warming is often associated with loss of earnings if extreme heat makes outdoor labour in fields or on construction sites impossible.

Extreme heat is particularly hazardous when it is compounded by very high humidity. If the air is so humid that water and therefore also sweat cannot evaporate, the human body's cooling mechanism begins to fail. As a result, the body steadily overheats, ultimately causing circulatory collapse and – in extreme cases – fatal heat stroke.

The human heat tolerance limit can be determined using the cooling limit temperature. This captures both ambient temperature and humidity. Until recently, it was assumed that a healthy individual cannot survive a cooling limit temperature of 35 degrees Celsius for more than around six hours. This limit is derived from the combination of temperature and humidity and corresponds to 35 degrees Celsius at 100 per cent humidity or 46 degrees Celsius when humidity is 50 per cent.

When researchers at Pennsylvania State University in the USA tested this assumption for the first time in heat stress experiments, they found that the theoretical threshold was far too high. In climate chambers with a high level of humidity, an ambient temperature of 30 to 31 degrees Celsius was enough to induce dangerously elevated core temperature in healthy young human test subjects. Contrary to all expectations, a slight decrease in humidity did not increase the test subjects' heat tolerance. Instead, the critical cooling limit temperature under these conditions was just 25 to 28 degrees Celsius – almost ten degrees Celsius lower than scientists had previously assumed. The explanation offered by the research team is that despite the reduction in humidity, the test subjects' sweat production did not increase above a certain temperature.

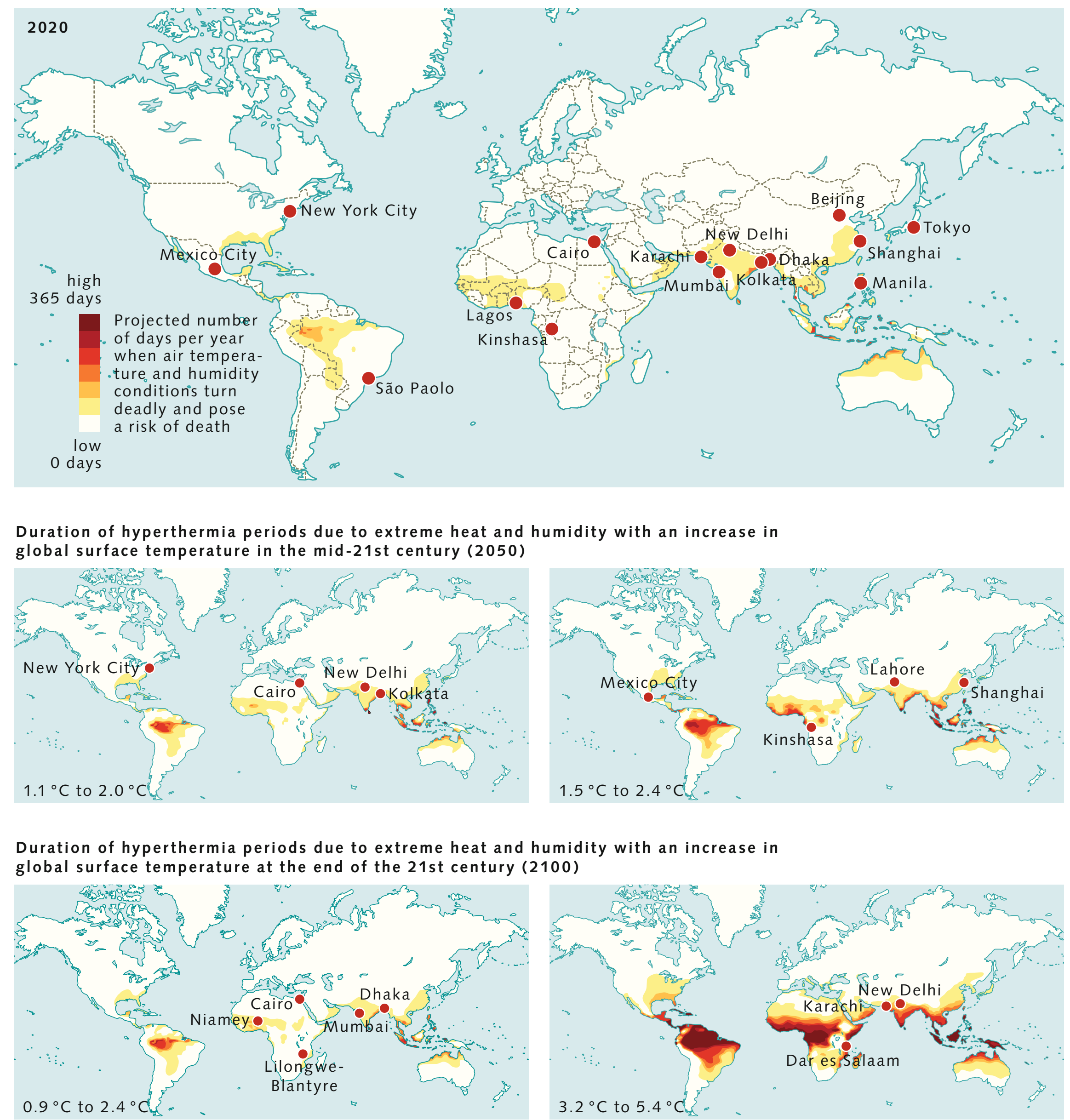
In the face of continued climate change, these research findings give cause for concern. They show that the heat risk to human health has been underestimated and that with accelerated global warming, more regions will be periodically affected by a level of heat stress that will make it impossible to survive without additional cooling.

In the long term, the situation is likely to be particularly challenging for the many millions of people living in mega-cities in the tropics and subtropics. Firstly, air temperature and humidity here are consistently high for most of the year, and secondly, the heat island effect also comes into play. This is a term used to describe the observation that conurbations reach higher daytime temperatures than less built-up outlying areas. Urban areas also cool down more slowly at night. It may be concluded from this that in mega-cities in the tropics and subtropics, it would only take a comparatively small amount of warming to push inner-city air temperature to such a

high level that many people's heat tolerance limit is exceeded.

There is much evidence to suggest that city dwellers are generally exposed to much higher temperatures than those reported for a wider region. For example, during the severe heatwave in India and Pakistan in May 2022, when daytime temperatures climbed as high as 51 degrees Celsius, temperatures remained high overnight, at 35 to 39 degrees Celsius, in the Indian capital New Delhi and neighbouring towns, whereas the air cooled to a tolerable 15 degrees Celsius in nearby fields and forests. Subsequent analyses by an international research team found that human-induced climate change had made this record-breaking heatwave 30 times more likely.

Duration of hyperthermia periods due to extreme heat and humidity



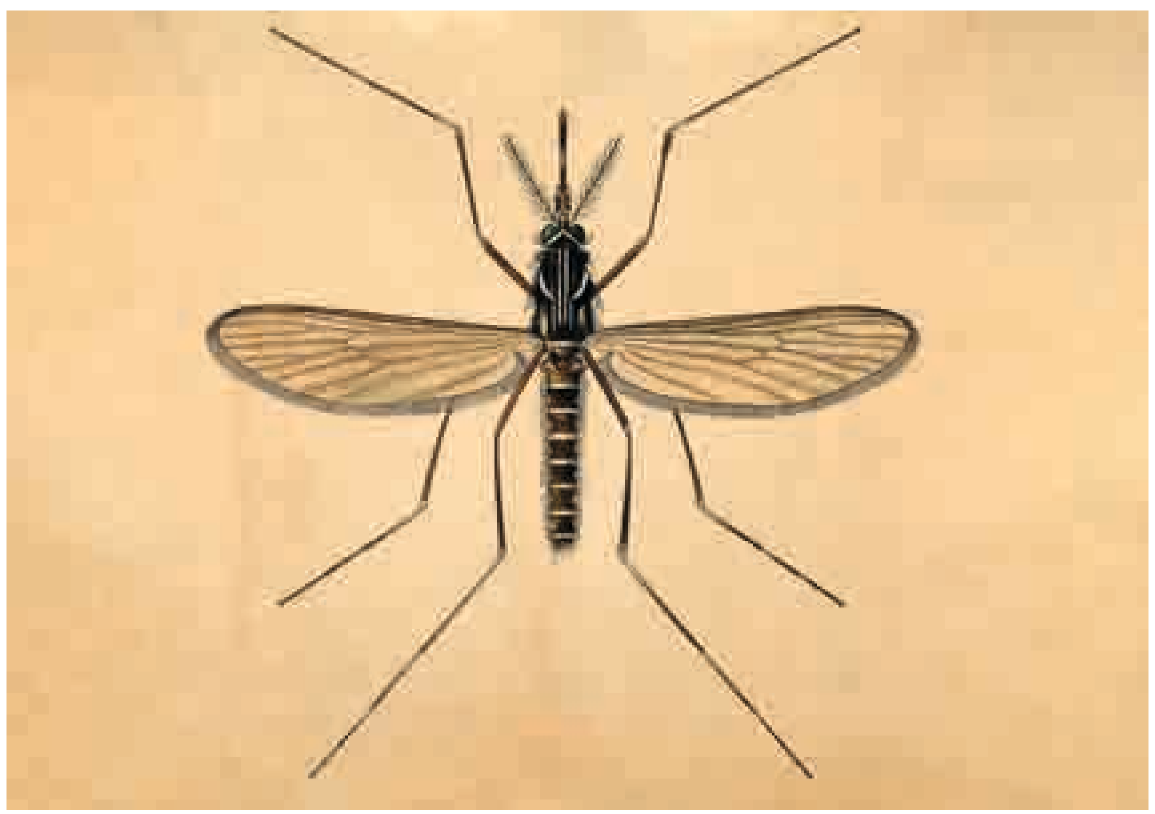
1.9 > When extreme heat is compounded by high humidity, the human body can quickly overheat – a potentially life-threatening situation. This figure from the IPCC shows the various regions of the world where people will be exposed to the risk of overheating (hyperthermia) in future and for how many days a year. The core message: the sooner climate change is curbed, the fewer people will be exposed to this threat to life.

Climate change also increases the occurrence of many infectious diseases. Droughts, for example, heighten the risk that wells will dry up, while heavy precipitation can cause contamination or flooding of wells. In both cases, if communities then extract their drinking water from contaminated sources, their risk of contracting bacterial infections such as cholera increases. Higher temperatures enable *Aedes* mosquitoes to expand their habitat range north- and southwards from the tropics. These insects carry the dengue fever and yellow fever viruses, among others. The risk of contracting dengue fever is already increasing worldwide. Due to the more frequent occurrence of forest fires across larger areas, the risk of respiratory diseases is also increasing in affected regions.

Sea-level rise – land under water!

As a consequence of sea-level rise, the climate risks to people, nature and built assets in the world's coastal areas will increase at least tenfold by 2100, mainly due to the greater frequency of extreme floods. Sea-level rise poses a particular threat to the many millions of people living in low-lying coastal areas and on small islands. Higher tidal floods destroy the species-rich ecosystems in the tidal range, cause salinization of groundwater reservoirs and inundate large areas of land, affecting coastal forests and croplands, as well as coastal districts of large metropolitan areas. Due in part to these areas' uncontrolled growth, ongoing sea-level rise will put increasing numbers of people at risk over time. In Africa, for example, some 108 to 116 million people will be living in high flood-risk areas by 2030, compared with just 54 million in 2000.

Globally, the numbers affected are very much higher: according to figures from the IPCC, more than a billion people in coastal cities and conurbations worldwide will be living with a high flood risk in 2050. The threats they face include recurrent storm surge, as well as the prospect of permanent flooding of their villages and districts.



1.10 > *Aedes* mosquitoes are also known as yellow fever or dengue mosquitoes as they are vectors of both these diseases. As a result of climate change, their range is expanding. Originally found only in the tropics and subtropics, they are now spreading further north and south.

1.11 > The eye-catching collage on the title page of the IPCC's report *Impacts, Adaptation and Vulnerability*, published in February 2022. Its key message: humanity knows what needs to be done to mitigate the impacts of climate change. What is lacking is resolute global action.

Climate change adaptation – the world is unprepared

In order to mitigate the impacts and risks of climate change, people and nature must adapt to the new environmental conditions. For us humans, this primarily entails taking measures to protect our lives, goods and property against high temperatures, weather extremes and sea-level rise. This can be achieved if we relocate from at-risk regions or make local lifestyle changes – for example, by greening our settlements and cities in order to minimize the heat island effect, or by conserving water so that we have sufficient reserves available during droughts.

The list of potential solutions is long. Nevertheless, the IPCC concludes that globally, there is a substantial gap between current adaptation planning and implementation and the levels needed to provide effective and sustainable protection for everyone. What is certain, however, is that there is now a greater awareness of the growing risks. More than 170 countries and many cities are now including adaptation in their climate policies and planning processes. Private sector and civil society actors are also engaging for more adaptation. Pilot projects are being implemented in various sectors, although in many cases, they simply aim to minimize the local storm, flood, heat or drought risk and therefore result in only minor changes with regional and time-limited impact.

In order to mitigate the impending climate risks on a long-term basis, holistic policies and fundamental

Climate justice – the heaviest burden falls on the poor

Climate change confronts humankind with a growing justice problem, namely that the impacts of global warming and more frequent extreme events are felt mainly by low-income and marginalized population groups. For these groups, climate change often poses an existential threat, for it multiplies – by several orders of magnitude – their already substantial economic, social and health challenges and concerns. The greater vulnerability of low-income and marginalized population groups to climate risks stems from three sources:

- The poorest communities generally live in regions where they are particularly exposed to weather extremes and other natural hazards. Examples are slums by rivers (flood risk), illegally constructed housing on mountain slopes (risk of landslides after heavy rainfall) and settlements without mature trees to provide shade and cooling during periods of extreme heat.
- Low-income families often lack access to the financial resources and infrastructures needed for resilience to climate and weather extremes. These resources include energy and water security, access to sanitation and emergency shelters, a well-performing health system, and a reliable supply of all the staple foods. Furthermore, low-income groups very often work in occupations in which both their earnings and their food supply are heavily dependent on the climate, such as agriculture and fishing.
- Low-income and marginalized population groups are often excluded from decision-making at the political level and their needs are rarely, if ever, considered. The IPCC concludes, inter alia, that the adaptation gap between the measures currently being implemented and the levels needed to respond to impacts is significantly greater in low-income regions than in areas inhabited by higher-income groups.

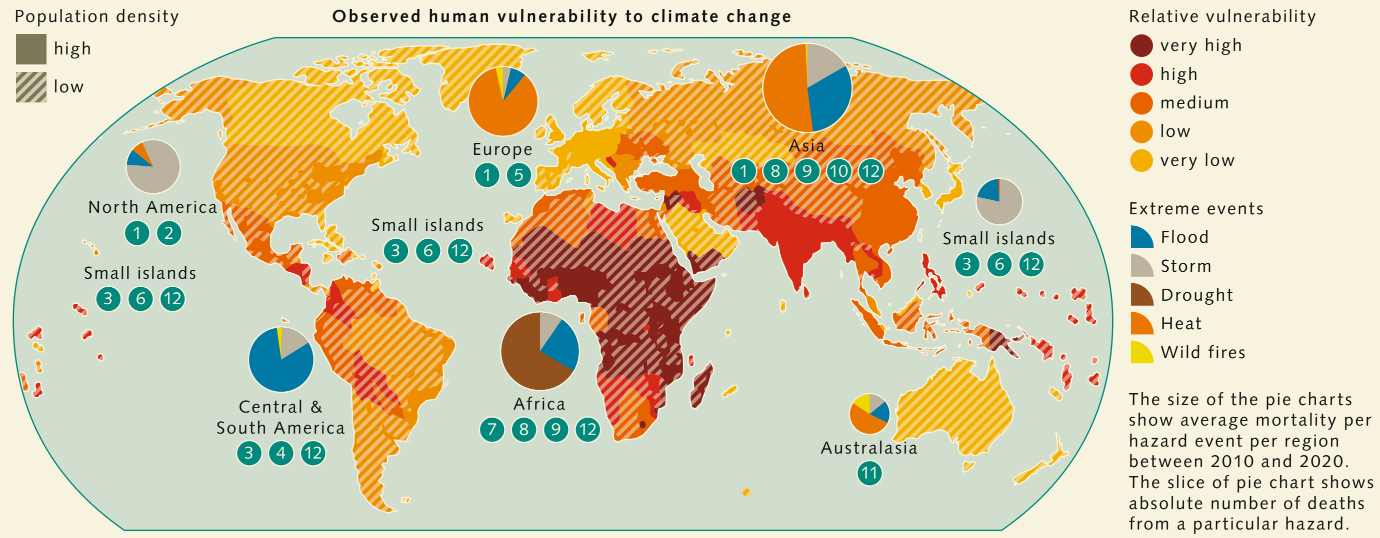
Worldwide, 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change impacts. The implications of this are illustrated by the mortality rates, among other things: over the last decade, human mortality from storms, floods and droughts was 15 times higher in highly vulnerable regions, compared to countries with very low vulnerability. Members of low-income groups are also exposed comparatively often to extreme heat as they tend to be employed in outdoor occupations such as farming, landscaping, construction and artisanal trades.

Adaptation and inclusion – building the resilience of vulnerable groups
Based on these findings, the IPCC has developed an approach for climate resilient development, which focuses primarily on the needs of the most vulnerable population groups. In essence, this approach adroitly combines climate change adaptation and mitigation strategies in such a way that many other social challenges – such as poverty, hunger and discrimination against women – can be addressed at the same time.

Its successful implementation, however, is contingent on various conditions which, in essence, necessitate a transformation of human society and a shift away from current values, economic systems and life goals. If efforts to preserve Earth as a liveable planet for people and nature are to be successful, humankind must take the following action without delay:

- *conserve and sustainably use at least 30 to 50 per cent of Earth's land and ocean areas:* this means only removing the amount of a natural resource (fish, timber, etc.) that can regenerate itself;
- *in decision-making, include all affected population groups in the debate from the outset:* this requires transparent, democratically organized processes in which there is cooperation across all social divides, as well as efforts to achieve a fair balance between diverse interests, values and worldviews;
- *base all decision-making on expert knowledge:* alongside representatives of science and engineering, it is essential to give a hearing to representatives of local expertise and to local interest groups and indigenous communities;
- *prioritize issues of justice and fairness:* the precarious situation of low-income or marginalized population groups will change only if they are given a voice and this voice is heard and considered. In many regions, these still marginalized groups mainly include women, young people and members of indigenous communities;
- *provide adequate funding for climate change adaptation measures and for the transformation of the economy and society;*
- *cooperate on a transboundary and transnational basis.*

Even in a world without climate change, effecting this transformation would be an immense challenge for society. If climate-related loss and damage are factored in, the situation becomes very much worse, for every additional tenth of a degree of warming further limits our scope for action. The IPCC (Intergovernmental Panel on Climate Change) sums up what is at stake: in a world that has warmed by more than two degrees Celsius, humankind will likely have no chance of creating a liveable future for all the Earth's citizens.



Vulnerability at the national level varies. Examples of particularly vulnerable groups in local contexts are:

1. Indigenous Peoples of the Arctic: health inequality, limited access to original hunting grounds and culture
2. Urban ethnic minorities: structural inequality, marginalization, exclusion from planning and decision-making processes
3. Smallholder coffee producers: limited market access and stability, single crop dependency, limited institutional support
4. Indigenous Peoples in the Amazon: land degradation, deforestation, poverty, lack of support
5. Older people, especially those poor and socially isolated: health issues, disability, limited access to support
6. Island communities: limited land, population growth and coastal ecosystem degradation
7. Children in rural low-income communities: food insecurity, sensitivity to undernutrition and disease
8. People uprooted by conflict in the Near East and Sahel: prolonged temporary status, limited mobility
9. Women and non-binary: limited access to and control over resources, e.g. water, land, credit
10. Migrants: informal status, limited access to health services and shelter, exclusion from decision-making processes
11. Aboriginal and Torres Strait Islander Peoples: poverty, food and housing insecurity, dislocation from community
12. People living in informal settlements or slums: poverty, limited basic services and often located in areas with high exposure to climate hazards

1.12 > People throughout the world are exposed to the impacts of climate change. There are, however, some particularly vulnerable groups with less resilience to extreme events such as heat, drought, storms, floods and forest fires.

1.13 > A vivid comparison: In the US city of Los Angeles, an adequate number of roadside trees to provide shade exists only in districts where residents have sufficient resources to pay for the trees' upkeep (above). Trees are absent in poorer districts, partly because the city government does not invest in roadside trees. As a result, there is no cooling shade for local residents when temperatures soar.

adjustments to our lifestyles are required, which must include how we work, how we produce our food and treat the natural environment, and how we plan and construct our cities and settlements. The IPCC concludes that at present, humanity is completely unprepared for all the challenges that lie ahead as a result of climate change – particularly if the world warms by more than 1.5 degrees Celsius. Scientists refer in this context to an adaptation gap.

This gap is particularly large in regions where people are poor and highly exposed to climate risks. Furthermore, if the adaptation measures currently being planned are compared with the climate impacts predicted by scientists, it is already clear that this adaptation gap will widen steadily.

The limits to adaptation

Also new is the clarity with which the IPCC now describes the limits to human adaptation to climate change. In doing so, it differentiates between hard and soft limits. Hard limits are those where adaptive actions are no longer possible. For example, if an atoll is inundated by waves due to sea-level rise, resulting in the complete salinization of all the drinking water reserves, the island dwellers' only long-term option is to leave. The same applies to flora and fauna that have already reached their upper temperature limit. If their habitats continue to warm, they are forced to migrate.

Soft limits, by contrast, are ones where options for adaptive action may exist. However, this requires political commitment, sufficient financial resources, scientific knowledge and local know-how. If all four factors are in place, it may be possible, for example, for farmers in drought-affected regions to cultivate new species that are resistant to aridity and to install modern irrigation systems in order to reduce their demands upon lakes, rivers and groundwater resources.

It is already clear, however, that many species of flora and fauna have already reached or are about to reach their hard adaptation limits. If they were to die out locally, this would destroy the livelihoods of the many millions of farming, fishing and pastoralist families who depend on these species. With global warming of 1.5 degrees Celsius or more, the ongoing decrease in snowfall and glacier retreat will mean that communities whose water supply depends on meltwater no longer have access to adequate water resources. And with warming of two degrees Celsius or more, it will become far more difficult to make a success of arable farming in many of the world's cereal-growing areas.

As these few examples of adaptation limits show, the more quickly humankind acts to curb climate change, the more opportunities there will be to adapt to the new conditions and the more effective these options will be. Actions which will work with warming of 1.5 degrees Celsius may prove to be completely ineffective once warming reaches two degrees Celsius. For that reason, the effectiveness of all adaptation actions must be continuously monitored and the effects of the various measures regularly reviewed.

Climate, people and nature can only be winners together

The IPCC's *Sixth Assessment Report* also highlights the scientific community's new understanding of the close interconnections and interactions between nature, people and the climate. For example, if humans impair species diversity by destroying natural habitats and exploiting their resources, they deprive themselves of their most important partner in the fight against climate change. Yet at the same time, humanity is forcing the climate-related decline of natural ecosystems with its persistently high greenhouse gas emissions.

Breaking out of this conflict spiral and reversing past mistakes must henceforth be the goal of all human action. Among other things, this means thinking holistically about people, nature and the climate – in our daily lives and in all our decision-making, whether at local, national or international level. Only then will it be possible to identify solutions that benefit all three systems in the long term and guarantee a liveable future on Earth for present and future generations.

Solutions to the greenhouse gas problem?

> Climate change is man-made and undeniably a consequence of the unchecked emission of greenhouse gases. Stopping emissions is thus the only way out of the climate crisis. There is presently an abundance of suggestions for how human societies can avoid a large portion of their emissions. However, it will certainly not be possible to eliminate all emissions by the year 2050, even if a great effort is made towards that end. Residual amounts will thus have to be compensated for by the deliberate removal of carbon dioxide from the atmosphere.

Humankind alone is responsible for climate change and its consequences

Halting climate change and preventing its drastic consequences is the duty of humans because they alone are responsible for the global warming that has occurred up to now. There is no longer any doubt that climate change is man-made. According to the Intergovernmental Panel on Climate Change, global warming over the past 120 to 170 years can be clearly attributed to human-induced greenhouse gas emissions. The primary contributors include carbon dioxide, methane, nitrous oxide (laughing gas) and chlorofluorocarbons (CFCs), as well as 16 additional chemicals.

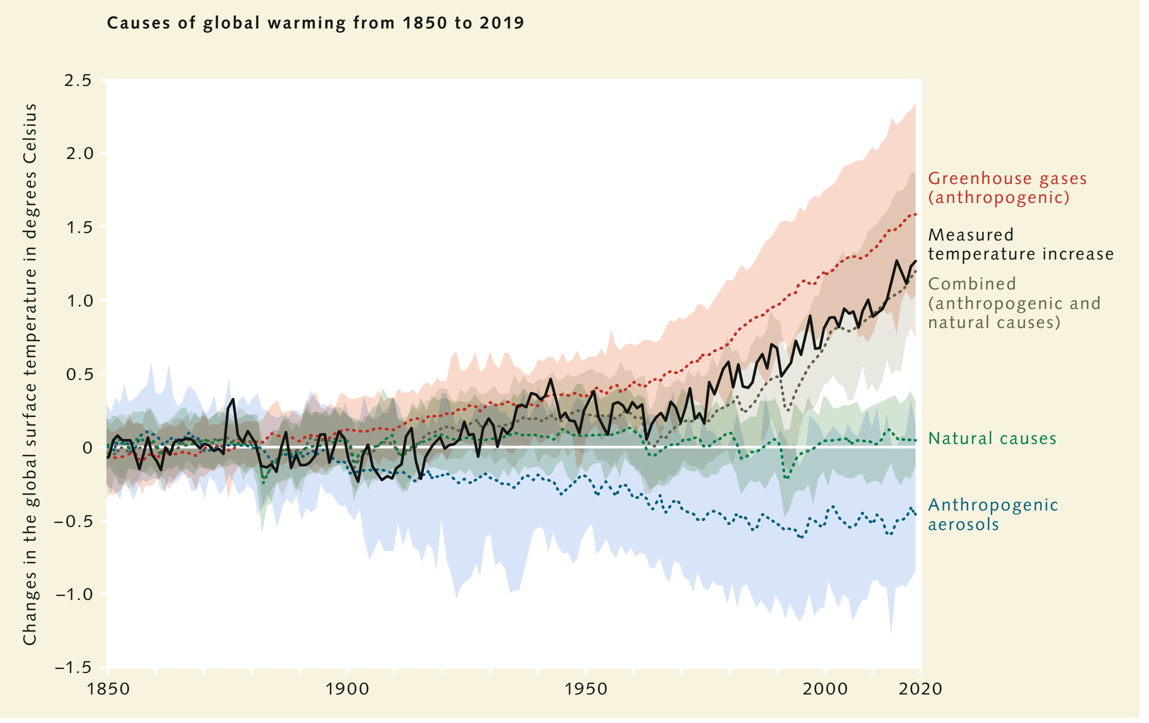
The enrichment of these greenhouse gases in the atmosphere is steadily reducing our planet's ability to radiate heat energy into space. The surplus heat in the Earth's atmosphere first warms its air masses, then subsequently also the ocean. This process is based on the same physical principle that warms a garden greenhouse. The consequences of increasing atmospheric greenhouse gas concentrations are therefore known as the greenhouse effect. It is important to understand that a significant portion of the total warming triggered by greenhouse gases is not yet being observed by humans or in nature because it is masked by the cooling effects of aerosols like soot particles and sulphur dioxides, as well as by changes in the reflectivity of the Earth's surface. Without these cooling components the level of global warming would already be at 1.5 degrees Celsius today.

The concentrations of greenhouse gases in the Earth's atmosphere are being monitored around the world by research institutions such as the US American National Oceanic and Atmospheric Administration (NOAA). Each year NOAA publishes its *Annual Greenhouse Gas Index* (AGGI). This is a numerical expression of how much additional heat energy has remained in the atmosphere as a result of man-made greenhouse gas emissions compared to the reference year 1990, and is continuing to drive global warming. In 2022 the NOAA Greenhouse Gas Index rose to a value of 1.49. This means that the greenhouse gases released by human activities trapped an astonishing 49 per cent more heat energy in the Earth's atmosphere in 2022 than they did in the reference year.

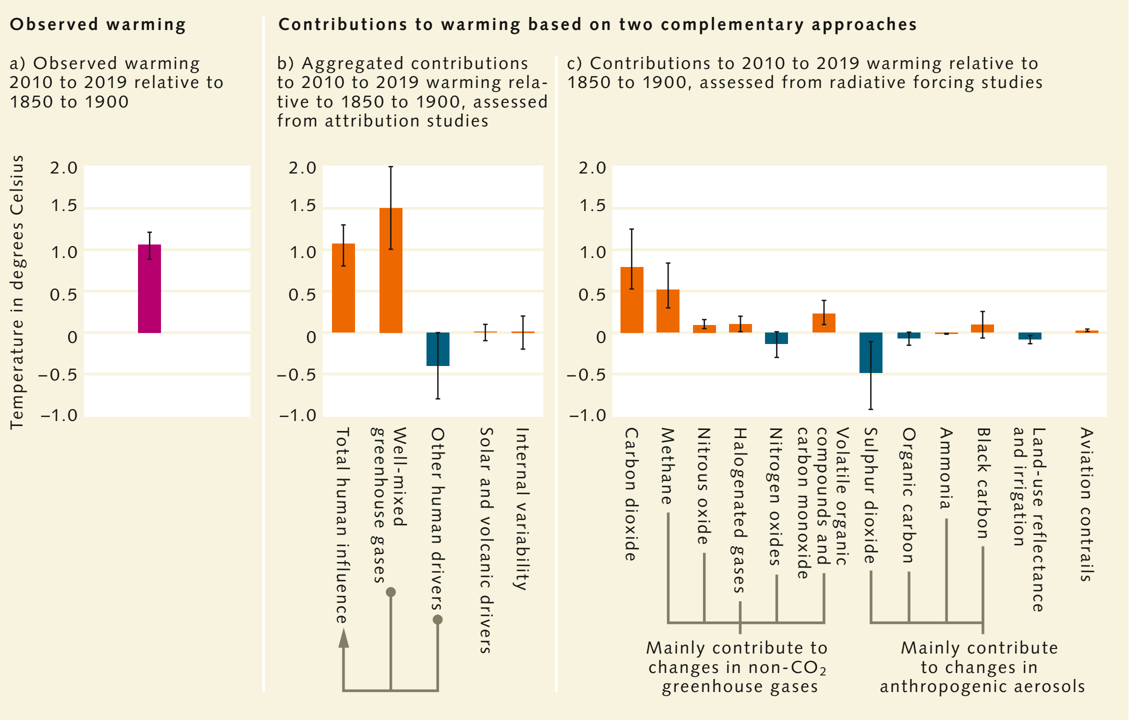
The greatest proportion by far of this increasing heat accumulation, around 80 per cent, has been contributed by carbon dioxide (chemical formula: CO_2). This greenhouse gas is especially long-lived. It does not break down chemically in the atmosphere, and thus can only be removed through a variety of processes (such as CO_2 uptake by plants). For this reason, carbon dioxide can remain in the Earth's atmosphere for as long as 1000 years and thus has a long-term effect on the climate.

Carbon dioxide is emitted as a product of almost all human activities. It is primarily produced by:

- *the burning of fossil fuels such as coal, oil and natural gas:* According to the Intergovernmental Panel on Climate Change, around 34 per cent of the global carbon dioxide emissions in the year 2019 came from the energy sector, while the traffic and transport sector accounted for 15 per cent and the industrial sector for 24 per cent;
- *the decomposition of organic materials (animal and plant remains) due to land-use changes:* Agricultural, forestry and other land-use changes accounted for around 22 per cent of the global carbon dioxide emissions in 2019;



1.14 > Humans are causing climate change. This is clearly evidenced because the measured warming of the Earth (black line) can only be realistically represented in climate models when they combine the natural with all human-influence factors (grey dotted line and shading).



1.15 > Global warming is a result of anthropogenic greenhouse gas emissions. Aerosols released by human activities, mainly sulphur and nitrous oxides, have so far had a cooling effect by reflecting incoming sunlight back into space.

Total direct and indirect anthropogenic greenhouse gas emissions for the year 2019 (in $GtCO_2eq$) in sectors or subsectors

OTHER EMISSIONS RELATED TO ENERGY PRODUCTION 12 %
● Direct 10 % ● Indirect 2 %

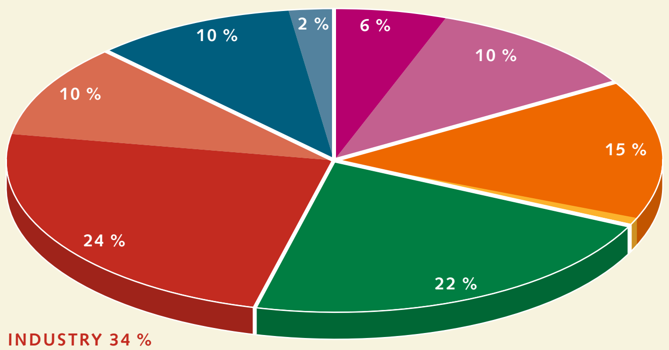
- Petroleum refining 1.1 %
- Coal mining fugitive emissions 2.2 %
- Oil and gas fugitive emissions 4.4 %
- Other (energy systems) 4.7 %

BUILDINGS 16 %
● Direct 6 % ● Indirect 10 %

- Non-CO_2 (all buildings) 0.1 %
- Non-residential buildings 5.9 %
- Residential buildings 11 %

TRANSPORTATION 15 %
● Direct 15 % ● Indirect < 1 %

- Inland shipping 0.3 %
- Rail 0.4 %
- Domestic aviation 0.7 %
- Other (transport) 0.9 %
- International aviation 1.1 %
- International shipping 1.3 %
- Roads 10 %



AGRICULTURE, FORESTRY, AND OTHER LAND USE (AFOLU)
● Direct 22 %

- Biomass burning (CO_2, CH_4) 0.1 %
- Application of synthetic fertilizers (N_2O) 0.75 %
- Manure management (N_2O, CH_4) 0.7 %
- Rice cultivation (CH_4) 1.7 %
- Managed soils and pastures (CO_2, N_2O) 2.5 %
- Enteric fermentation (CH_4) 5 %
- Land use, land-use change and forestry (LULUCF) (CO_2) 11 %

INDUSTRY 34 %
● Direct 24 % ● Indirect 10 %

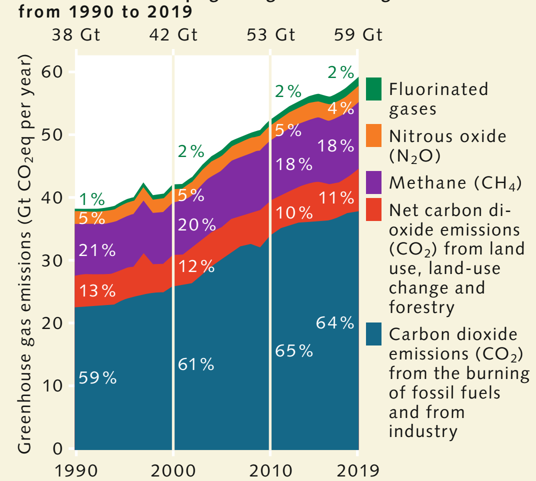
- Cement (process only) 2.6 %
- Waste 3.9 %
- Chemicals 6.3 %
- Metals 7.8 %
- Other (industry) 13 %

1.16 > Overview of the direct and indirect greenhouse gas emissions for the individual sectors in the year 2019. The total emissions are recalculated to carbon dioxide equivalents. The percentage values shown in the sums do not always add up to 100 per cent due to rounding.

Direct and indirect emissions
Direct emissions are closely related to activities within a clearly defined area, region, sector or company (for example, CO_2 emissions by the burning of oil in the heater of a building). Indirect emissions, on the other hand, are produced outside the defined area (heating a building by district heat: Indirect emissions result from combustion in the geographically removed gas or coal power plant).

- *industrial processes such as the production of cement:* Cement is made of limestone, which is burned at temperatures of 1450 degrees Celsius to achieve the required material properties. During the burning process, carbon dioxide escapes from the primary material in large quantities. The process-related emissions from cement production alone accounted for around 2.6 per cent of the total global carbon dioxide emissions in the year 2019. This amount does not include indirect emissions, which include the energy used in the process and for transport. In Germany, the production of one tonne of cement is responsible for around 600 kilograms of carbon dioxide emissions. Approximately two-thirds of this amount are due to raw-material processing emissions, and one-third to fuel emissions.

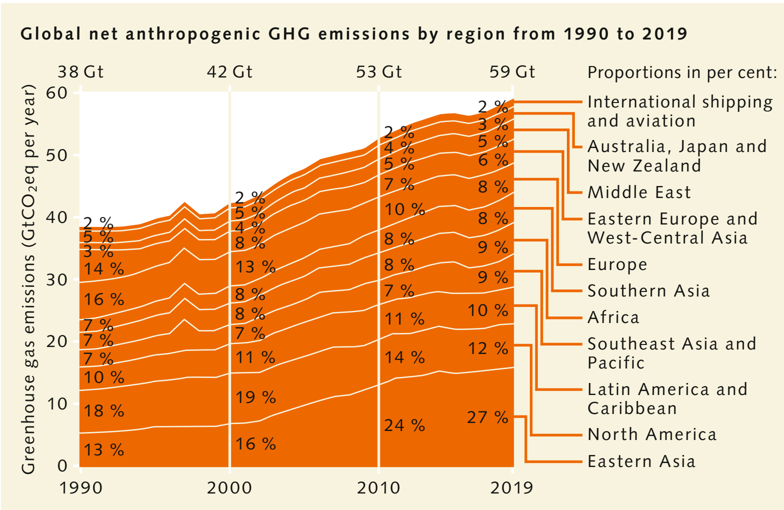
Global net anthropogenic greenhouse gas emissions from 1990 to 2019

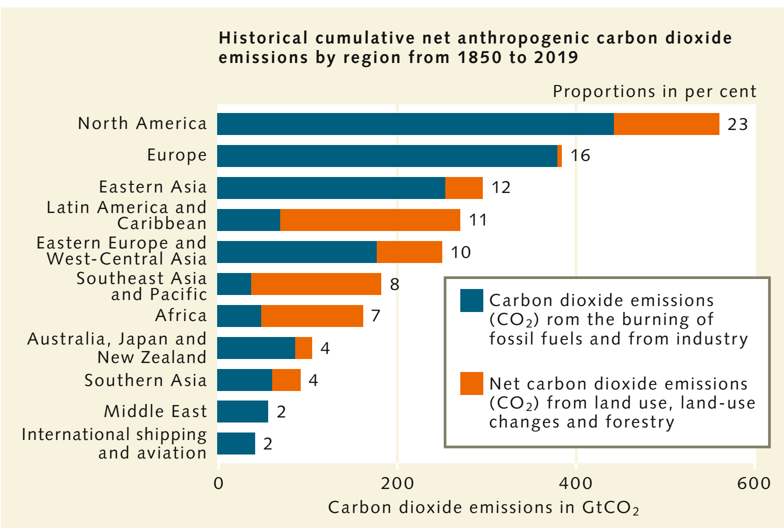


1.17 > The amount of all relevant anthropogenic greenhouse gases has steadily increased during the period from 1990 to 2019.

The annual worldwide carbon dioxide emissions resulting from cement production and the burning of fossil raw materials now add up to around 36 billion tonnes of CO_2. Added to this are the emissions from agriculture and forestry as well as changes in land use, at levels of around four billion tonnes of carbon dioxide. On a global scale, these emissions have been increasing for the past 270 years, although their growth has slowed down for the present.

1.18 > Gravel is produced at a Chinese quarry. Industrial companies like this one are responsible for more than one-third of the world's greenhouse gas emissions.





1.19 and 1.20 > **Various regions of the world contribute to greenhouse gas emissions to greatly different degrees – both at present and in retrospect, whereby all emissions are added cumulatively.**

Record values – every year

Consistently high emission levels are resulting in a steady rise in carbon dioxide concentrations in the Earth's atmosphere. For the month of May 2023, the carbon dioxide monitoring station at the Mauna Loa Observatory on the Island of Hawaii observed a record-high monthly value of 424 parts per million (ppm), an increase of 3.0 ppm compared to the value of may 2022, and the highest atmospheric CO_2 concentration in the past two million years. Carbon dioxide is definitely the strongest driver of climate change, but it is not the only one. In addition to the long-lasting gas, human societies are also increasingly releasing more short-term climate-impacting pollutants such as methane (CH_4), laughing gas (N_2O) and fluorinated greenhouse gases. Unlike carbon dioxide, these compounds break down chemically in the atmosphere. As a rule, their effect on climate becomes negligible in less than 20 years. But for as long as they exist in the atmosphere, the short-lived greenhouse gases do contribute significantly to climate change. Methane, for example, over a period of 20 years, retains 80 times more heat in the Earth's atmosphere than the same amount of carbon dioxide.

In its current report, the Intergovernmental Panel on Climate Change concludes that the increased emissions of methane from 1850 to 2019 were responsible for around 0.5 degrees Celsius of the global warming observed during that time. Converting methane concentrations and their climate impacts to carbon dioxide equivalents reveals that anthropogenic methane emissions accounted for around 18 per cent of total emissions in 2019.

Methane concentrations in the Earth's atmosphere have been directly measured since 1983. According to NOAA, the average methane concentration in the year 2022 was exactly 1911.8 parts per billion (ppb). In the year 1750, based on climate archives, it was only 729 ppb. This means that the Earth's atmosphere now contains 162 per cent more methane than it did at that time. Methane concentrations have not been this high in the past 800,000 years.

Methane is released, on the one hand, through natural sources such as swamps, mangrove forests, salt marshes and seagrass meadows. But it is also released by human activities, particularly:

- *in agriculture:* digestive processes of ruminants, rice cultivation, and manure, slurry and digestate management;
- *in the energy sector:* coal production, oil and natural gas production and transport, burning of biomass and biofuels; as well as
- *in solid waste and wastewater management:* releases from landfills, wastewaters and sewage sludges.

These anthropogenic methane emissions can be reduced with relatively little effort. Furthermore, because atmospheric methane breaks down chemically within a time frame of about nine to twelve years, thus losing its impact on climate, strategies to reduce the release of methane are seen as especially promising measures in the struggle against climate change. Recent research indicates, for example, that by the year 2050 around 0.25 degrees Celsius of additional warming could be prevented through the immediate implementation of all the presently known options for curbing man-made methane emissions.

When will global warming exceed the 1.5-degree mark?

Every additional tonne of released greenhouse gases continues to advance the progress of global warming. This near-linear relationship has been well documented by science, at least for carbon dioxide. It is now known that 1000 billion tonnes (one thousand gigatonnes) of carbon dioxide emissions cause the global surface temperature to rise an additional 0.27 to 0.63 degrees Celsius – and this occurs every time that the atmosphere is newly enriched by this amount of carbon dioxide.

But a much more common question in the climate change debate is when a particular warming level will be reached. The 2015 Paris Climate Agreement, for example, sets a target of limiting global warming to well below two degrees Celsius, and if possible to 1.5 degrees Celsius compared to preindustrial levels. A difficulty with this, however, is that the Agreement explains neither how the specific warming levels are defined, nor exactly what time period is meant by the term "preindustrial".

Climate researchers, therefore, have agreed on a common baseline. The warming level is defined with respect to the time period from 1850 to 1900 – although with full

Carbon dioxide equivalent
In order to compare the impacts of the different greenhouse gases, researchers calculate how much carbon dioxide would be required, within a certain time frame, to produce the same effect on a particular climate parameter with a given amount of methane, laughing gas, or a mix of other greenhouse gases. This calculated amount of CO_2 is referred to as the carbon dioxide equivalent.

1.21 > Farmers in the province of Sindh, Pakistan, herd their goats over flooded terrain. Heavy rains and flash floods in July and August 2022 inundated large areas of Pakistan, causing severe damage in half of its provinces.

1.22 > Climate change could be mitigated effectively if human societies were able to reduce their methane emissions. The steps needed to do this are well known. But the solutions would have to be implemented comprehensively.

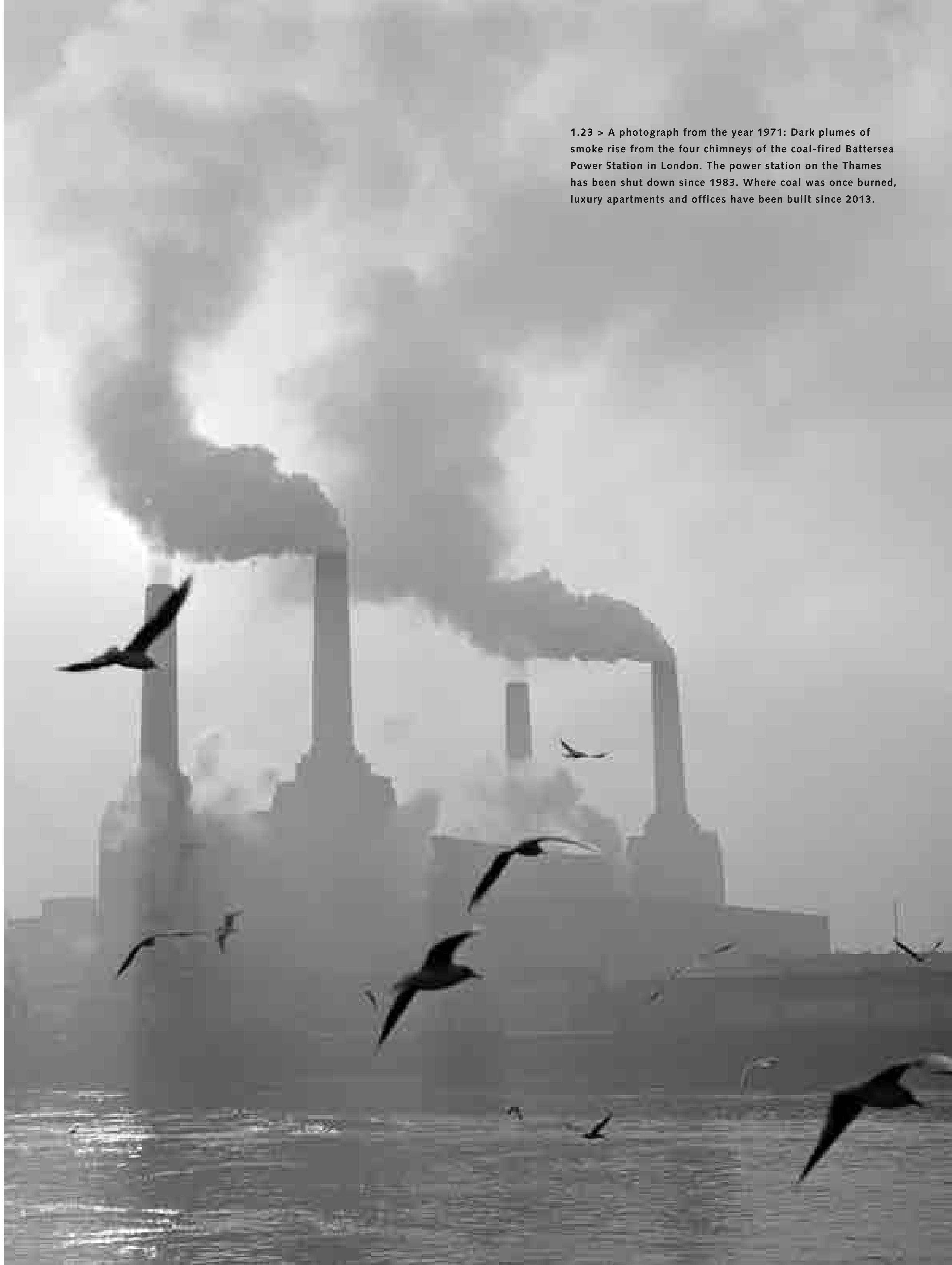
Sector	Selected measures to reduce anthropogenic methane emissions
Farming: livestock	• Use of a pre-treated, more easily digestible animal feed • Feeding seaweed and other emission-reducing additives • Improved herd management • Improved handling of manure (e.g. covering) • Introduction of anaerobic fermentation systems for cattle and pig manure • Use of the slurry in biogas plants • Breeding livestock that produce less methane • Behavioural change: largely abstaining from meat and changing to a plant-based diet
Agriculture, especially rice cultivation	• Improved irrigation and cultivation techniques, including regular flooding of rice fields and allowing them to dry out again • Use of new rice varieties • Measures to improve soils • Behavioural change: reduction of food waste
Oil, natural-gas and coal production	• Recovery and utilization of escaping gas • Sealing methane leaks at active boreholes and pipelines • Avoiding methane leaks during transport of oil and gas • Closing boreholes no longer in use • Employing modern pumping and production technology • Flooding of disused coal mines • Ending the use and production of fossil fuels
Waste and wastewater management	• No landfilling of organic waste, instead utilize it in biogas plants • Recovery of landfill gases and their direct use for production of energy • Recycling of industrial and municipal waste • Conversion from open sewers to aerobic wastewater treatment • Conversion of the treatment of household wastewater to anaerobic treatment with biogas recovery and utilization • Conversion of industrial-wastewater and sewage-sludge treatment to a two-stage process – anaerobic treatment with biogas recovery followed by aerobic treatment

awareness that industrialization had actually begun 100 years earlier and that carbon dioxide emissions had already risen rapidly, especially in Great Britain. Data of acceptable quality on the global surface temperatures of the Earth, however, only extend back to the year 1850. Researchers have therefore selected the period of 1850 to 1900 for comparison purposes.

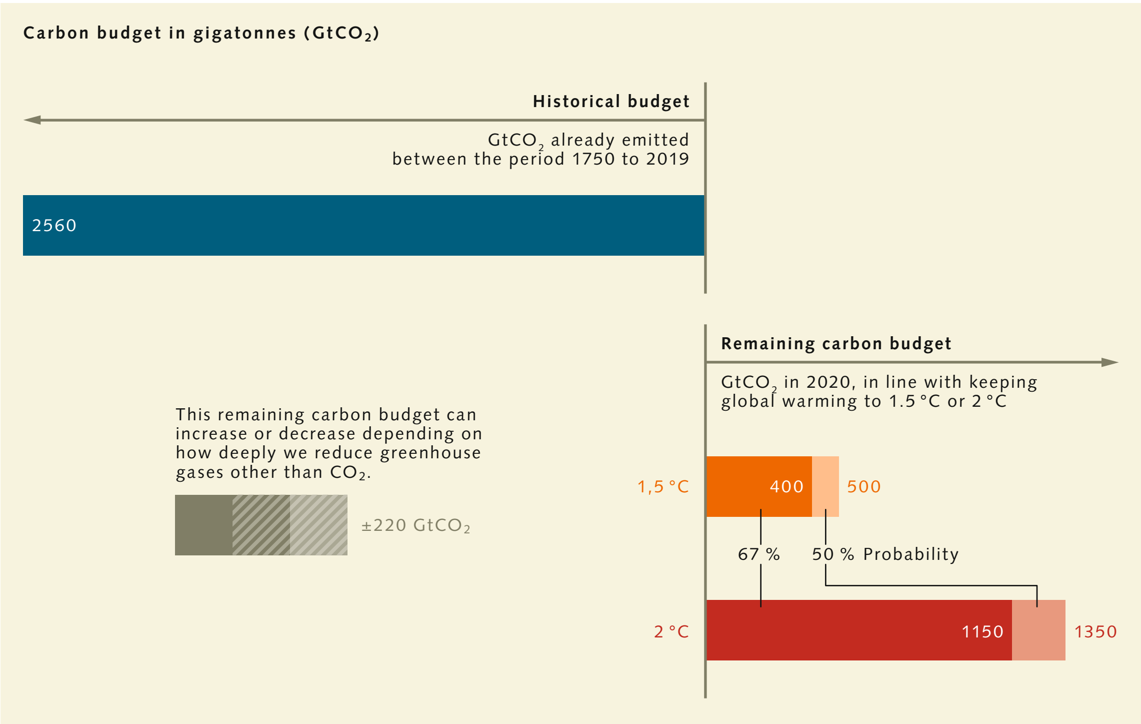
The answer to the question of when global warming exceeds a certain temperature limit is constrained by calculating warming as an average value over a 20-year period. For climate researchers, this means that the 1.5-degree limit is reached when the average surface temperature over a 20-year period lies 1.5 degrees Celsius above the average value between 1850 and 1900. But what exactly would that value be?

Precisely predicting the trend of temperature change is still difficult because the amount of future warming depends on four factors: the amount of future greenhouse gas emissions, the internal variability of the climate system (i.e., the natural fluctuations), climate sensitivity, and the uncertainties in determining the temperature levels for the reference time period of 1850 to 1900.

Researchers use the term “climate sensitivity” to refer to the amount of long-term climate warming that would be triggered by an abrupt doubling of the carbon dioxide concentration in the Earth’s atmosphere. According to current figures from the Intergovernmental Panel on Climate Change, there is a 90 per cent probability that this value would be between two and five degrees Celsius, whereby it would take several decades to centuries for the warming



1.23 > A photograph from the year 1971: Dark plumes of smoke rise from the four chimneys of the coal-fired Battersea Power Station in London. The power station on the Thames has been shut down since 1983. Where coal was once burned, luxury apartments and offices have been built since 2013.



1.24 > Because carbon dioxide accumulates in the atmosphere, scientists can calculate the amounts that can still be released before a certain level of warming is reached. In the year 2020 this amount was an additional 400 gigatonnes of carbon dioxide for the world to reach the 1.5-degree target with a probability of 67 per cent.

to occur and for the climate system to return to a state of equilibrium after the disturbance (i.e., after the doubling of the carbon dioxide concentration).

Because the range of this value has a span of three degrees Celsius, climate models can produce significantly different results. If scientists use an intermediate sensitivity value in their climate models, calculations based on the five Shared Socioeconomic Pathways indicate that the 20-year average temperature in the time frame from 2020 to 2039 will reach the 1.5-degree limit, totally regardless of what amounts of greenhouse gases humans release in the coming years. If emissions remain at the present high levels or continue to increase, global warming will exceed the limit of two degrees by the year 2050.

The amount of time remaining to curb climate change can be assessed by what scientists call the carbon budget, which is an expression of how much carbon dioxide can still be emitted by human activities before a given level of warming is reached. The calculations for this are based on the assumption that the global surface temperature rises by around 0.45 degrees Celsius (0.23 to 0.65 degrees) when humankind releases an additional 1000 billion tonnes of carbon dioxide into the atmosphere. Other factors that are considered include past warming, the contribution of greenhouse gases other than carbon dioxide to future warming, and the question of how long the warming will continue to progress even if humans manage someday to reduce their carbon dioxide emissions to zero.

During the period from 1750 to 2019, human societies emitted around 2560 billion tonnes of carbon dioxide. Taking all methodological uncertainties into account, the Intergovernmental Panel on Climate Change finds that this amount of greenhouse gas is probably already enough to reach the 1.5-degree mark. According to the experts, this means that the remaining carbon budget would be zero, although the probability of this would be low. However, if the "best estimates" are used for the most important parameters, the calculated carbon budget is greater than zero.

Nonetheless, the results indicate that it is still small: If humans want to limit global warming to 1.5 degrees Celsius with a probability of 67 per cent, they can only release a total of 400 billion tonnes of carbon dioxide, calculated for the period beginning on 1 January 2020. This corresponds roughly to the amount of carbon dioxide emitted by the international community over the past decade (2010 to 2019). The budget for the two-degree target is 1150 billion tonnes. Based on constant continued emissions at the current level of around 40 billion tonnes per year, the two budgets would be exhausted by the years 2030 or 2050, respectively.

Paris Climate Agreement
The Paris Climate Agreement was adopted on 12 December 2015 at the 21st Climate Conference in Paris and entered into effect on 4 November 2016. By September 2022, 194 countries and the European Union had signed and ratified the agreement.

The following statistic also shows how little margin we have remaining: If humankind were to allow all fossil infrastructures already in operation in 2018 – i.e., coal and natural-gas power plants, oil refineries, blast furnaces, combustion engines, etc. – to continue running at the same capacity as they have in the past until the end of their respective lifetimes, an additional 660 billion tonnes of carbon dioxide would be released in the coming decades. If this calculation is expanded to include all of the installations that were planned or under construction in the year 2018, another 187 billion tonnes of carbon dioxide would have to be added to that sum. Limiting global warming to less than two degrees Celsius under these conditions would be in serious jeopardy. A ban on new coal or natural-gas power plants would thus be an important step towards preventing future emissions.

The ultimate goal: greenhouse gas neutrality

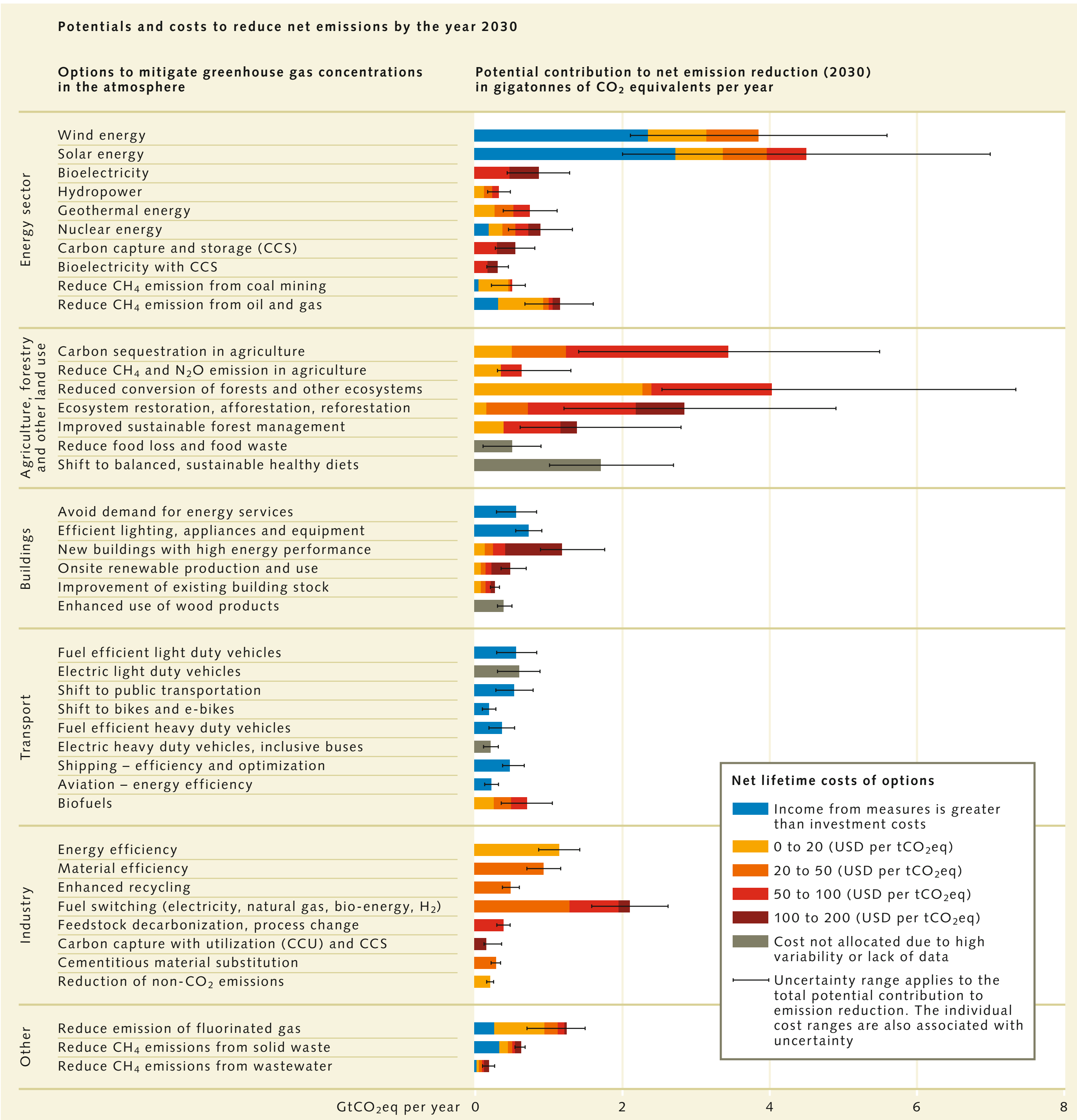
Limiting global warming to 1.5 degrees in the coming decades will now hardly be possible – at least not without overshooting the temperature target for a few decades (surplus scenario). Through a huge effort, however, it may be possible to limit global warming to less than two degrees Celsius. To realize this goal would require immediate and wide-ranging reductions of global greenhouse gas emissions, as well as achieving net zero carbon dioxide emissions by the year 2050.

There are ideas for far-reaching emission reductions in every sector. According to the Intergovernmental Panel on Climate Change, it is possible to cut global greenhouse gas emissions in half by 2030 based on known options. More than half of the potential reduction can be realized through measures that would cost less than 20 US dollars per tonne of carbon dioxide that is eliminated, a fact that is especially important for poorer countries. Examples of these include the worldwide expansion of wind-power and photovoltaic systems for generating electricity from renewable sources, an end to deforestation and the draining of wetlands, improved carbon storage capacities in many fields through sustainable and soil-conserving agriculture, a substantial reduction in meat consumption, construction of energy-efficient buildings, the use of alternative fuels in industry, and measures to curb methane emissions.

This may appear to be a perfectly feasible programme. It requires, however, the successful implementation of comprehensive structural and societal changes, as well as restructuring and rethinking at all levels, including new ideas about what people need (and must consume) and do not need to live. Furthermore, cutting the emissions by half would only be the first step.

This would have to be followed by a reduction of greenhouse gas emissions to such an extent that greenhouse gas neutrality is achieved as soon as possible. The term "greenhouse gas neutrality" and the synonymously used term "net-zero greenhouse gas emissions" both describe a world in which humans or individual entities such as states and companies only release as much greenhouse gas as they can remove again from the Earth's atmosphere. Experts distinguish the terms "carbon neutrality" (net zero carbon dioxide emission) and "greenhouse gas neutrality" (net zero of all greenhouse gas emissions, including carbon dioxide). The reason, in terms of climate physics, is that the global surface temperature could be stabilized if humans would release only as much carbon dioxide as they can remove, while at the same time reducing the release of short-lived air pollutants such as methane and laughing gas by a certain amount. If all greenhouse gas emissions could be reduced to net zero, on the other hand, the global temperature would even begin to fall over the long term. A net zero of carbon dioxide emissions is thus a major, indeed fundamental prerequisite to halting global warming. But with the added help of a net zero of all greenhouse gas emissions it would even be possible to roll back global warming by a small amount.

Surplus scenario
A development in which the global surface temperature rises above a defined climate target (for example, 1.5-degree target) for an initial time period of one or more decades, but subsequently falls again below the temperature threshold, is called a surplus scenario. However, the temperature decline can only occur if the greenhouse gas concentration in the atmosphere is really decreased through a process of carbon dioxide removal.



1.25 > Approaches are now available that would effectively reduce greenhouse gas emissions in all areas of life by the year 2030. This figure from the Intergovernmental Panel on Climate Change lists the most effective measures and shows the costs at which the reductions would be possible. It is important to note that investing in such reductions would cost much less than remedying the consequences of continued climate change.

Methods for carbon dioxide removal

The term "carbon dioxide removal" (CDR) is used to discuss and research the methods that can be applied for removing carbon dioxide from the atmosphere. Although ideas for the removal of methane are also beginning to be suggested, scientific assessment of their feasibility is not yet possible due to insufficient research at present.

CDR covers a wide range of processes that can be used to remove carbon dioxide from the atmosphere and then store it permanently. Possible storage sites include the deep geological subsurface, the oceans and sites on land, especially soils and vegetation. A fourth option would be to use the extracted carbon dioxide to make various products from carbon.

Carbon dioxide removal – offsetting residual emissions that are difficult to avoid

Climate researchers assume that the international community, despite its highly ambitious climate policies, will still be emitting several billion tonnes of residual greenhouse gases (carbon dioxide, methane, laughing gas) by the middle of the 21st century. These hard-to-avoid residual emissions will be generated, for example, in the production of cement and steel, in aviation and heavy-duty transport, and in agriculture and waste incineration.

To achieve greenhouse gas neutrality, these residual emissions will have to be compensated for using carbon dioxide removal methods. There are various proposals for solutions that involve either the expansion of natural carbon sinks or technological approaches. Experts assign the numerous CDR methods to four categories:

- enhancement of the biological carbon dioxide sinks on land, e.g. through reforestation,
- enhancement of the biological carbon dioxide sinks in the ocean, e.g. through the restoration of damaged or dead mangrove forests and seagrass meadows,
- geochemical approaches, and
- chemical methods.

It is important to note that only those methods can be counted that result from human efforts to enhance the removal of carbon dioxide from the atmosphere. Trees that naturally establish themselves somewhere, photosynthesize, absorb and sequester carbon dioxide should not be included in the CDR balance. The official CDR definition of the Intergovernmental Panel on Climate Change is so narrow that even approaches in which carbon dioxide from fossil sources is captured at the emission site and subsequently stored underground (Carbon Capture and Storage, CCS) or processed into products (Carbon Capture and Utilization, CCU) may not be considered as CDR. In this case carbon dioxide is not actually removed from the atmosphere, rather its escape into the atmosphere is simply prevented.

The IPCC's definition of CDR
The term "carbon dioxide removal methods" applies exclusively to such practices in which the carbon dioxide removed comes from the atmosphere, its subsequent storage is durable, and its removal is an outcome of human action and is thus additional to the natural carbon dioxide removal processes of the Earth system.

Some CDR methods have been carried out for centuries, although not with the explicit purpose of removing carbon dioxide from the atmosphere. These include the reforestation of deforested areas, the sustainable management of existing forests, and the conservation of peat- and wetlands. They also include regenerative types of agriculture that lead to increased humus or carbon content in the soil by removing carbon dioxide and other carbon compounds from the atmosphere and storing them in the soil, mostly in the form of organic material (plant remains, manure, etc.). The best-known practices for enriching soils with carbon include the cultivation of perennial grasses and legumes, improved crop rotation including catch cropping, the application of compost and manure, and reduced soil tillage.

There are other comparatively new CDR methods, however, whose specific purpose is to decrease greenhouse gas concentrations in the atmosphere. These include methods such as the capture of carbon dioxide from the air and its subsequent storage (Direct Air Carbon Capture and Storage, DACCS) or the generation of bioenergy with subsequent carbon dioxide capture and storage (Bioenergy with Carbon Capture and Storage, BECCS). Experience and knowledge of these approaches are growing, but they are still being applied on a comparatively small scale.

Furthermore, CDR methods differ with respect to the length of time that the carbon dioxide is removed from the

Afforestation and reforestation
The Intergovernmental Panel on Climate Change defines the term "afforestation" as the planting of trees in an area that was not forested in the past. One could therefore also refer to this as "forestation". "Reforestation", on the other hand, means the planting of young trees in an area whose former forest cover has been destroyed by clearing, fire or other human activities.

atmosphere. The possible time frames range from a few decades to millions of years, and depend specifically on the storage site. Carbon dioxide that is absorbed by the ocean or is stored in deep-lying rock layers usually remains there for a longer time than carbon dioxide that is sequestered by forests on the land. Natural storage sites on land are also more susceptible to disruption. Wetlands, for example, can dry out, and forests can burn down. In both cases the carbon dioxide will escape into the atmosphere again. The risk of escape is somewhat lower when trees are felled and used for durable timber elements (e.g. roof beams) or when long-lived products are made from captured carbon dioxide.

Last of all, the various CDR methods differ from one another in the extent to which they can be applied, how much carbon dioxide can be removed from the atmosphere with their help, what possible risks and advantages a method poses, the costs associated with their large-scale application, and whether the necessary technology has even been developed and is ready for implementation. Science is presently searching for the answers to these and many other questions in various research projects.

No substitute for comprehensive emission reductions

Considering the enormous speed at which the Earth's climate is changing, there is no longer any question as to whether mankind must remove carbon dioxide from the atmosphere in order to limit global warming to a tolerable minimum level for humans and nature. Without a doubt the answer is yes! But the unresolved questions now are how, to what extent, with what goals, and under what basic conditions such removal should and can happen.

It is certain that if humankind is to achieve the Paris climate goal, removing carbon dioxide can never be accepted as a substitute for comprehensively reducing emissions. The Intergovernmental Panel on Climate

1.26 > Iceland has achieved some small-scale success in removing carbon dioxide from the atmosphere and sequestering it underground. The process involves dissolving the extracted gas in fresh water and injecting it into the warm volcanic basalt rocks. The components of the rocks react chemically with the carbon dioxide, resulting in its mineralization and conversion to rock material itself.

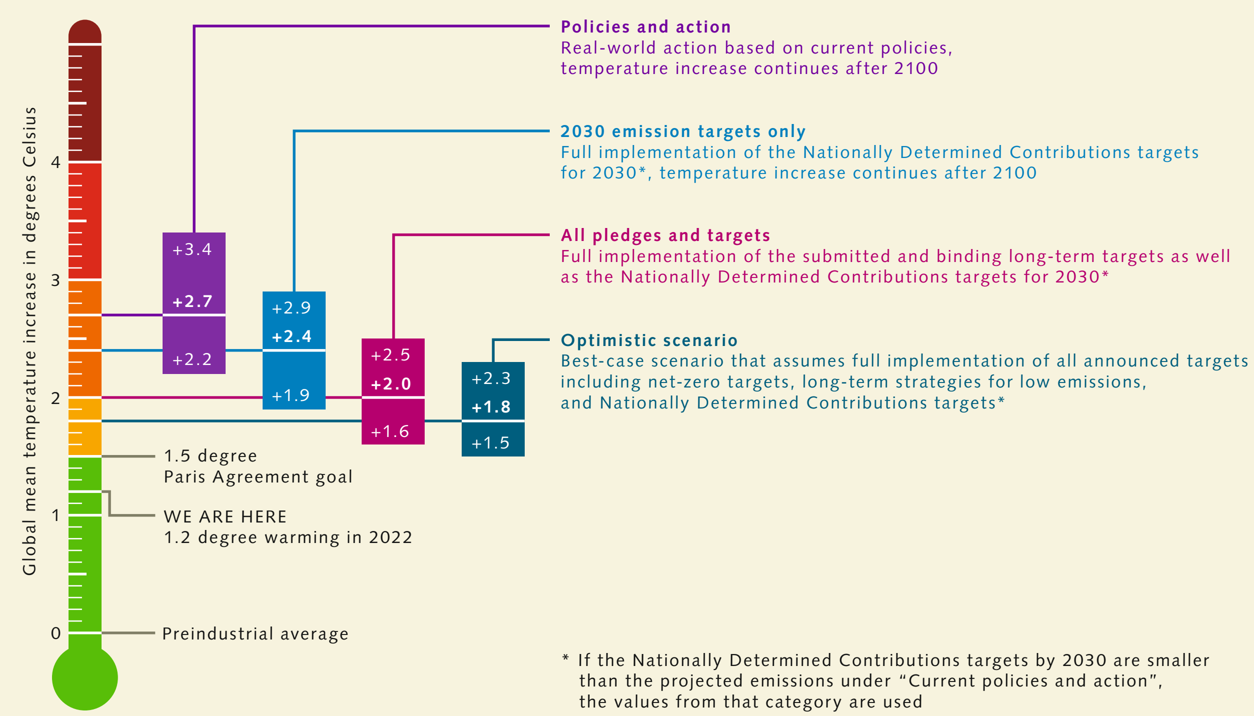
Climate goals – progress at a snail's pace

In the Paris Climate Agreement, all signatory states committed to limiting global warming to well below two degrees Celsius. A prerequisite for this is net-zero greenhouse gas emission by the second half of this century. To achieve this goal, the countries are all required to develop a national long-term climate strategy and to establish and publish Nationally Determined Contributions (NDCs) every five years. More than 140 states have already complied in this task. The Federal Republic of Germany, for example, has committed to becoming greenhouse gas neutral by the year 2045. This commitment will be facilitated by the Climate Change Act, amended in June 2021, which imposes mandatory emission caps on the energy sector, industry, agriculture, transport and buildings. By the year 2030, according to the plan, German greenhouse gas emissions will be reduced by 65 per cent compared to the year 1990.

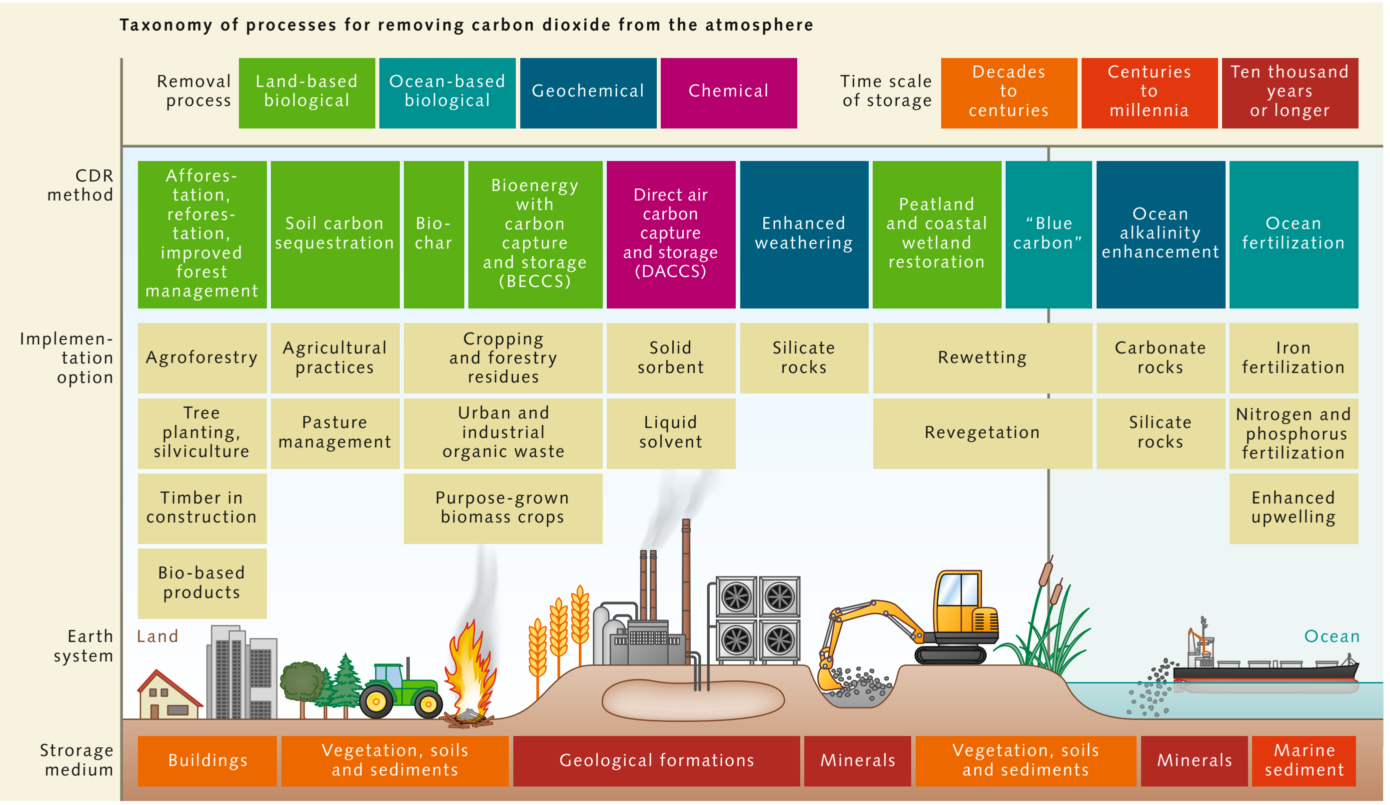
However, Germany and many other countries are lagging behind in the implementation of their self-imposed climate targets. Progress in the fight against climate change is still moving at a snail's pace worldwide.

Based on the current climate protection laws and catalogues of measures, experts are projecting global warming of two to 3.6 degrees Celsius by the year 2100. More commitment, political will and investment in climate action are therefore vital. According to the International Energy Agency (IEA), in the year 2022 almost 89 per cent of the record-high global carbon dioxide emissions in the energy sector were still attributable to the burning of fossil raw materials and the accompanying industrial processes (production, processing). This confirms that humanity is still firmly entrenched in the fossil age.

Global temperature increase by 2100, calculated by Climate Action Tracker experts (date: November 2022)



1.27 > Experts at the Climate Action Tracker regularly analyse international climate policies and, based on climate action taken and pledged by all countries, calculate how much warming the planet is approaching by the year 2100. In November 2022, the measures implemented up to that point indicated a warming of 2.2 to 3.4 degrees Celsius.



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

Change says that the level of greenhouse gas emissions is far too high for that. The use of CDR methods is conceivably a way to compensate for residual emissions that are difficult to eliminate. They can help to reduce the net anthropogenic emissions more quickly in the near future. In the long term, CDR would help humanity to compensate for unavoidable carbon dioxide residual emissions as well as the emissions of other greenhouse gases. In the best case, it would one day be possible to achieve net-negative emissions. This would mean that the amount of carbon dioxide being removed from the atmosphere would exceed the amount of CO_2 equivalents being released. As a consequence, the greenhouse gas concentrations in the atmosphere would decrease, which would be followed by a decline in the global surface temperature.

But the first milestone along this path would be to achieve net-zero carbon dioxide emissions. The goal of comprehensive greenhouse gas neutrality would then follow after about ten to 40 years, or maybe even much later depending on the amount of residual greenhouse gas emissions (methane, laughing gas, etc.) that would have to be compensated for by carbon dioxide removal.

For a global net zero of carbon dioxide emissions, not all countries would have to offset their residual emissions. If some countries are able to remove more carbon dioxide than they release into the atmosphere by emissions, there would be a condition of net-negative emissions, or an emission credit. Other countries could then redeem this credit. They would then have more time to reduce their own greenhouse gas emissions without an increase in the overall carbon dioxide concentrations in the Earth's atmosphere and the accompanying rise in average global temperatures.

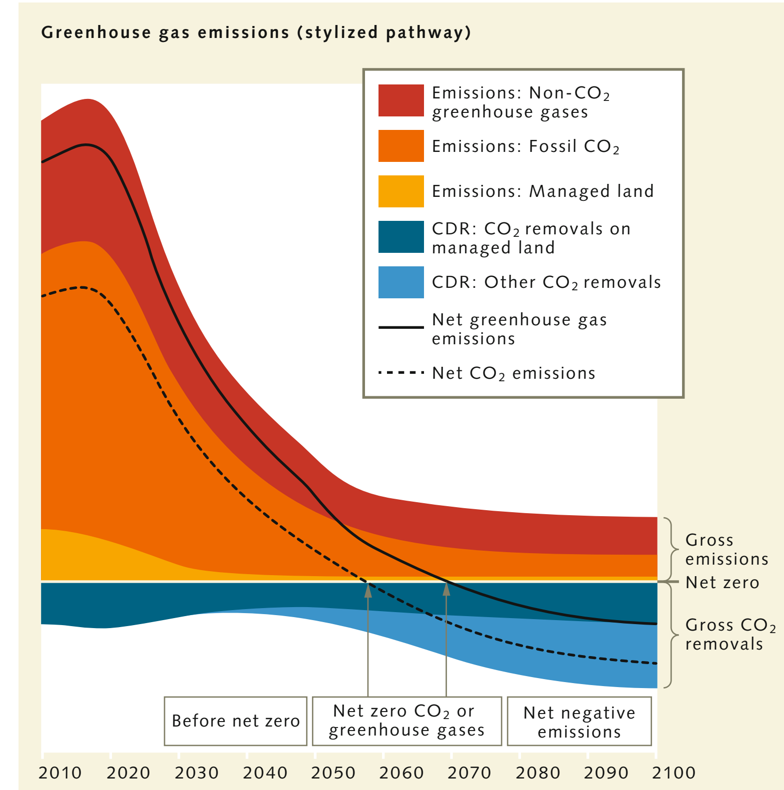
Major concerns and many unanswered questions

So far, only a few countries have adopted CDR methods beyond afforestation and reforestation in their long-term climate strategies. Nevertheless, according to the Intergovernmental Panel on Climate Change, there is concern in many circles that simply the theoretical possibility and feasibility of increased carbon dioxide removal could lull governments and other societal stakeholders into half-hearted attitudes in implementing ambitious greenhouse gas reduction plans, or lure them into placing their trust in technologies that have not yet been sufficiently developed and researched in the fight against climate change.

A further misgiving is that the hope for effective CDR measures could induce decision-makers to fail to rigorously address the challenges associated with drastic greenhouse gas reductions, and instead defer action to the future. This would mean that the next generation would have to deal with the steadily growing problem. It is also unclear how the costs, risks and burdens of large-scale CDR efforts can be evenly distributed, and how negative effects can be avoided, particularly in the areas of food production, biodiversity and the availability of land.

Furthermore, reliable and globally standardized methods would be needed to measure, verify and assess the carbon dioxide removal and storage achieved through CDR measures. A transparent and functioning market, in which emission credits could be traded and financial resources generated for the implementation of CDR measures, can only be realized when these conditions are met.

In the view of the Intergovernmental Panel on Climate Change, there are still many challenges that need to be overcome before CDR methods more sophisticated than reforestation can be implemented on a large scale. These include the many unanswered research questions, the immature state of technological development, high costs, and the fact that the possible implementation of new kinds of CDR methods in the future needs to conform with the overarching development and sustainability goals of the international community. This calls for matching laws and regulations, along with the corresponding decision-making processes, before novel CDR methods can be implemented.



1.29 > 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.

How much CDR is needed in the future?

Science is investigating approaches and ideas for the struggle against climate change with the help of Integrated Assessment Models (IAMs). These are being developed in order to understand how particular societal or economic developments affect nature and the climate. To this end, the models are fed with information about the Earth system as well as about society. The models thus consider natural laws as well as the behavioural changes of humans, and they also assess the undesirable side effects or desired advantages of particular measures and decisions. Although the model predictions are always subject to some degree of uncertainty, IAMs do provide valuable insights. They can demonstrate, for example, how our economy, society and energy supply would have to change in order to achieve a given climate goal, or show us what impacts certain emission reductions would have for humans and nature.

Researchers in IPCC Working Group III evaluated thousands of such integrated assessment models for the *Sixth Assessment Report* of the Intergovernmental Panel on Climate Change. This work has clearly illustrated that all models that project a limit on global warming of two degrees Celsius or less include a robust implementation of methods for carbon dioxide removal at significantly higher levels than any that are being carried out at present.

The amount of carbon dioxide that will have to be removed from the atmosphere in the future in order to stabilize the climate has not yet been clearly determined. The model results only allow rough estimates. But for land-based biological methods such as afforestation and reforestation, the estimates fall within the order of 900 million tonnes of net carbon dioxide in the year 2030. In this case, net means that the carbon dioxide removal through afforestation and reforestation must be 900 million tonnes greater than the sum of global land-use emissions produced at the same time (such as deforestation in certain regions). Two decades later the net removed amount would have to be almost three billion tonnes of carbon dioxide if global warming is to be held to less than two degrees Celsius over the long term. In addition, similarly large amounts of carbon dioxide would have to be removed through energy generation from biomass and through direct air capture. For both of these methods the captured carbon dioxide would subsequently have to be safely and permanently stored somewhere.

In light of these high estimates, the IPCC has concluded that existing programmes of land-based carbon dioxide removal need to be expanded massively and very rapidly. It is questionable, however, whether this can be achieved at the necessary scale.

The assessment models being studied by the IPCC have not yet been able to integrate ocean-based methods of carbon dioxide removal. The *Sixth Assessment Report* therefore does not provide any information on how much they could contribute to achieving the Paris Climate Agreement goals. The first research teams, however, including scientists from Germany, have begun to take on the task of developing IAMs with components of marine-based carbon dioxide removal. Their motivation for this work is fuelled by the knowledge that the ocean has already absorbed and stored one quarter of the carbon dioxide emissions caused by human activities in the past, with wide-ranging consequences for humanity and nature.

1.30 > Here, near the Brazilian city of Porto Velho, slash-and-burn clearing of the Amazon rainforest has provided arable land for the cultivation of soya beans. Along with the forests, enormous areas of carbon storage are lost because the trees store carbon in their wood and leaf mass as well as in the forest soils.

Conclusion

There is only one solution to the climate crisis – greenhouse gas neutrality

With their emissions of greenhouse gases over the past 120 to 170 years, humans have caused global surface temperatures to increase by around 1.15 degrees Celsius. Because of this warming, many components of the Earth’s climate have been changing at rates that our planet has not experienced in thousands of years. The consequences of climate change are harming humanity and nature to an increasing degree and are slowly depriving people of their basic needs. Foremost among these are health and physical integrity, along with sufficient water and food.

All regions of the Earth are being affected by climate change. The magnitude of the changes and the consequences and risks for people and nature, however, vary from one region to another. The increasing occurrence of extreme events presents a particular danger. If heat waves, heavy rains, severe storms, droughts or floods occur simultaneously, the overall risk is multiplied and it becomes more difficult for people and nature to respond effectively. Climate change also magnifies the risks of other man-made stressors such as environmental degradation, resource over-exploitation and urbanization, further curtailing the adaptive capacities of all inhabitants of the Earth.

Every additional tenth of a degree of warming provides climate change with more momentum. This means that the magnitude and the extreme rate of the changes, as well as the consequences and risks, increase with every added temperature rise. Escalation of the climate and biodiversity crises can only be addressed through effective adaptive measures, along with avoidance of any further greenhouse gas emissions (greenhouse gas neutrality).

Even with very ambitious climate policies, climate scientists assume that the international community will still be emitting residual greenhouse gases in the middle of the 21st century including carbon dioxide residues, but especially methane (CH_4) and nitrous oxide (N_2O). These hard-to-eliminate residual emissions are generated by cement and steel production, aviation and heavy-duty transport, but also by agriculture and the burning of waste.

To stop global warming, the residual emissions will have to be offset. This will require equal amounts of carbon dioxide to be removed from the atmosphere, and feasible ideas exist for achieving this. They focus either on the expansion of natural carbon sinks or are based on technological approaches. Furthermore, the capture methods are classified according to the time frame in which the carbon dioxide is removed from the atmosphere and by the scale at which they can be applied.

In many cases, however, the possible risks associated with a given method are not clear, particularly the costs and whether the necessary technology is sufficiently developed and ready to be employed. Thus, elementary knowledge is lacking for measures that will soon need to be carried out at industrial scale to achieve the goal of greenhouse gas neutrality in the future. One thing is certain: Measures to remove carbon dioxide can never be used as an excuse to continue the avoidable emission of greenhouse gases because, ultimately, every single tonne of carbon dioxide avoided counts in the fight against the climate and biodiversity crises.

2 The role of the ocean in the global carbon cycle

> The world ocean is the second largest carbon reservoir on Earth. It stores around 40,000 billion tonnes of carbon. The amount of carbon contained in the ocean exceeds that in the atmosphere by a factor of greater than 50. The ocean and atmosphere, however, are constantly exchanging carbon. With increasing concentrations of carbon dioxide in the atmosphere, more carbon dioxide is absorbed by the ocean, which slows the rate of climate change.

How the ocean absorbs carbon dioxide

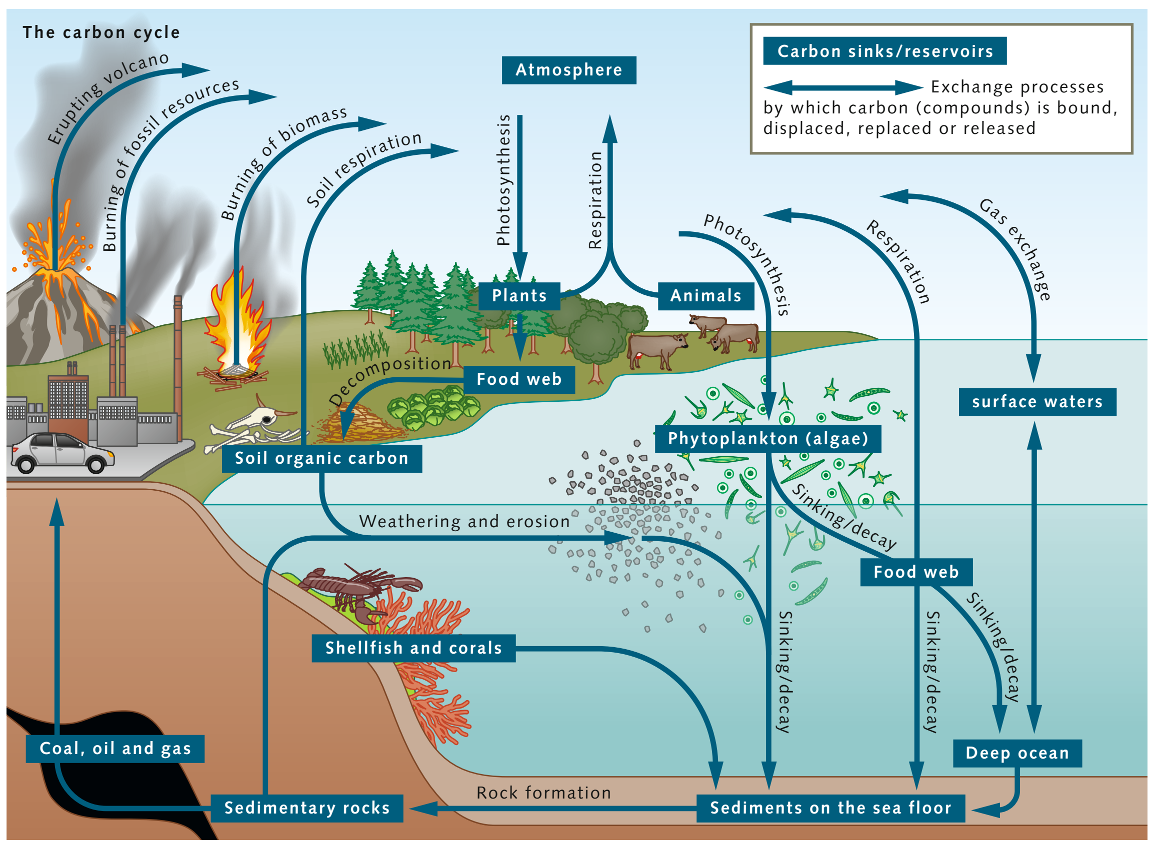
> In recent decades, the world ocean has absorbed around 25 per cent of the carbon dioxide emissions produced by human societies, thus retarding the progress of climate change significantly. This climate service is achieved through three natural carbon pumps whose functions may seem rather complex. Taken together, they are the reason that the world ocean is the second largest carbon sink on Earth. There is, however, a high price for this service in the form of ocean acidification.

Carbon – an essential element

Carbon is an essential building block for life on our planet. All of the tissues produced by living organisms, including plants, animals and people, are comprised of compounds that contain carbon. Carbon is required for animal and plant cells to function. It is in our food, in wood and coal, marble and limestone, as well as oil-based synthetic materials and fuels. This is due to the high bonding capacity of the carbon atom. In particular, it is often contained in compounds with hydrogen, oxygen, nitrogen and phosphorus. There are presently more than a million different carbon compounds known to science, and more are being added every year. These form the basis of the field of chemistry known as organic chemistry.

Because of its chemical properties and extensive distribution, carbon is constantly being naturally captured or released, chemically bonded or converted, everywhere around the globe. Furthermore, it is involved in almost all of the biological processes in which energy is either produced or consumed. These include, among others, photosynthesis, oxygen respiration and chemosynthesis. This means that carbon is in constant motion and, through time, migrates through all of the components of the Earth system. For the various steps of this journey, which is known as the carbon cycle, carbon requires different amounts of time. Sometimes it or its compounds are released (respiration, combustion, volcanic eruptions) or taken up (photosynthesis, dissolution in seawater) within a few short minutes, while in other situations it can be stored for thousands or even millions of years in one location (permafrost, formation of fossil resources). At the same time, its physical state also changes: Carbon and its compounds can occur in gaseous form, as carbon dioxide and methane, for example, or in the liquid or solid state.

The carbon dioxide concentration in the Earth's atmosphere, which is of crucial importance for the climate, is determined by various biogeochemical processes occurring both on land and in the sea. These determine whether this greenhouse gas is removed from the atmosphere and stored (carbon sinks) or is released into it (carbon sources).

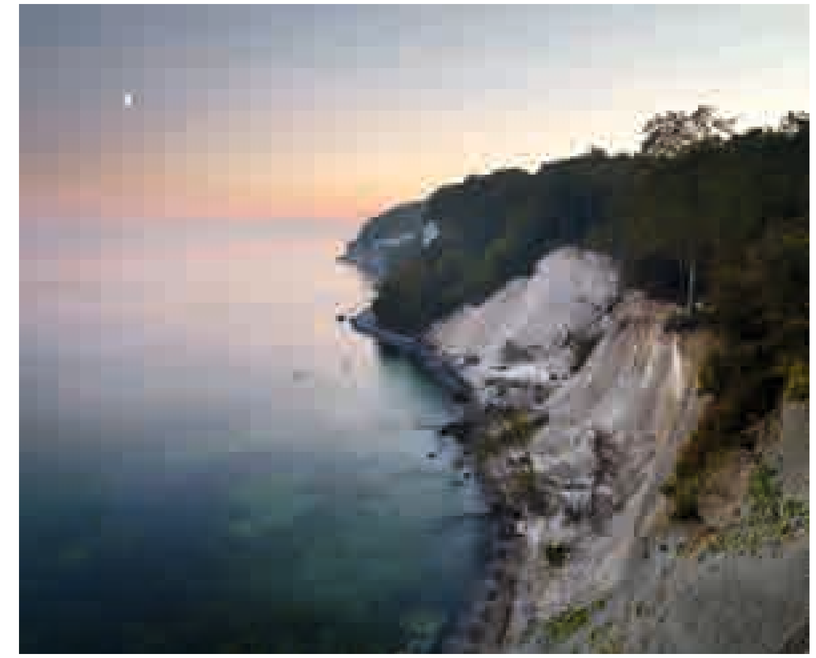


2.1 > The Earth's natural carbon cycle: Carbon sinks, or reservoirs, in which carbon or one of its many compounds are stored, are shaded in blue. The arrows represent exchange processes through which carbon or one of its many compounds are bound, stored, exchanged or released.

Ocean carbon reservoir

The ocean is our planet's second-largest carbon sink after the Earth's rocky shell (sedimentary rocks on land and the sea floor). It contains around 40,000 billion tonnes of carbon, the greatest share of which is dissolved in seawater. With this carbon reservoir, the ocean exceeds the carbon content of the atmosphere by a factor greater than 50. These two systems are in a state of constant carbon exchange. More than 150 billion tonnes of carbon in the form of the greenhouse gas carbon dioxide move back and forth between the ocean and atmosphere every year. Using an atomic weight conversion factor of 3.664, the annual global exchange of gases between the ocean and the atmosphere thus comprises more than 549 billion tonnes of carbon dioxide.

Because carbon dioxide concentrations in the atmosphere are increasing due to the emissions produced by human societies, the ocean is also absorbing more carbon dioxide. In contrast to preindustrial times, it is now taking up more carbon dioxide from the atmosphere than it releases elsewhere. The result is that the world ocean has absorbed around 25 per cent of the carbon dioxide released into the atmosphere by humans in recent decades, thus significantly inhibiting the progress of global warming. An estimated 40 per cent of the anthropogenic carbon dioxide emissions taken up by the world ocean were absorbed in the Southern Ocean. The especially great absorptive capability of the Southern Ocean, however, is subject to large natural fluctuations, which make a precise evaluation of the balance of the world ocean's carbon dioxide uptake very difficult.



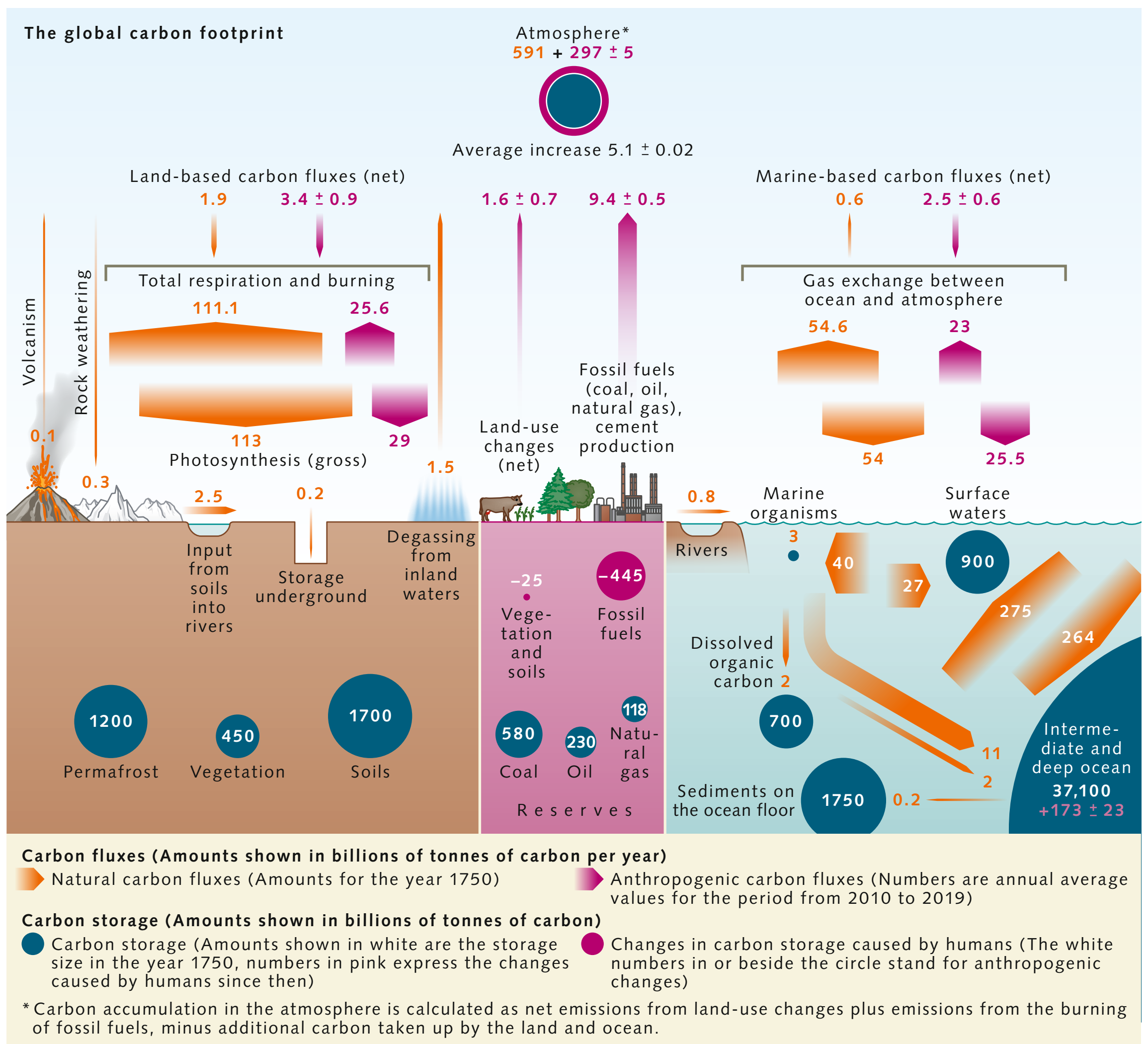
2.2 > The chalk cliffs on Germany's island of Rügen are composed of carbonate rocks. When carbon dioxide-rich rainwater falls on these rocks they weather readily, and acid-binding solution products are washed into the Baltic Sea. These react with free protons in the seawater and reduce its acidification.

Carbon dioxide uptake by the ocean occurs at the sea surface, where it is dissolved from the air into the seawater. Whether atmospheric carbon dioxide dissolves in the water, and the amount dissolved, depends primarily on the difference in carbon dioxide partial pressure between the seawater and atmosphere. Simply stated, this is the pressure generated by carbon dioxide dissolved in the surface water and that in the atmosphere. The natural exchange of gas between the seawater and the atmosphere always works towards a balance of these pressures. This means that surface waters with a lower partial pressure of carbon dioxide than the overlying atmosphere will take up carbon dioxide from the air until the pressure difference is no longer present. The pressure-equilibration process also works in the opposite direction from the water into the atmosphere.

The water temperature, as well as salinity, wind, waves and currents, also affects carbon dioxide absorption by the ocean. The temperature and the salinity of the surface waters have an effect on the amount of gas that can be dissolved. The warmer and saltier the water is or becomes, the less carbon dioxide it can absorb or store, and the more it thus tends to release into the atmosphere.

This physical principle explains, among other things, why the world ocean releases carbon dioxide into the atmosphere in the warm, equatorial part of the Pacific, for example, while it absorbs large amounts of carbon dioxide in the cooler Southern and North Atlantic Oceans.

At the same time, wind and waves mix the surface waters, which effectively balances the carbon dioxide concentrations within the upper water layer. Marine currents keep the water masses in motion, and ensure, for example, that new deep water is constantly brought to the surface in upwelling zones, where it can engage in gas exchange with the atmosphere.



2.3 > 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.

A chemical equilibrium reaction

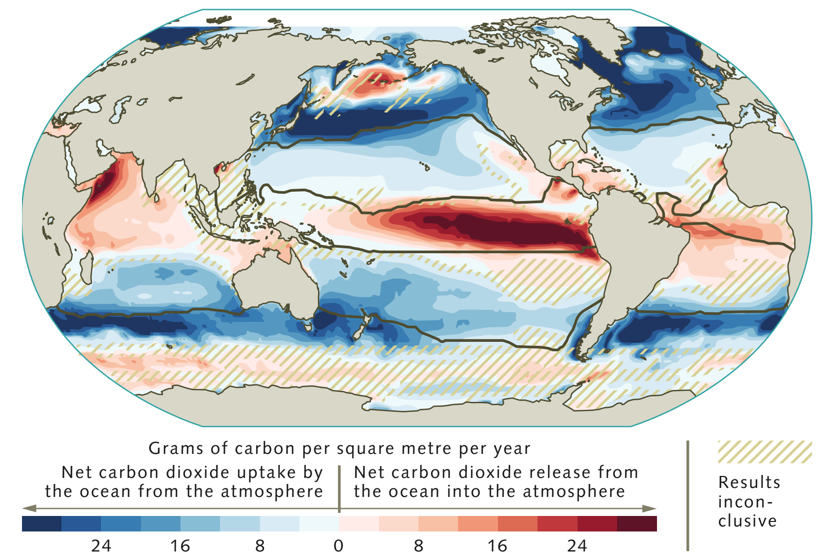
When the carbon dioxide concentration in the atmosphere increases, it usually leads to a rise in the carbon dioxide concentration in the surface waters of the ocean within a few months. As carbon dioxide dissolves in seawater, a chemical change occurs in the surface waters because, unlike oxygen for example, carbon dioxide does not simply dissolve in the sea. A certain proportion of the CO_2 reacts with the water molecules to form carbonic acid. With very few exceptions, these molecules, in turn, immediately split into hydrogen carbonate plus one hydrogen cation (which is a proton). If the hydrogen carbonate loses another proton, a carbonate anion is formed.

The surface water thus contains carbon in three different dissolved forms:

- as carbon dioxide (CO_2), which can also be released into the atmosphere again. It makes up only about one per cent of the carbon stored in the ocean, but it determines the partial pressure of carbon dioxide for the seawater;
- as hydrogen carbonate, which accounts for around 90 per cent of the carbon stored in the ocean;
- as carbonate, which, it should be noted, is not only formed as a result of the carbonic acid chain reaction, but is also released as a result of rock and mineral weathering on land (more on this later).

These three forms exist in a balanced state of concentration equilibrium with each other, which means that a change in one parameter immediately leads to compensating reactions in the other two. As an important example, when water and dissolved carbon dioxide react to form carbonic acid, hydrogen carbonate is also formed. This results in a decrease in the proportion of dissolved carbon dioxide in the seawater and thus the partial pressure of carbon dioxide. As a result, the ocean takes up more new carbon dioxide from the atmosphere in order to balance the partial pressure between the ocean and atmosphere. The chemical chain reaction then starts again from the beginning. This process, however, cannot be continued indefinitely. Carbon dioxide absorption shifts the concentration equilibrium between dissolved carbon dioxide, carbonic acid, hydrogen carbonate and carbonate to such an extent that carbon dioxide uptake by the surface water will eventually come to a standstill, unless other additional or new processes disturb or shift the equilibrium again.

Net carbon dioxide flux between atmosphere and ocean (1994 to 2007)



2.4 > The ocean does not absorb the same amounts of carbon dioxide from the atmosphere everywhere in the world. As this map illustrates, carbon dioxide uptake occurs primarily in the cold Southern Ocean and in the North Atlantic and North Pacific Oceans (blue shading). In the warm tropical regions, on the other hand, the ocean releases considerably more carbon dioxide into the atmosphere than it absorbs (red shading). In the hatched areas, the situation is inconclusive.

Ocean acidification – a matter of free protons

The protons released by carbonic acid increase the acidity of the water. If the ocean absorbs large amounts of additional carbon dioxide, the sea is in danger of acidifying, which results in deteriorated living conditions for many marine organisms. The number of protons actually released by the carbonic acid reaction, however, depends on the acid-binding capacity of the seawater. This is determined by acid-binding components of mineral origin (again, carbonates) in the water that originate primarily on land. They have been dissolving there over millions of years through the weathering of rocks, and were eventually washed into the sea by rainwater, brooks and rivers.

If the proportion of this influx of acid-binding solution products of rock weathering is large, the seawater has a

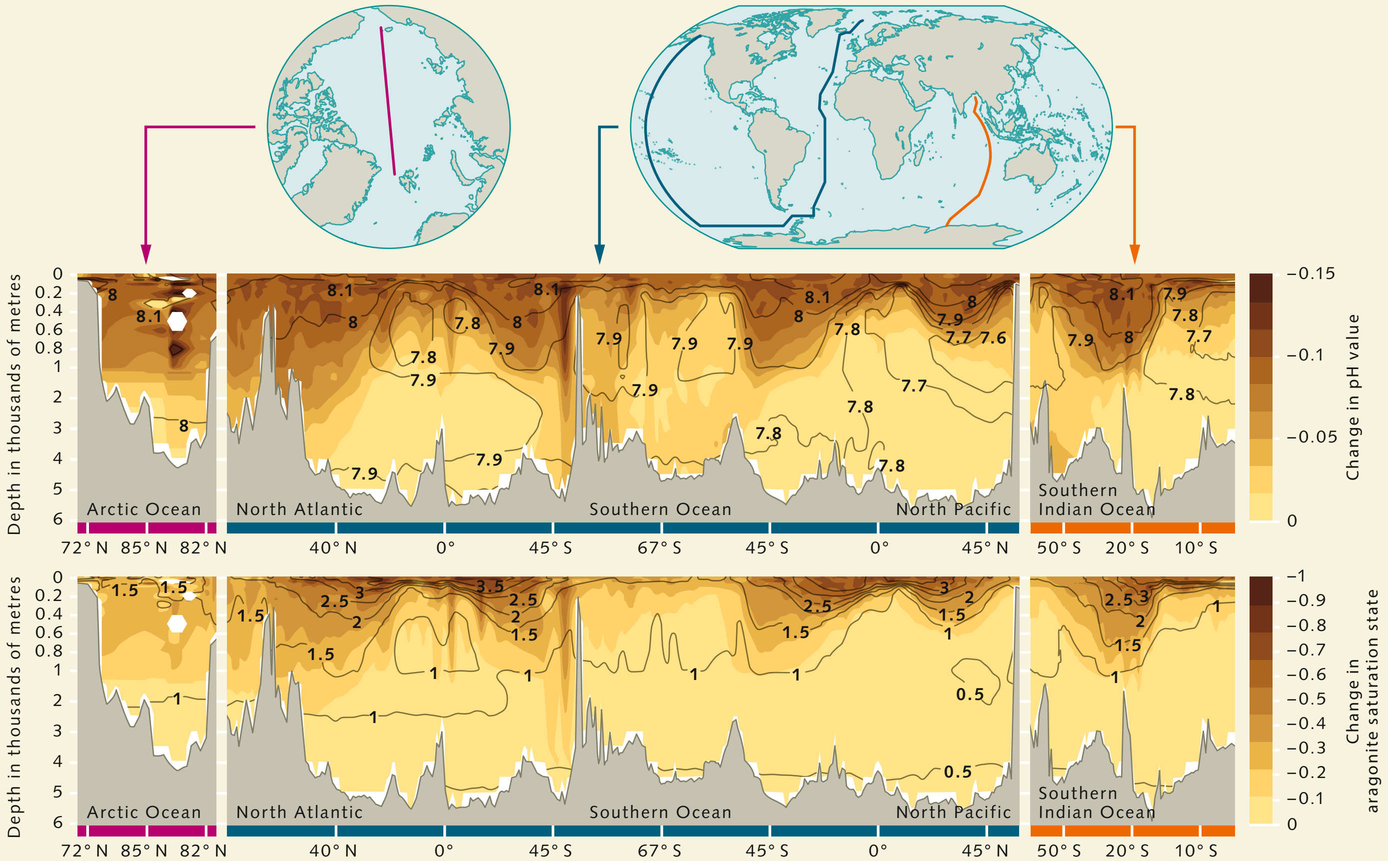
Ocean acidification – the great carbon dioxide problem

When the ocean absorbs carbon dioxide from the atmosphere, fundamental changes occur in the carbonate budget of the ocean. Carbonates are consumed in the surface waters through the carbon dioxide reactions, and hydrogen cations (protons) may be released. The number of free hydrogen cations, in turn, determines the acidity of the seawater. The greater their number, the more acidic the water is.

The concentration of hydrogen cations in a solution is measured using a number known as the pH value. It indicates how acidic or basic a liquid is. The scale of the pH value ranges from 0 (very acidic) to 14 (very basic). This means that the more hydrogen cations a solution contains, the smaller its pH value is.

The average pH value at the ocean surface has decreased since the onset of industrialization from 8.2 to 8.1. This seemingly small step on the logarithmic pH scale represents a real acidity increase of about 26 per cent, a change in magnitude that has not been experienced by the world ocean or its inhabitants in millions of years. The acidification signal now reaches depths of up to 2000 metres, and even deeper in the North Atlantic and Southern Oceans. If humans continue to emit as much carbon dioxide as they have in the past, the pH value of the oceans is predicted to fall by another 0.44 units by the year 2100. This does not mean that the oceans are actually acidic technically speaking, because values of 7.6 to 7.7 are still considered to be chemically basic, but relatively speaking they are more acidic than before.

Expansion of ocean acidification from the surface to the inner ocean (2002) since preindustrial times



2.5 > Water chemistry changes as a result of CO_2 uptake at the ocean surface. Its pH value decreases as does the aragonite saturation state. The measurement profiles show the changes in these two parameters during the period from 1800 to 2002. The black lines and numbers indicate values measured in 2002.

Together with the pH values, carbonate concentrations in the ocean are also falling with increasing carbon dioxide absorption. The saturation of seawater with carbonate ions, however, is a vital parameter for all marine organisms that construct their shells or skeletal structures with calcium carbonate. Marine organisms use carbonate primarily in the forms of aragonite and calcite, whereby aragonite is particularly susceptible to dissolution. Carbonate-saturated water masses possess a carbonate saturation state (Ω) of 1. This corresponds to a carbonate concentration of 66 micromoles per kilogram of water. If the concentration is slightly higher than this value, the seawater is considered to be supersaturated. If a water mass falls below that, however, it is referred to as undersaturated and the aragonite formed by the organisms will dissolve in the water.

Undersaturated seawater is present in all of the oceans because, due to the increasing solubility of carbonate with decreasing water temperature and increasing pressure, the deeper layers of the oceans, as a rule, are undersaturated. The boundary between the undersaturated and supersaturated water layers is called the saturation horizon. According to reports by the Intergovernmental Panel on Climate Change, the increasing inflow of carbon-rich surface waters at intermediate and greater water depths is shifting this boundary, below which the carbonate dissolves, further and further toward the ocean's surface. In some regions of the western Atlantic Ocean, for example, the calcite saturation horizon has risen by around 300 metres since the onset of industrialization. In the Arctic Ocean, the depth of the aragonite saturation horizon has shifted upward towards the surface by 270 metres during the period from 1765 to 2005. This means that ever larger portions of the water column there are being affected by carbonate deficiency.

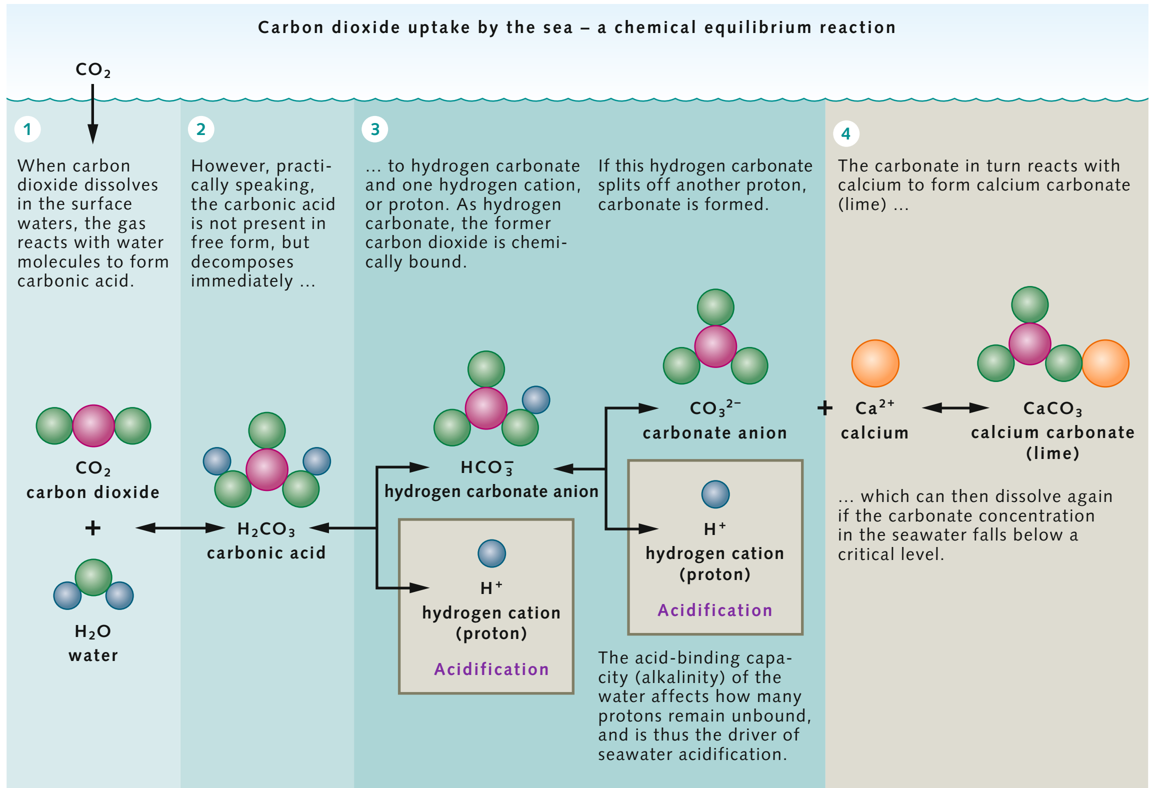
Uncertainty about adaptability

Increasing acidification of the seas has an impact on a variety of biological processes, and thus on the lives of many marine organisms. Due to the decreasing availability of carbonates, it is becoming more difficult for carbonate-forming organisms such as corals, bivalves, conchs and foraminifera to build their calcareous shells or skeletons. They are becoming thinner and more delicate. Evidence from echinoderms such as sea urchins and starfish indicates that they grow less and die earlier as acidification increases.

The degree to which inhabitants of the sea are endangered by acidification and increasing carbon dioxide concentrations, however, depends on the species and the family. For corals, molluscs and echinoderms, for example, the risks are greater than for crabs and shrimps. The danger for fish is primarily in the embryo or egg stage, or for the larvae. In these early development stages, the animals do not yet have a functioning system for acid-base regulation. This system prevents or minimizes damage later when the body liquids of the fish also gradually acidify in carbon dioxide-rich water. As a result, a portion of the young animals die, others experience growth difficulty or develop abnormally. There is also evidence that ocean acidification influences the behaviour of marine animals in complex ways, for example by affecting neural processes or the learning or visual abilities of the organisms.

Some algae and sea grasses, on the other hand, actually benefit from carbon dioxide-rich water. During photosynthesis they are able to take up more carbon dioxide and transform it to biomass. That means that the organisms grow faster, and in some cases are able to cope better with heat stress. It is still uncertain to what extent the various marine organisms are able to adapt to ocean acidification. Single-celled algae and small zooplankton with short reproductive cycles appear to be better equipped than larger organisms with longer reproductive cycles. Additionally, researchers are becoming more convinced that increased ocean acidification combined with the declining oxygen content in the seas has a negative influence on the temperature tolerance of the individual species, especially in tropical and polar waters. This means that the temperature range in which these species can survive is shrinking with the falling pH value of the water. This development, in turn, has an effect on the geographical distribution of species and populations, and even on their basic chances of survival.

Important to know: The acidification of the seas is a development that can be attributed exclusively to the increase in carbon dioxide in the atmosphere. Other greenhouse gases are not involved in this. For an effective protection of the oceans, therefore, the prevention of anthropogenic carbon dioxide emissions and a targeted reduction of carbon dioxide concentrations in the Earth's atmosphere are doubly important. Such action would help to limit both global warming and ocean acidification.



2.6 > Seawater stores carbon in three dissolved forms: as carbon dioxide, hydrogen carbonate, and carbonate. These three types maintain a balanced state of concentration equilibrium with each other, which means that a change in one results in an immediate compensating reaction in the other two. Scientists refer to these as equilibrium reactions.

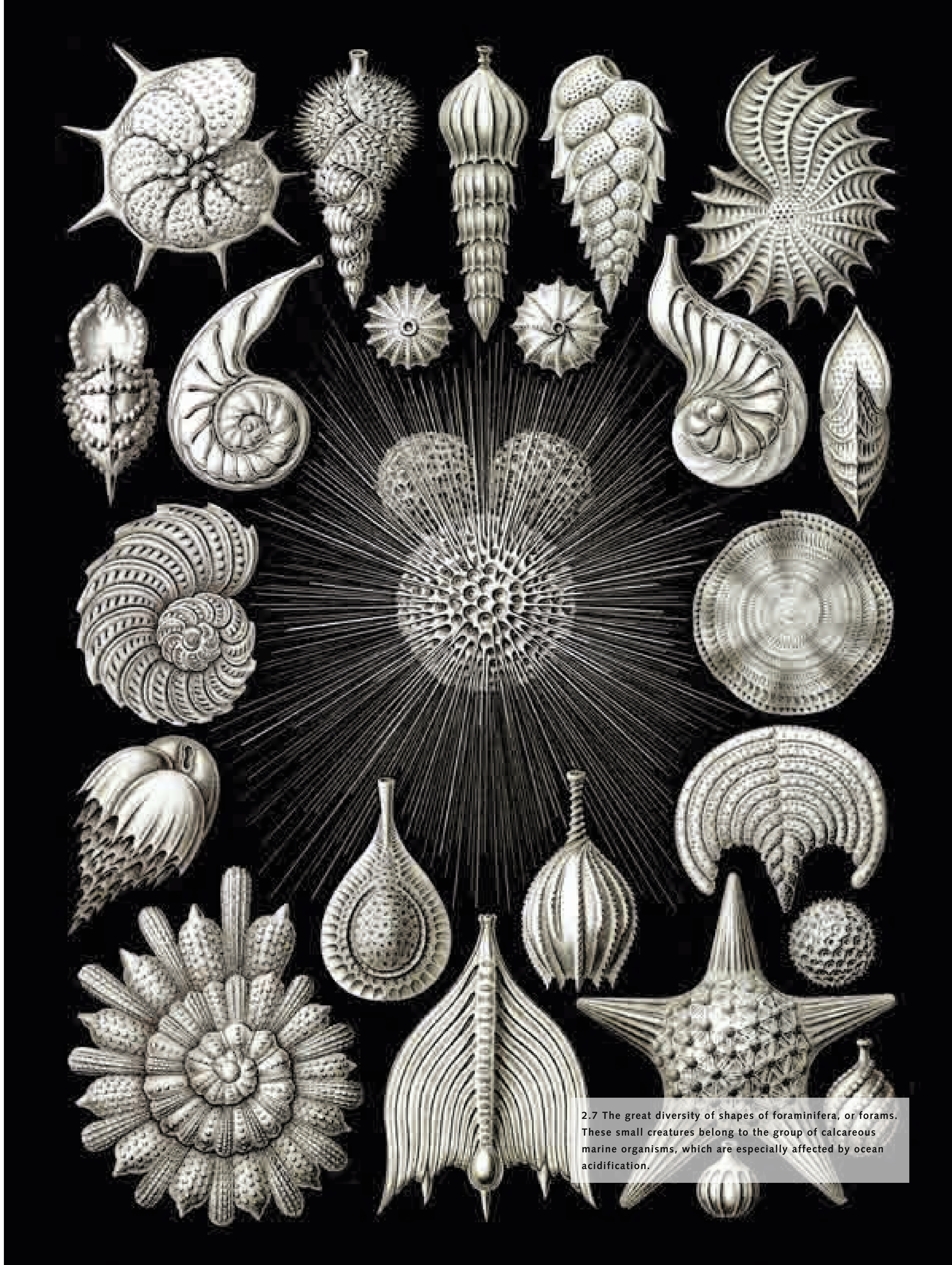
Mineral
In contrast to rocks (mixtures of various minerals), a mineral is an individual element or a single chemical compound that as a rule is crystalline and is formed by geological processes. At room temperature minerals are usually solids, with the element mercury being an exception.

high acid-binding capacity. Scientists also refer to this water as having a high alkalinity. In this situation, a large number of protons are not even actually released, but in the course of the carbonic reaction are immediately bound by the introduced solution products. Hydrogen carbonate is produced in this reaction as well, while the carbonate mineral is broken down and the acidification of the water is buffered. If the water only contains small amounts of acid-binding components of mineral origin, however, the acid-binding capacity is limited. The number of free protons increases and the sea becomes increasingly acidified.

When considered over periods of millions of years, the Earth's carbon cycle always compensates for the carbon dioxide content of the sea by the influx of weathered acid-binding minerals. For example, if the carbon dioxide concentration increases both in the sea and the atmosphere, the warming of the two systems will lead, in the long term, to an increase in the weathering of rocks, both on land and on the sea floor. This results in larger amounts of minerals being carried into the sea, reduction of the acidity of the water, and the ocean again taking up more CO_2 from the atmosphere in order to re-establish the concentration equilibrium discussed above. This decreases the carbon dioxide concentration in the atmosphere, and the warming slows down. But this process requires millions of years.

The three carbon pumps of the sea

When the chemical equilibrium reaction is completed in the surface waters and carbon is present in its three dissolved forms of carbon dioxide, hydrogen carbonate and carbonate, it begins its journey through the marine carbon cycle. This trip can happen in three different ways, all of which are designated as carbon pumps, but which are significantly different in their basic mechanisms. Scientists differentiate these as a "physical" ocean carbon pump and two biological ocean carbon pumps, one "organic" and one "inorganic".



2.7 The great diversity of shapes of foraminifera, or forams. These small creatures belong to the group of calcareous marine organisms, which are especially affected by ocean acidification.

The physical carbon pump

The physical carbon pump is driven by the ocean currents and their differences in temperature and salinity. It distributes the dissolved carbon (carbon dioxide, hydrogen carbonate, carbonate) through the sinking or upwelling of water masses in the ocean. This process is the primary mechanism for transporting anthropogenic carbon dioxide emissions into the deep ocean.

In order to sink, water masses must cool down so that they become denser and heavier. This process occurs mainly in the polar regions because the solubility of carbon dioxide in colder water is particularly high, and the surface water is thus carbon-rich. The colder and more saline the water is, the deeper it sinks, taking the dissolved carbon with it to greater depths. Once there, the water masses subsequently spread around the entire world on a global conveyor belt of marine circulation.

Decades or centuries pass before this carbon-rich deep water returns to the ocean surface to take part in the gas exchange with the atmosphere once more. But eventually the water masses rise again, usually at one of the coastal upwelling zones along the western coasts of Africa, South or North America, or along the equator, primarily in the Pacific Ocean. When it reaches the sea surface, the water is warmed and releases a portion of its dissolved carbon dioxide into the atmosphere as a gas again.

Although the long journey of the carbon-rich water through the deep ocean can be seen as beneficial from the perspective of CO_2 emissions because it sequesters the dissolved carbon in the deep sea, it also comes with a significant drawback: If the water masses at the sea surface become more acidic – a development that is now observable globally – their long-term circulation at great depths means that this acidification would have to be considered irreversible on human time scales.

The special roles of the shelf seas and vegetation-rich coastal ecosystems

On the coasts and the continental shelves (0 to 200 metre water depths) a large portion of the plankton biomass is not broken down in the water column but sinks to the sea floor. There, in part, the biomass is incorporated into the sediments. The shelf sediments are therefore much larger carbon reservoirs than the deep-sea sediments. More than 90 per cent of the permanent carbon burial occurs in the shelf sediments. On geological time scales, oil and natural gas are formed from the biomass in these sediments. A large proportion of human-induced greenhouse gas emissions results from the fact that, by extracting oil and gas, we remove carbon that was sequestered there long ago. We then burn the fuel and release the carbon into the atmosphere as carbon dioxide.

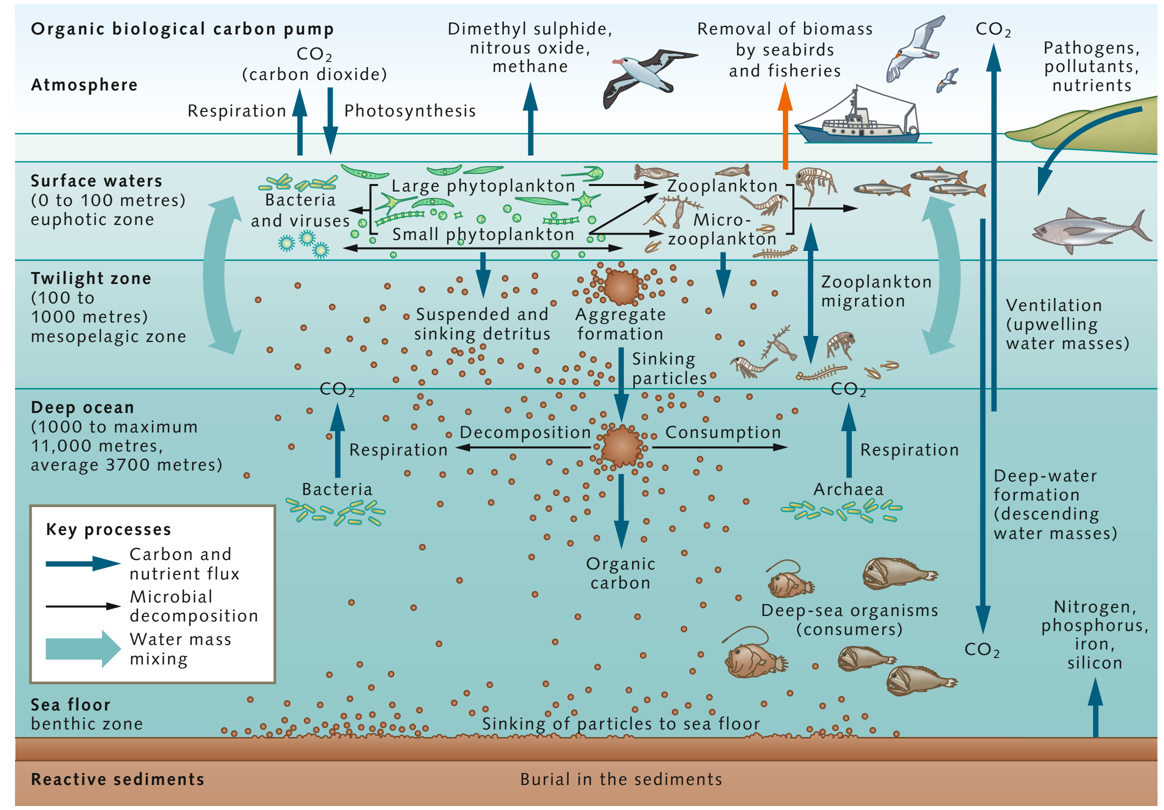
Vegetation-rich coastal ecosystems such as salt marshes, seagrass meadows and mangrove forests also play special roles in the carbon cycle of the sea. Although they cover only less than one per cent of the total marine area, they are responsible for a significant portion of the natural carbon sequestration in the sea floor, and are thus key components in the Earth's carbon cycle.

These plant communities flourish in tidal and shallow-water areas and take up carbon dioxide from the surface waters as well as from the air. They subsequently store the carbon bound by photosynthesis predominantly in the subsurface – partly in their dense root systems, and partly directly in the coastal sediments as dead plant material (foliage, deadwood, etc.).

Because the marine meadows and forests also filter large amounts of suspended material out of the water and these particles are deposited between their stems and roots, the plant communities grow steadily upwards. Through the deposition of the particles abundant washed-in animal and plant material is incorporated in the sea floor. These two processes lead to an accumulation of large amounts of carbon beneath the salt marshes, mangroves and seagrass meadows. These deposits can be more than ten metres thick and they continue to grow as long as the ecosystems are healthy. In ideal situations they are preserved for hundreds, and sometimes even thousands of years.

The organic biological carbon pump

The organic biological carbon pump is driven by the biological communities in the surface waters of the ocean. This is where photosynthesis is carried out by single-celled algae (phytoplankton), macroalgae and seagrasses. They use the sun's energy to produce biomass. For this, the plants require carbon dioxide as a building material, which they obtain mostly from the surface waters in its dissolved form. They incorporate the carbon contained in the CO_2 into their biomass.



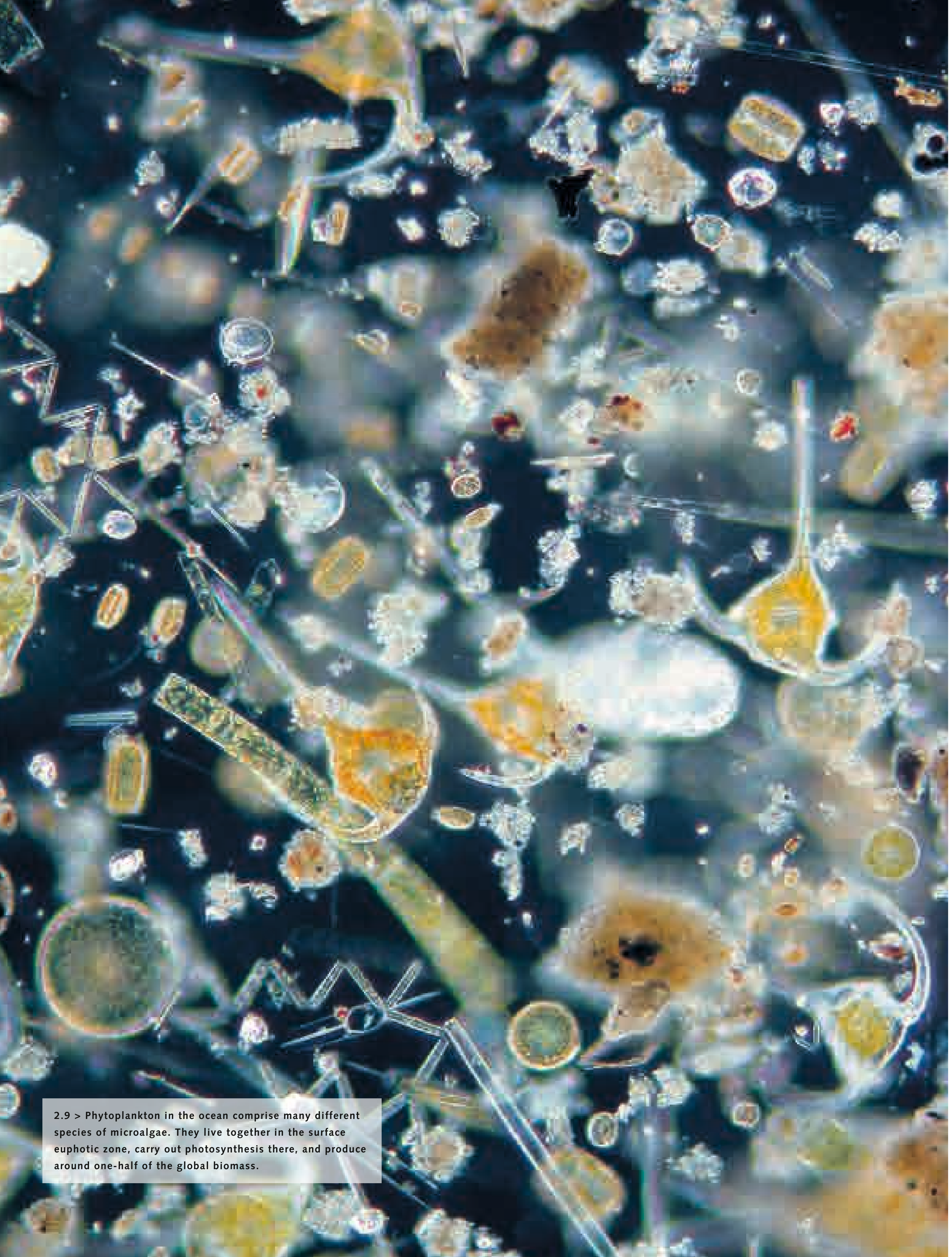
2.8 > The organic biological carbon pump of the sea involves the processes by which algae and plants absorb CO_2 from the well-lit surface waters and convert it into biomass, which then sinks towards the seabed. The crucial question for the balance of global emissions and the continued progress of climate change is how much of the biomass sinks to the water levels below the surface layer mixed by winds and waves. In the intermediate and deep waters (twilight zone/deep ocean), in fact, the organic material along with the carbon it contains is trapped for decades to centuries, regardless of whether the biomass is eaten and respired or continues to sink toward the sea floor.

When the algae or seagrass is eaten, the consumers naturally also ingest the carbon contained in it. A portion of the carbon is returned to the sea as carbon dioxide through respiration by the animals. The remaining amount is retained in the form of muscle mass or body fat, for example, and some is excreted as faecal pellets. Subject to the natural processes of the ocean, carbon may thus migrate through the entire marine food web: from small crustaceans to various species of fish, to marine mammals such as whales and seals – and at each step carbon is respired, converted into biomass, or released in the form of faeces.

But the plants and algae may also simply die. When this happens, they descend through the water column, along with the mortal remains of their consumers and their faecal matter. On the way towards the sea floor the dead biomass encounters bacteria and other microorganisms, which break down a large proportion of the material before it can reach great water depths or the sea floor. Through this process, the stored carbon is again released into the seawater in the form of carbon dioxide. The remaining material settles into the deep sea as "marine snow". It is estimated that only ten to 30 per cent of the carbon bound up in biomass reaches a water depth of 1000 metres or more. The rest will be consumed before that.

Upon reaching the sea floor, the remaining carbon-bearing material, whether unicellular organisms, faecal particles or whale carcasses, is almost entirely consumed by the inhabitants of the deep sea. What remains is significantly less than one per cent of the original carbon that was taken up by the algae. If the carbon originates from other sources (wood, whale bones, etc.) the proportion may be higher. The ultimate remaining amount is incorporated into the sediments, which removes the carbon from the natural cycle for a very long time.

Sequestration in sediments becomes a significant quantity when considering the carbon cycle on a geologi-



2.9 > Phytoplankton in the ocean comprise many different species of microalgae. They live together in the surface euphotic zone, carry out photosynthesis there, and produce around one-half of the global biomass.

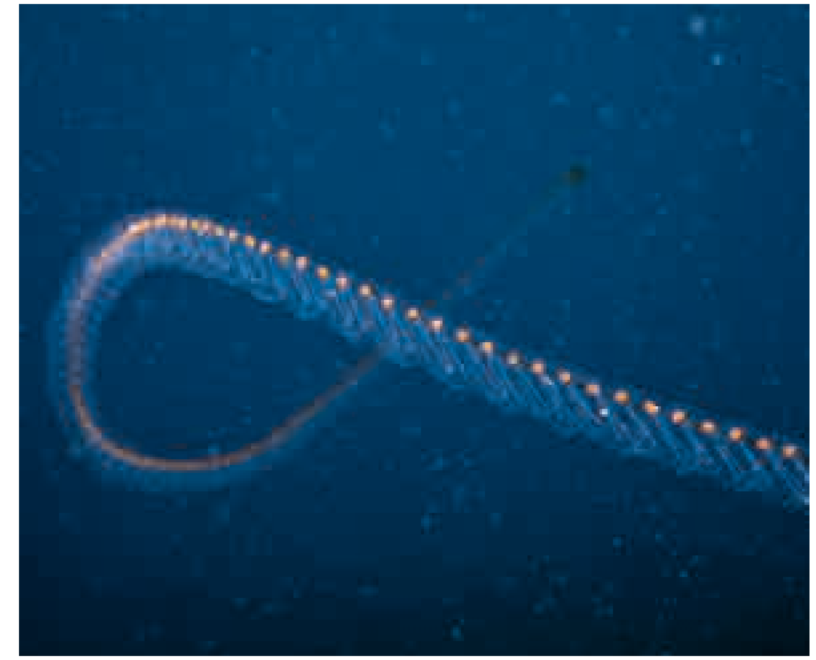
cal time scale, i.e., over millions of years. For the current development of climate change, however, it is the amount of carbon bound up in algae and plants that sinks to water depths below the surface mixed layer that counts. This is the layer near the sea surface in which the water masses are regularly mixed by winds and waves.

Once carbon-bearing particles have left the surface layer, decades or even centuries may pass before they or their respired products can return to the sea surface and are able to escape into the atmosphere again as carbon dioxide. Scientists therefore use the term "sequestered" (taken up and stored) to refer to all carbon that is transported by the organic biological carbon pump to depths that are no longer mixed by wind and waves.

The inorganic biological carbon pump

In addition to photosynthesis, there is a second process by which marine organisms biologically fix dissolved carbon from the water and ultimately transport it to greater depths. This is achieved through the construction of calcareous shells or skeletons. In this process, carbonate-forming organisms such as calcareous algae, bivalves, corals, conchs and foraminifera extract the dissolved hydrogen carbonate from the seawater, and transform it into calcium carbonate to use as their building material. When the organisms die, their calcareous shells sink to the sea floor where they are incorporated into the sediments. In this way, the carbon contained in them is removed from the natural cycle for millions of years.

With respect to the carbon dioxide balance in the atmosphere, however, the inorganic biological carbon pump of the ocean is negative. The explanation for this is that during calcite formation hydrogen carbonate is removed from the water. As a product of the accompanying chemical reaction, dissolved carbon dioxide is formed in the water. This, in turn, increases the carbon dioxide partial pressure of the seawater, thus facilitating the release of carbon dioxide into the atmosphere. If, on the other hand, the carbonate dissolves – which does happen under certain chemical conditions in the sea – carbonic acid is consumed and the seawater then tends to absorb more carbon dioxide from the atmosphere.



2.10 > Salps are cylinder-shaped tunicates that often live in colonies. The colony of animals forms a long chain that goes hunting for plankton.

Climate change as a constraining factor

With the acceleration of climate change and the accompanying warming of the seas, the ocean's capacity to take up carbon dioxide and store it will decrease. There are two primary reasons for this. The first is physical in nature: Warm water cannot store as much dissolved carbon dioxide as cold water. The second is related to the biological carbon pump. One effect of climate change is that the density-related stratification of water masses in the water column is strengthened. As a consequence, the layer of warm, light, and often nutrient-poor surface water becomes less prone to mix with the underlying nutrient-rich intermediate and deep waters. To a certain extent it is cut off from the nutrient supply from below. Due to the paucity of nutrients in the well-lit surface water, there is more of a tendency for the growth of smaller algal species instead of abundant large and more productive diatoms. The smaller species produce less biomass than the diatoms and are therefore also able to store less carbon.

In addition, rising water temperatures accelerate the metabolic processes of marine organisms. They all need more food, which means that organic material is more rapidly consumed, broken down and recycled, and usually at shallower water depths. The carbon dioxide released through these processes is then returned by the organisms to the surrounding seawater. The carbon-dioxide partial pressure of the water thus increases, enhancing the tendency of the carbon dioxide to escape from the sea into the atmosphere.

Furthermore, climate-induced changes in species compositions can also have a negative impact on the transport of carbon to the deep ocean. Research off the coast of the Antarctic Peninsula, for example, has shown that the faecal pellets of Antarctic krill *(Euphausia superba)* generally sink to greater water depths than the excrement of salps. In the course of ocean warming the latter are advancing further and further into the krill's home waters while the crustaceans retreat southwards.

Unlike the krill, however, salps do not pack their comparatively large faecal pellets in a protective membrane. This makes the faeces easy game for other zooplankton and for microorganisms. Within the time frame of the investigation, these had consumed around 80 per cent of the carbon-rich salp excrement before it reached a water depth of 300 metres. Of the well-packed krill faeces, on the other hand, 72 per cent was still preserved at that depth. The researchers were thus able to conclude that if the retreat of the Antarctic krill continues and salps become the dominant species throughout the area, the waters along the Antarctic Peninsula will store significantly less carbon in their depths than previously.

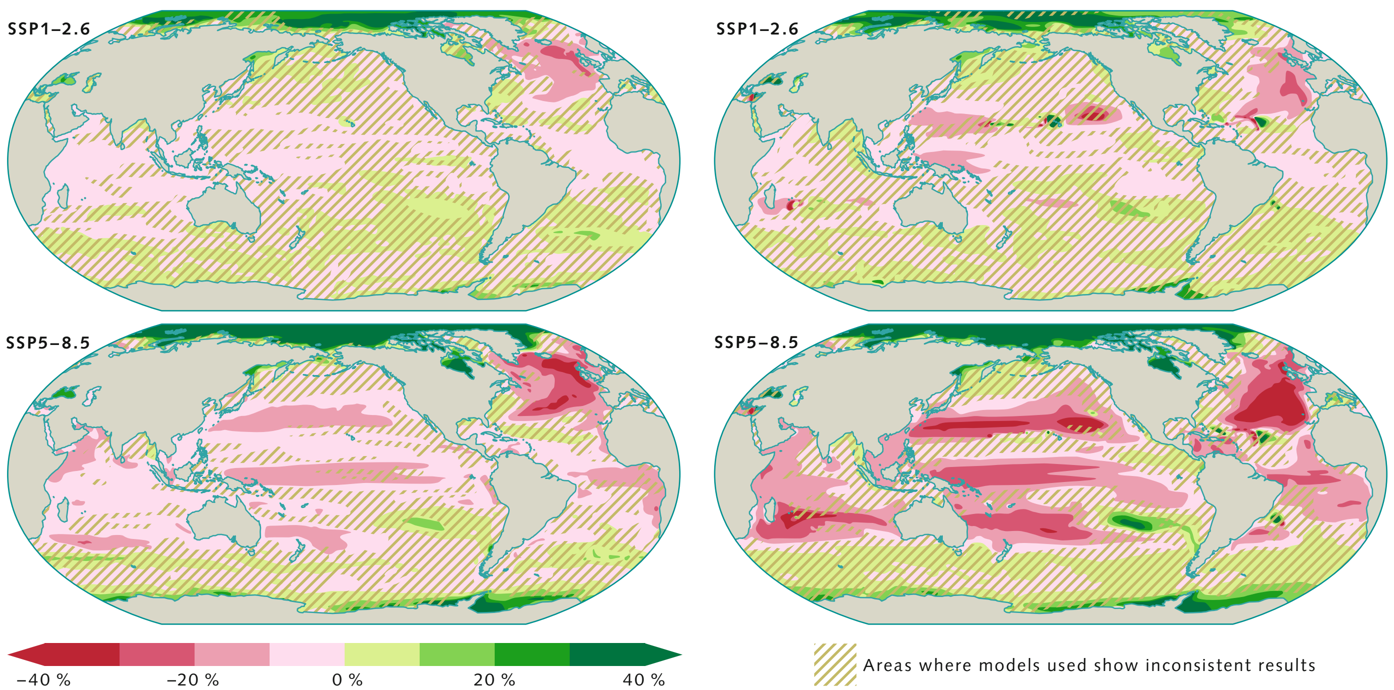
It could look very different in marine regions where both the biomass production of phytoplankton and the abundance of zooplankton increase in the coming decades as a result of climate change. According to the Intergovernmental Panel on Climate Change, this would be the case in the Arctic Ocean, for example. On a global scale, however, scientists anticipate that biomass production by phytoplankton will decline in most parts of the world ocean as a consequence of climate change, and with it the carbon export to the deep ocean.

Projected change in marine phytoplankton biomass

Average change for the period from 2090 to 2099 compared to the period from 1995 to 2014

Projected change in marine zooplankton biomass

Average change for the period from 2090 to 2099 compared to the period from 1995 to 2014



2.11 > As a consequence of climate change the abundances and distributions of phytoplankton and zooplankton will change. In tropical and subtropical marine regions they will decrease, and in the temperate and polar latitudes they will increase.

Conclusion

The ocean as a carbon reservoir – huge, efficient and endangered

The Earth's climate system uses physical, chemical and biological processes to extract carbon dioxide (CO_2) 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 plays a major role in 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. Its carbon reserve exceeds that of the atmosphere by a factor of more than 50.

There is a continuous exchange of carbon between the ocean and 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 CO_2 emissions from the atmosphere, thus significantly inhibiting the progress of global warming.

CO_2 uptake by the ocean occurs at the sea surface, where CO_2 in the air is dissolved in the seawater. A chemical equilibrium reaction is consequently initiated in the surface waters that leads to the carbon from the carbon dioxide being chemically fixed to a large extent. The surface waters then contain carbon in three dissolved forms: as carbon dioxide, as hydrogen carbonate, and as carbonate anions.

The carbon then begins its journey through the sea and may be stored for millennia at great water depths. The journey can occur in different ways: through the ocean currents (physical carbon pump), through the food web (organic biological carbon pump), or by the formation of calcareous shells and skeletons (inorganic biological carbon pump). In the latter two, a portion of the carbon is even stored in the sea-floor sediments, which means it is locked away for millions of years.

The ocean carbon cycle, however, is not a one-way street because the three forms of dissolved carbon exist in a state of balanced concentration equilibrium with one another. Changes in one parameter lead immediately to compensating reactions by the two others.

One of the most important chemical changes that results from the increasing uptake of carbon dioxide by the world ocean is increasing acidification. Since the beginning of industrialization, the acidity of the ocean has increased by 26 per cent, a change not experienced in the seas over the past millions of years. In some regions the acidification signal now extends to depths of greater than 2000 metres, and impacts the lives of many organisms. It is not yet clear to what extent they will be able to adapt to ocean acidification.

What is certain, however, is that with increasing climate change the CO_2 uptake and storage capacity of the ocean will decrease. This is firstly because warmer water cannot store as much dissolved carbon dioxide as cold water can. And, secondly, it will occur because increasing water temperatures strengthen the stratification of water masses and enhance the metabolic rates of marine organisms. Both of these processes inhibit the biological carbon pump, with the result that less carbon can be exported to the deep sea.

3 Harnessing the untapped potential of terrestrial ecosystems

> Terrestrial ecosystems store significantly less carbon than the oceans. Nevertheless, they can make a valuable contribution to the fight against climate change. We must protect existing forests, grasslands and wetlands to this end, engage in large-scale ecosystem restoration and return to sustainable methods of farming and forestry. We've known how to do this for a long time. The only thing that's missing is the will to actually do it.

Forests, grasslands and soils as carbon stores

> Whenever people ask how nature could help us humans in combatting the climate crisis, the answer is often to "plant trees". While that answer is quite valid, it is far from the only option. There are dozens of known methods we can use to help terrestrial vegetation and its soils absorb more carbon dioxide from the atmosphere. But we must employ these methods in the right places, leave enough room for nature and treat the soils with care. To date, none of this is happening to the extent necessary.

Natural climate solutions

Although the concentration of carbon dioxide in the Earth's atmosphere has been rising steadily for decades, carbon dioxide itself makes up only a tiny fraction of the air itself. The concentration of CO_2 in the atmosphere is 0.04 per cent by volume. If one wanted to extract one cubic metre of carbon dioxide from the atmosphere, one would have to filter at least 2500 cubic metres of air to do so. For one tonne of carbon dioxide, this would be around 1.27 million cubic metres of air, even at 100 per cent filtering efficiency.

Soil carbon
The term "soil carbon" refers to the quantifiable carbon content of organic matter in the soil. It includes both living and dead biomass and makes up between two and ten per cent of the soil mass. The soil carbon stock is the basis for vital services provided by the soil, such as the storage and provision of water and nutrients as well as the breakdown of pollutants.

Technical systems that can remove carbon dioxide from the air are expensive and consume a lot of energy. Many experts therefore advocate so-called Natural Climate Solutions (NCS), i.e. measures that increase natural carbon dioxide uptake and carbon sequestration by oceans, terrestrial areas and their respective vegetation, or measures that prevent future greenhouse gas emissions.

However, the term "natural" does not automatically imply that all such measures are sustainable or environmentally friendly in the long term. Large-scale tree plantations (monocultures) for example can certainly be counted among the natural climate solutions, but they come at the expense of species diversity. Moreover, plantation-type forests store significantly less carbon in the long term than a species-rich, naturally grown mixed forest. It is for this reason that experts now vehemently call for all greenhouse gas emissions avoidance and atmospheric carbon dioxide removal measures to also be assessed in terms of their impact on nature and human communities, and to weigh up their potential risks against and benefits. A best-case situation is for all three – climate, nature and humankind – to benefit.

The discussion on natural climate solutions has so far focused primarily on the Earth's forests, wetlands, savannas and grasslands, as the way we have been utilizing these ecosystems has significantly impacted the Earth's carbon cycle and thus also the climate.

Land-use change impacts the climate globally as well as locally

The effects of land-use change on the climate are now well understood. At a global scale, they mainly throw off the balance of important greenhouse gases such as carbon dioxide, nitrous oxide and methane. Carbon dioxide, for example, is released in large quantities when we clear (burn) forests, convert natural grasslands and wetlands into cropland, drain peatlands or overuse pastures and fields to such an extent that their capacity to store carbon and grow vegetation is increasingly diminished. In contrast, the uptake of carbon dioxide by terrestrial vegetation is enhanced when forests are (re)planted, grow back naturally or when livestock grazing ceases on natural grasslands and the native animal and plant community can recover.

Methane and nitrous oxide emissions arise primarily in farming. Nitrous oxide is released when nitrogenous fertilizers are used and when farmers collect and spread slurry on agricultural land or burn biomass. Methane emissions mainly come from intensive livestock farming, rice cultivation and incomplete biomass combustion.

When humans change the way they use terrestrial vegetation, the physical surface properties also change. This in turn can alter the local climate in different ways, depending on the location and type of vegetation in

3.1 > The carbon stored in a forest's leaves, branches and twigs is highly susceptible to disturbance. Often a forest fire is enough to destroy this carbon store and release it back into the atmosphere in the form of carbon dioxide and ash particles.

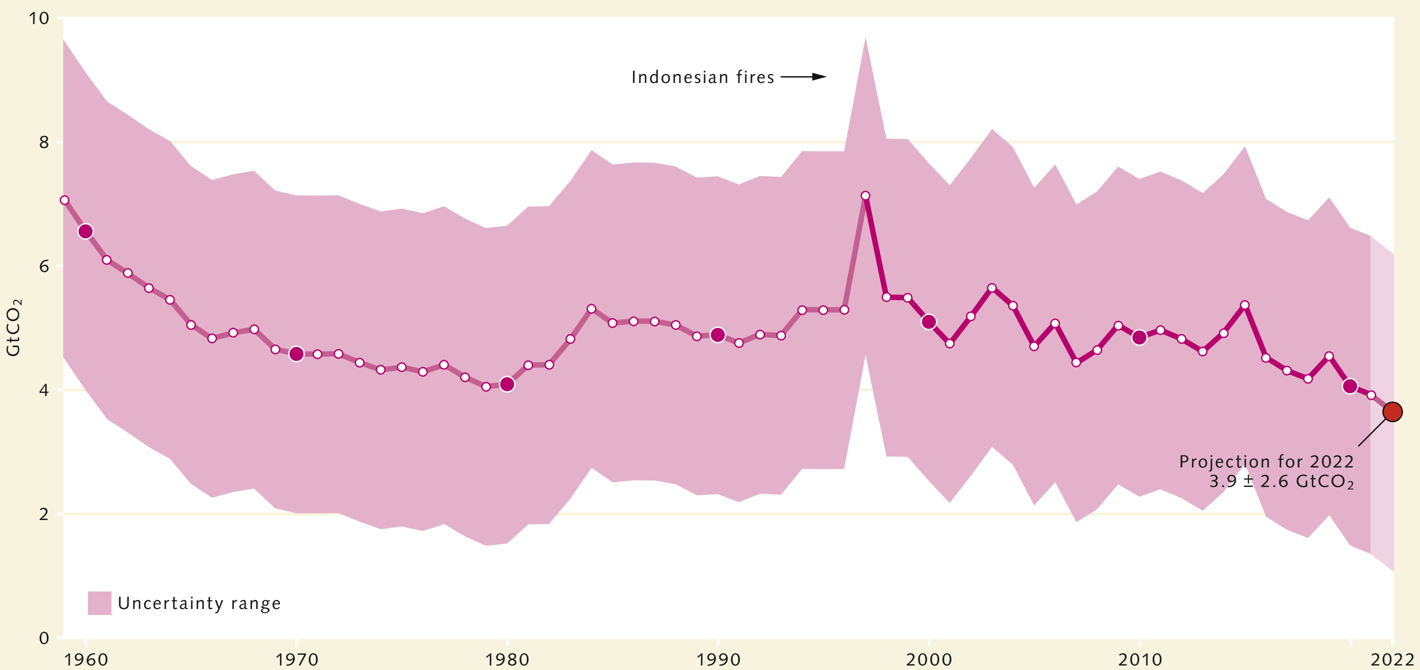
question. If, for example, the forest is cleared in a region, the reflectivity (albedo) of the earth's surface changes, as does the surface roughness. Moreover, the region's "leaf area" is reduced, through which forests contribute to evaporation and cooling. As a result, the region's radiant balance changes and along with it important climate parameters such as surface temperature, evaporation rate, soil moisture, air circulation, heat fluxes and many more.

The extent to which changes in the local climate can result from land-use change is evidenced by deforestation in the Amazon rainforest. Due to the vast area it covers and its high levels of evapotranspiration, this forest was previously able to form its own high-precipitation climate. However, as a result of large-scale deforestation and slash-and-burn farming, the original forest area has shrunk to such an extent since the 1980s that the forest's own evaporation is no longer sufficient to generate enough precipitation. Dry conditions, droughts and the risk of forest fires are increasing, so that the remaining rainforest is now at risk of turning into a dry forest. A dry forest not only sequesters significantly less carbon than the original rainforest, it is also more susceptible to fire.

Terrestrial vegetation and its soils as carbon dioxide source and sink

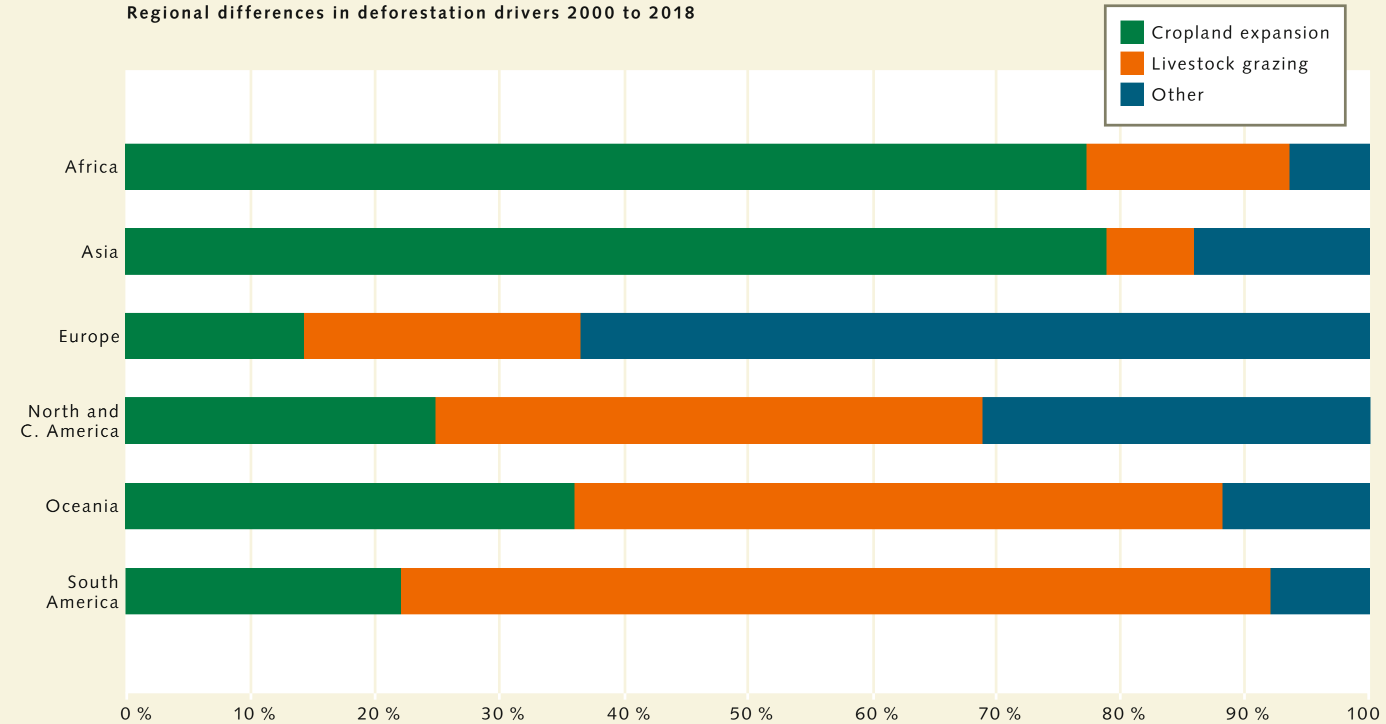
Scientists use a range of different methods to study the effects of land-use change on the Earth's greenhouse gas balance. Their most important tools include vegetation and climate models as well as vegetation data from satellite observations. However, their work is made more difficult by the fact that so far it has not been possible to

Annual CO_2 emissions from land-use change



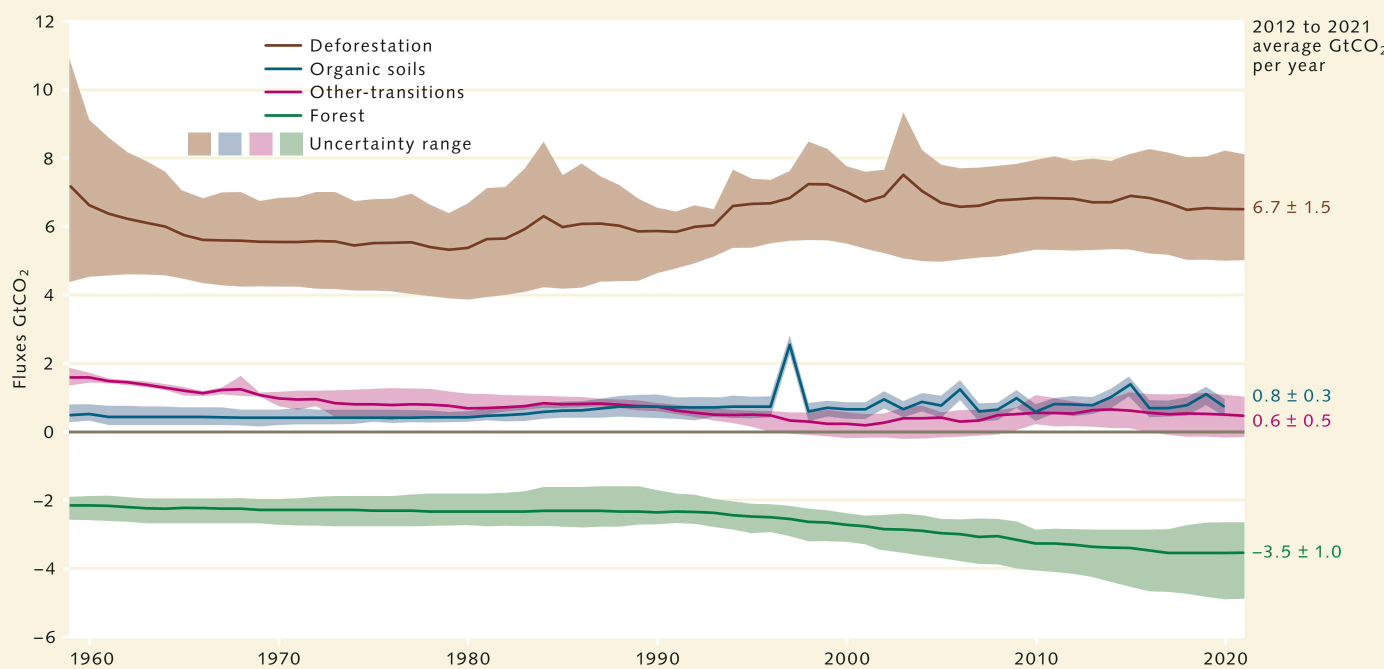
3.2 > Total carbon dioxide emissions due to land-use change have decreased slightly in recent years. The record emissions in 1997 were due to forest fires in Indonesia, triggered by drought and overexploitation of forests and wetlands.

Regional differences in deforestation drivers 2000 to 2018



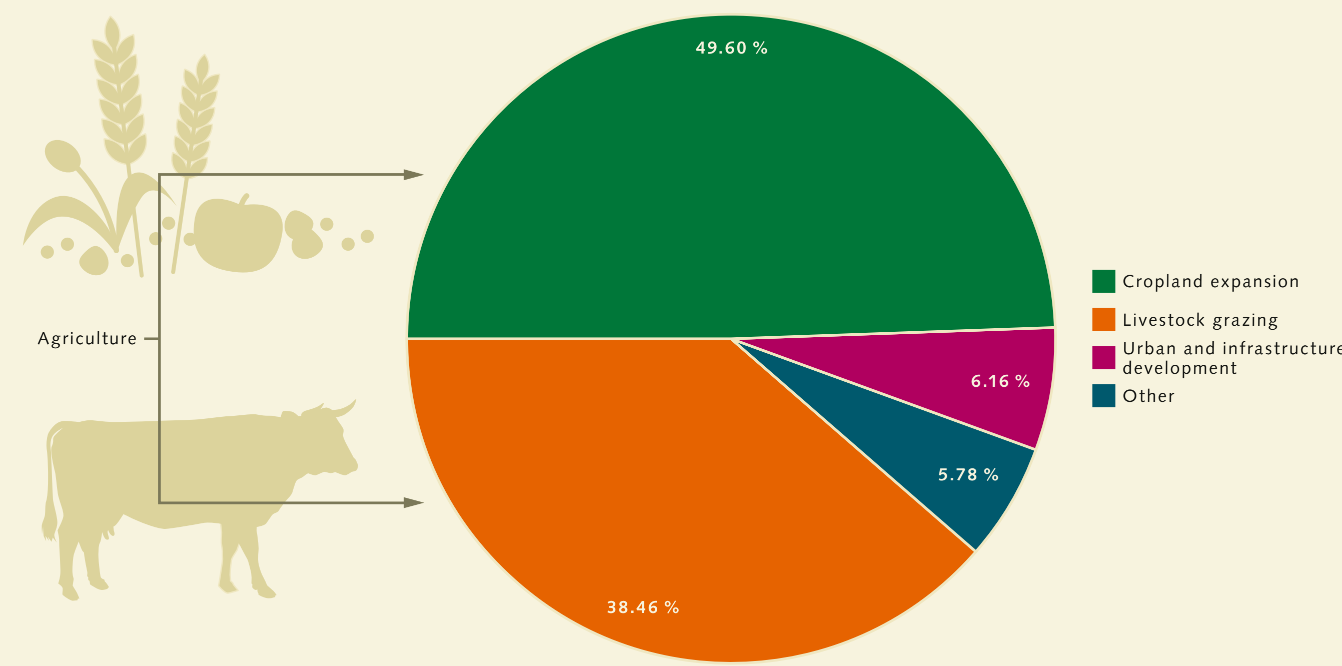
3.4 > In the period from 2000 to 2018, forests were cleared primarily to gain arable or grazing land in all regions of the world, apart from Europe. In contrast, other drivers of deforestation, such as the construction of residential areas and roads, predominated in Europe.

Components of land-use change emissions

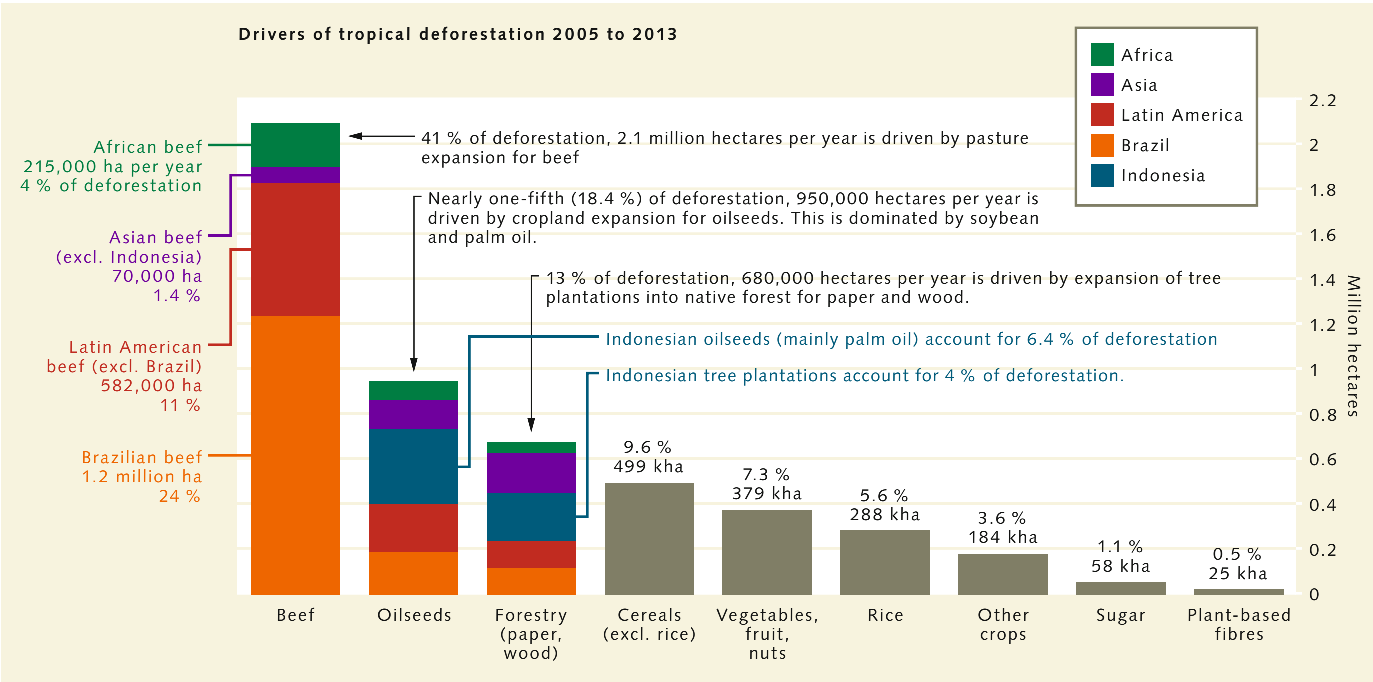


3.3 > Carbon dioxide emissions resulting from deforestation and slash-and-burn agriculture continued to account for the bulk of emissions from land-use change in 2021. (Re)afforestation measures and sustainable forest management were able to compensate for only about half of these emissions.

Global causes of deforestation 2000 to 2018



3.5 > Almost 90 per cent of the forest areas cleared worldwide in the period from 2000 to 2018 are now used as cropland or for grazing livestock. The remaining areas were converted into building land or lost, for example to dam construction or open-cast mining.



3.6 > Since the turn of the millennium, the world has lost around five million hectares of forest area per year, most of it in the tropics. Nearly 60 per cent of the deforestation in tropical rainforests is driven by the production of beef, palm oil and soybeans. As these commodities are largely exported, people in industrialized countries are indirectly responsible for a not insignificant part of the deforestation in the tropics.

clearly distinguish between natural and anthropogenic processes of change when recording global observation data, because these often occur simultaneously. If, for example, satellite observations show a decline in forest cover in a particular region, this may have been caused by deforestation. But it is equally possible that the trees have died as a result of pest infestations or climatic changes. Information on the global carbon balance of terrestrial vegetation and possible changes therein is therefore still fraught with uncertainty.

Nonetheless, researchers now have a clear idea of how crucial terrestrial vegetation and its associated soils are for the Earth's natural carbon cycle and what role, at best, they can play in the fight against climate change. Experts engaged in the international *Global Carbon Project (GCP)* have been keeping an annual record of how much carbon dioxide has been released so far as a result of the burning of fossil resources and land-use change, and what proportion of this has been naturally absorbed by terrestrial vegetation and the oceans.

According to the *GCP*, global land-use change emissions in 2022 amounted to 3.9 gigatonnes of carbon dioxide or one tenth of the total anthropogenic carbon dioxide emissions. Experts cite the continuing high levels of deforestation and forest fires as the main cause. Only half of the carbon dioxide release due to these causes (6.59 gigatonnes) was compensated by the additional carbon dioxide uptake of new, reforested or now sustainably managed forests (3.3 gigatonnes). Carbon dioxide emissions resulting from peatland fires, soil overuse or wetland drainage played only a minor role in the overall balance.

Regardless of land-use change, forests, wetlands, grasslands and agricultural fields still act as natural carbon sinks and thus slow down climate change, i.e. overall they absorb more carbon from the atmosphere than they release. According to the *Global Carbon Project*, the global terrestrial vegetation has absorbed approximately 31 per cent of anthropogenic carbon dioxide emissions since 1850 and sequestered the carbon below ground or in its biomass. Forest ecosystems, including their soils, have accounted for the largest share of this carbon sequestration. In the period from 2012 to 2021, carbon dioxide uptake by terrestrial vegetation totalled 11.4

3.7 > This coastal forest in Norway is among the roughly 28 per cent of the world's forests categorized as boreal coniferous forests – ecosystems consisting primarily of coniferous species such as pine, spruce and fir and occurring across eight countries: Canada, China, Finland, Japan, Norway, Russia, Sweden and the USA.

gigatonnes per year – 1.4 gigatonnes more than in the 2000s. For the year 2022, preliminary analyses indicate an increase to 12.4 billion tonnes of sequestered carbon dioxide.

The fertilization effect of an increasing atmospheric carbon dioxide concentration

Scientists are not surprised by the increasing carbon dioxide uptake. Quite the opposite – it confirms a long-term trend. Over the past 60 years, terrestrial plant communities have steadily absorbed more carbon dioxide from the atmosphere and incorporated the carbon it contains into their biomass, or to put it simply: plants have grown better.

This is due to the so-called carbon fertilization effect of rising atmospheric carbon dioxide concentrations on terrestrial vegetation, which, the Intergovernmental Panel on Climate Change notes, has been evident in the global carbon cycle since the 1980s. Simply put, the higher carbon dioxide concentration in the Earth's atmosphere makes it easier for plants to photosynthesize. Their photosynthetic rate increases, and the plants therefore grow better. At the same time, the more efficient photosynthesis means that the amount of water needed to produce a certain amount of biomass is reduced. This more efficient water use is due to the fact that plants can achieve sufficient carbon dioxide uptake with smaller stomatal apertures. As less water evaporates (transpires) from small stomata openings compared to wide open ones, plants can use their water reserves more efficiently. Moreover, due to global warming the growing season has also lengthened, especially in the northern hemisphere. This factor also contributes to increased atmospheric carbon dioxide uptake by terrestrial vegetation.

However, it is questionable whether this trend will continue, because plant growth does not depend solely on photosynthesis but is also determined by available amounts of water and nutrients, temperature and a number of other environmental factors. New research also shows that an increase in photosynthesis does not automatically mean that trees, for example, actually extensively incorporate the carbon from carbon dioxide into their biomass (leaves, twigs, trunks, root systems) and thus remove it from the atmosphere for long periods. The processes and interactions appear to be much more complicated than previously thought.

Reducing greenhouse gas emissions or removing carbon dioxide – two very different things

Three quarters of our planet's ice-free land areas are now used and shaped by humans, meaning that we have altered their original vegetation by clearing old-growth forests, draining peatlands and converting grasslands to cropland or using the land as building land or as pastureland for cattle, goats and sheep. Today, 85 per cent of all former wetlands are considered destroyed. As a result of this wide-scale change of the land surface and its vegetation, we have more than halved the natural carbon stocks of terrestrial ecosystems in the course of our human history, reducing them from the original 916 gigatonnes to a current level of 450 gigatonnes.

To achieve greenhouse gas neutrality by 2050, the natural carbon stores of terrestrial vegetation need to be vastly increased again. Land use thus needs to prevent future emissions from agriculture and forestry while ensuring that terrestrial vegetation can uptake additional carbon dioxide from the atmosphere. In the public discourse, a clear distinction is often lacking between measures to reduce greenhouse gas emissions and carbon dioxide removal processes respectively. Even experts often do not separate the two, usually using the all-encompassing term "mitigation options".

As a reminder, carbon dioxide removal (CDR) measures by definition only include actions taken by humans that lead to increased carbon dioxide uptake from the atmosphere. The avoidance of future emissions, however, is of much higher priority for climate change mitigation, as the more emissions we avoid, the less carbon dioxide we will ultimately have to remove from the atmosphere.

The most effective and cost-efficient way to avoid emissions from land-use change is to protect existing forests, grassland landscapes, wetlands and carbon-rich soils from destruction, overuse and fires. To simultaneously achieve increased carbon uptake and sequestration, we must also restore destroyed, degraded and overused terrestrial ecosystems and utilize them with a focus on long-term sustainability. The Intergovernmental Panel on Climate Change notes that, if properly implemented, sustainable agriculture and forestry, soil carbon enrichment measures and changes in consumer behaviour could achieve about 20 to 30 per cent of the greenhouse gas emission reductions and carbon dioxide removal needed by 2050 to limit global warming to below two degrees Celsius.

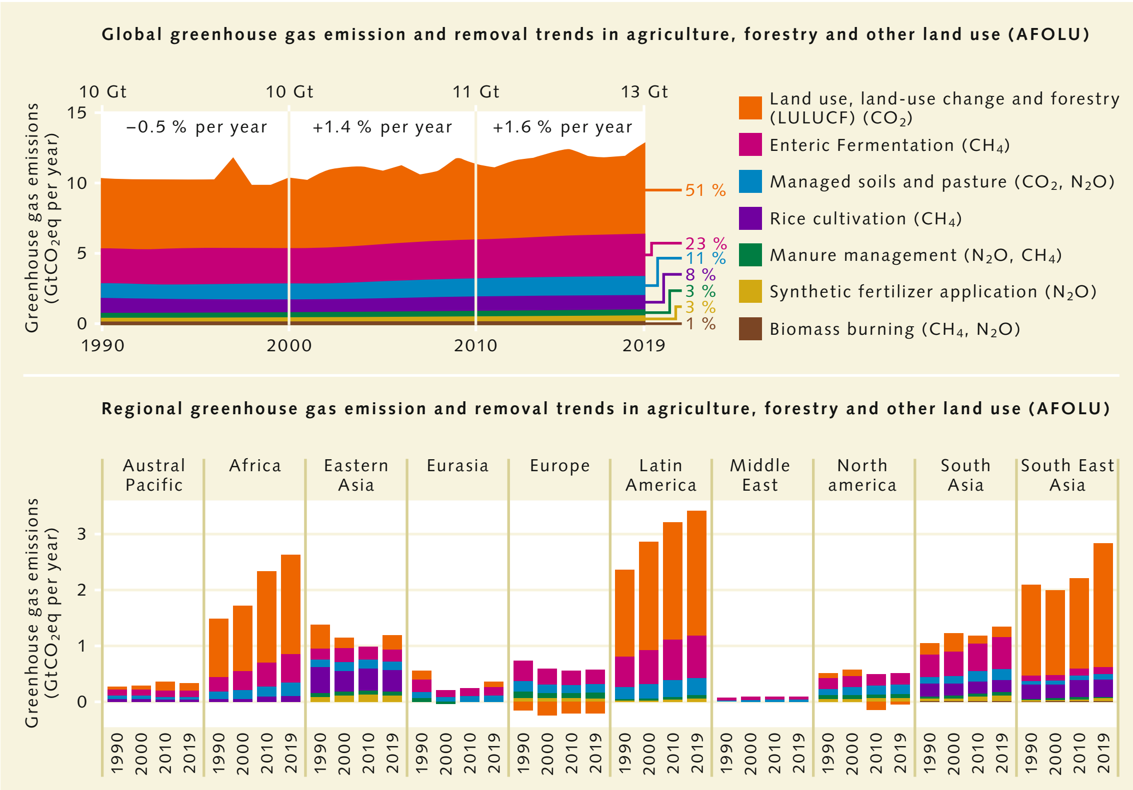
Sustainable land use and the proper use of land-based CDR practices would in many cases yield additional benefits for nature and humans: by protecting and restoring natural ecosystems, we strengthen global species diversity and the health of forests, grasslands and wetlands. There would be more clean water and food, and soil and air quality would improve. The bottom line is that we humans would live in a healthier environment and would also be better able to adapt to the impacts of climate change.

The use of land-based CDR methods is moreover supported by the fact that:

- some of the methods are already well researched and have been in use for centuries for other purposes in agriculture and forestry (e.g. reforestation, measures to increase soil carbon content, etc.);
- the climate change mitigation potential of the global terrestrial vegetation and its soils is high. Scientific studies show that sustainable land use and the proper

3.8 > Roughly 120,000 cattle live in the world's largest cattle feedlot, operated by the US company Monfort Beef in the US state of Colorado.

3.9 > With increasing livestock production, methane emissions in farming (enteric fermentation) have been rising for decades. In 2019, they accounted for about 23 per cent of total emissions from agriculture. The figures show that emissions from agriculture and forestry are particularly high in Africa, South America and Southeast Asia.



use of land-based CDR methods can achieve annual greenhouse gas emissions savings and carbon dioxide removal in the order of eight to 14 gigatonnes of carbon dioxide equivalents by 2050;

- many of the methods are cost-effective in their implementation;
- the public tends to perceive carbon storage in vegetation and soils as semi-natural and thus less risky than technical solutions.

Risks of land-based CDR methods

The use of land-based carbon dioxide removal (CDR) methods does however pose a number of risks to humans and nature. If not properly planned and implemented, certain methods lead to a decline in species diversity and jeopardize the functioning of natural ecosystems. Important services delivered by terrestrial vegetation may be lost, affecting primarily those who depend directly on nature for their food and livelihoods. Often these are the local communities.

Three striking examples of misguided measures to enhance natural carbon sinks on land are:

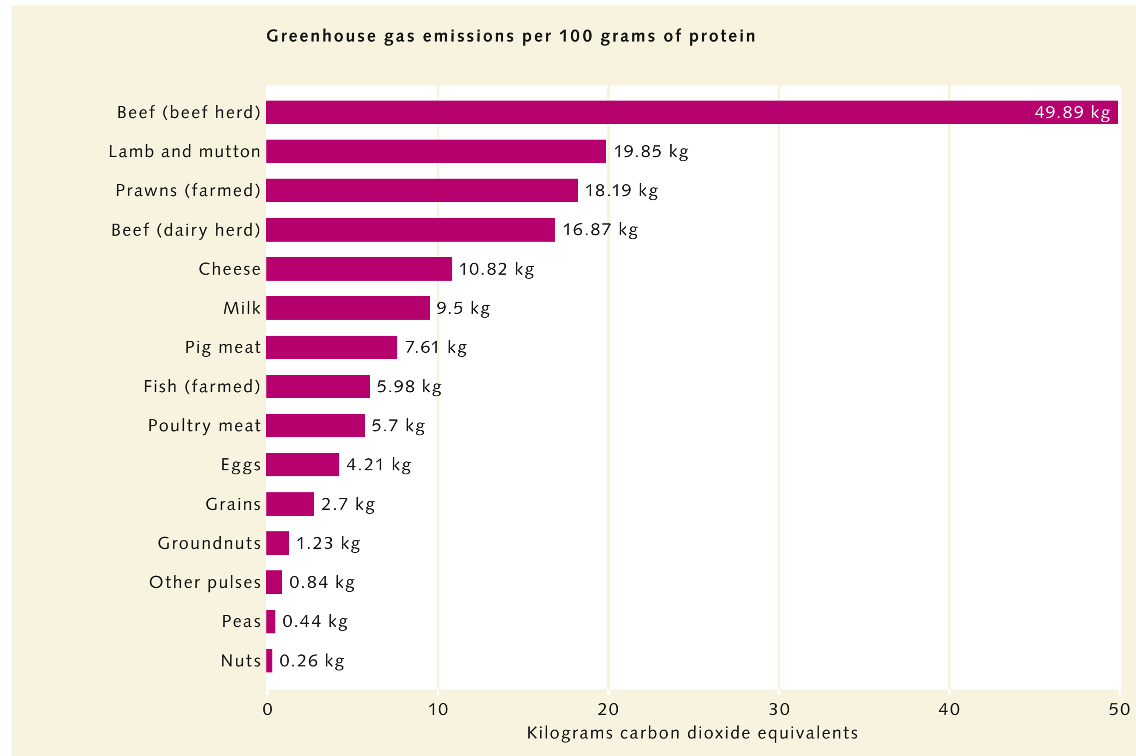
- *reforestation with monocultures* (This usually leads to acutely species-poor systems and renders the new forests susceptible to pests and diseases. Moreover, plantings of non-native species, e.g. eucalyptus in southern Europe, can increase the vegetation's water needs beyond the usual levels, thus putting at risk groundwater resources);
- *afforestation of natural grassland landscapes and savannas* (Interventions of this kind destroy the habitat of species of flora and fauna that are specifically adapted to these ecosystems; they alter local water cycles and can accelerate the decomposition of the large soil carbon stores);

- *the wide-scale cultivation of bioenergy crops, such as maize, in monocultures and aided by significant quantities of crop pesticides* (They result in species diversity declining to a minimum, soil quality deteriorating, and global competition for productive arable land intensifying).

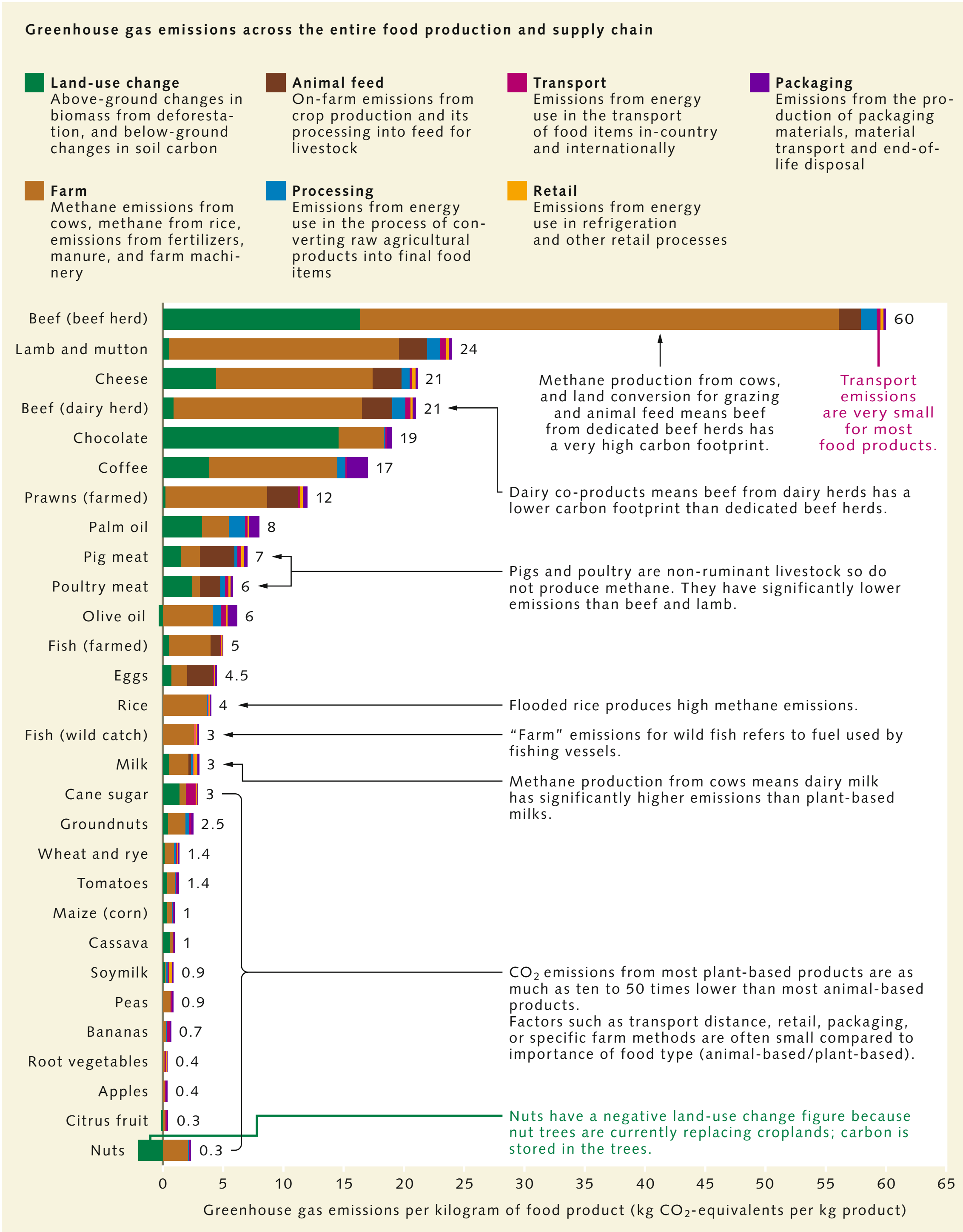
Mistakes of this kind can be avoided by favouring sustainable, biodiversity-enhancing CDR measures and with science-based planning, taking into account all local conditions and potential changes therein (e.g. due to climate change). Moreover, environmental protection, species and water protection, as well as all other UN Sustainable Development Goals, should be given high priority. Stakeholders and local experts should be consulted from the outset and involved in all decision-making processes. It has long been known that there is no one solution that fits all regions – CDR processes that worked well in one place and produce the desired results may harm people and the environment elsewhere. This is why transparent and evidence-based planning and decision-making are so important.

Are CDR measures a threat to our food security?

As part of the public discourse on the use of methods to increase carbon uptake by terrestrial vegetation, experts have repeatedly pointed out that the large acreage needed for reforestation and the cultivation of energy crops could jeopardize agricultural food production. In Germany, for example, it is estimated that roughly a quarter of the agricultural land would have to be afforested to offset the country's difficult-to-avoid emissions. Taking a global perspective, a land area the size of India would be needed to afforest a sufficient acreage by 2050 to remove enough atmospheric carbon dioxide to limit global warming to 1.5 degrees Celsius. And we would need additional land to produce bioenergy crops – an area equating to the area of Mexico by 2100. At least these are the assumptions under-



3.10 > The production of livestock-based foods such as beef, cheese and milk results in particularly high greenhouse gas emissions. A low-meat diet is therefore one of the simplest and most effective ways to reduce one's carbon footprint.



3.11 > Research conducted in 2018 showed that for most foods, the greatest share of the greenhouse gas emissions associated with their production was due to land-use change and farm management.

lying numerous scientific climate scenarios that ultimately reach the 1.5-degree target.

Widespread ecosystem restoration would have to be undertaken, particularly in the world's tropical and subtropical regions, as their rainforests and wetlands take up and store particularly large amounts of carbon. If the necessary measures were to be implemented, calculations suggest that roughly half of all utilized agricultural land in Southeast Asia, Central Africa, the Caribbean and Central America would be lost. As a result, competition for land would increase and, in the long term, food prices would rise in the affected regions. Both would primarily impact food security in these regions' poorer population segments.

If we consider the question of land use from a global perspective, the answers are not quite as clear. A large meta-study undertaken in 2018 concluded that the production of meat, eggs, milk and fish from aquaculture used roughly 83 per cent of the world's farmland (for livestock husbandry and, in particular, the production of animal feed). If global meat and dairy consumption were to sharply decline, large areas of farmland would be freed up and become available for reforestation and ecosystem restoration projects as well as for the sustainable cultivation of bioenergy crops – even if crop production had to be scaled up to meet the increasing demand for plant-based food. Other studies suggest that, if meat-rich diets and land management remain unchanged, the widespread cultivation of energy crops in particular could jeopardize the long-term and adequate supply of food for the world's growing population.

The 20 most important land-based measures to mitigate climate change

The Intergovernmental Panel on Climate Change breaks down processes for greenhouse gas emissions avoidance and increased carbon dioxide uptake by terrestrial ecosystems into four categories: (1) forests and other ecosystems, (2) farming, (3) biomass production for goods and energy generation from biomass, and (4) changes in consumer behaviour (demand-side measures).

Measures pertaining to *forests and other ecosystems* include:

- *the protection of existing forests, (coastal) wetlands, peatlands, grassland landscapes and savannas* from overexploitation, deforestation or destruction due to land reclamation, urban growth, resource extraction, fires, or pests and diseases. A particular focus in this category is on tropical rainforests and savannas;
- *reforestation of degraded forests and improved sustainable forest management* with a focus on species diversity and increased resilience to diseases and impacts of climate change;
- *restoration of degraded (coastal) wetlands, peatlands, grassland landscapes and savannas,* for example through rewetting and restoration of formerly drained areas, or by means of planting new mangrove forests and salt marshes;
- *improved fire management* in forests, grassland landscapes and savannas, for example through controlled burning of undergrowth.

Measures pertaining to *farming* include:

- *improved soil management on arable land to safeguard and increase soil carbon contents.* This necessitates, for example, improved species-rich crop rotations that include the cultivation of catch crops, dispensing with soil cultivation such as ploughing and harrowing, and using organic fertilizers such as manure;
- *improved grassland management* to safeguard or increase soil carbon content, especially immediately below the sward. Possible solutions include low-input grazing systems and the sowing of deep-rooted grasses;
- increasing use of *agroforestry land uses.* This involves farmers cultivating trees, shrubs and crops together on the same piece of land, ideally generating a range of different synergies. The benefits in a nutshell: trees and shrubs accumulate carbon in their biomass as well as in the soil, prevent soil erosion and improve water

3.12 > Intelligent irrigation methods and the targeted use of fertilizers can significantly reduce methane and nitrous oxide emissions from rice cultivation.

quality. They also provide shade that protects both crops and livestock from extremely high temperatures;

- *applications of plant-based biochar*. Biochar is produced from waste such as wood residues, sawdust, straw and other plant biomass in the absence of oxygen and at temperatures of 450 to 550 degrees Celsius. The carbon-rich biochar is considered a soil improver. It increases the soil's water and nutrient retention capacity and slows down the decomposition of carbon stored in the soil. Rice paddies treated with biochar emit less nitrous oxide, for example. Once applied to a field, biochar fulfils these important functions for decades, or even millennia. However, how successfully it can be used strongly depends on soil conditions and the feedstock used to produce the biochar;
- *a reduction in enteric fermentation*. This refers to measures that influence the digestion process of ruminant livestock in such a way that they generate less methane. These include, for example, feed additives or the targeted breeding of animals that produce less methane;
- *improved slurry management*, aimed at minimizing methane and nitrous oxide emissions. This includes, for example, the use of special feedstuffs, improved grazing management, treatment of slurry with fermentation inhibitors and optimized storage;
- *improved crop nutrient supply*. This can reduce nitrous oxide emissions from arable agriculture. The catalogue of measures includes a number of sustainable fertilizer application techniques and the use of various fertilizers, including organic fertilizers such as compost or manure.
- *optimized rice cultivation*, resulting in less methane and nitrous oxide escaping into the atmosphere. Improved irrigation methods and more targeted fertilizer use are among the options.

Category 3 contains solely processes that are summarized under the acronym BECCS (Bioenergy with Carbon Capture & Storage), referring to methods for *energy generation from plant biomass*, including wood and crop residues, organic waste and biomass from conventional food and feedstuffs such as maize. These can help reduce emissions if, firstly, the energy produced is used to power engines (biofuels) or for heat and electricity generation, replacing energy from fossil fuels. Secondly, the carbon dioxide emissions produced during combustion must be captured and then stored safely and permanently. Thirdly, the biomass should be grown or produced in a way that does not cause additional greenhouse gas emissions and does not have other adverse impacts on people and nature.

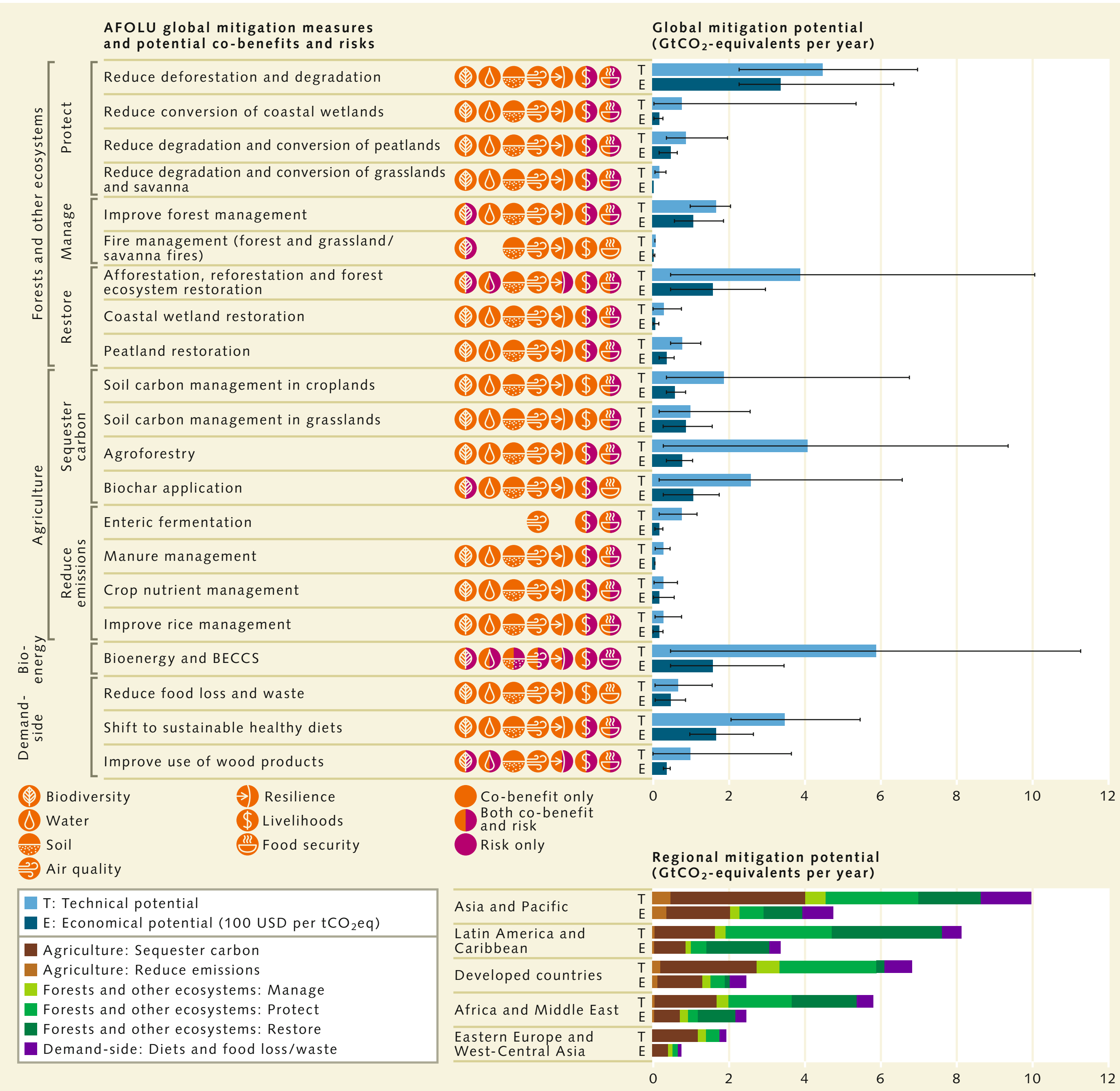
Measures to achieve *changes in consumer behaviour*:

- a *drastic reduction in food losses and food waste.* About one third of all food produced worldwide spoils on its way from the farm to the consumer or is discarded unused by consumers post-purchase;
- a *fundamental dietary shift for many people* towards a sustainably produced, largely plant-based diet. This is possible in many, but not all regions of the world;
- *increased and improved use of timber products.* When timber is used as a building material or manufactured into durable products, the carbon it contains remains sequestered for a long time. Timber use is emissions-reducing, for example, if it comes from sustainable forestry systems and substitutes for high-emissions construction materials.

Barriers and lacking frameworks

Despite their great potential, measures to save greenhouse gas emissions or to increase carbon sequestration in terrestrial vegetation have as yet contributed little to climate change mitigation. This is because so far they have been implemented on far too small a scale. The IPCC attributes this failure primarily to a lack of investment and insufficient political, institutional and societal support.

For example, policy-makers in many areas have failed to abolish subsidies for intensive farming enterprises and



3.13 > 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.

3.14 > Three quarters of our planet's ice-free land area is now used and shaped by humans. This also includes food production, as seen in this example, showing wheat cultivation in Tibet. It further means that these land areas are no longer in their original, natural state.

to invest the freed-up funds in sustainable arable and livestock farming instead. In addition, people in poverty-stricken rural areas whose livelihoods are based on arable farming or the timber trade (often illegal logging) often still lack alternative sources of income. Until 2020, the international community spent just 700 million US dollars per annum on measures to reduce emissions from land use. By 2030, however, investments of 178,000 million US dollars per year will be needed in the global forestry sector alone if carbon dioxide emissions of five gigatonnes per year are to be avoided or additionally sequestered – 254 times as much. To put this into perspective: five gigatonnes of carbon dioxide equate to just under half the amount of carbon dioxide that terrestrial vegetation naturally absorbs per year.

International programmes for the protection of tropical rainforests and wetlands report both successes and failures, depending on which nation one looks at. In countries where livestock farming controls large tracts of forested and non-forested land (such as Brazil), incentives to reduce the national herd in favour of reforestation are low. In Germany and other countries, complex responsibilities and ownership structures are barriers to reforestation and large-scale sustainable forest management. Yet both are urgently needed, especially on foot of the forest dieback in Central Europe due to the drought summers of 2018 to 2022.

Last but not least, the shift from conventional to sustainable farming and forestry requires investments in new or different technologies. The associated financial risks are too great for many farmers and foresters – in part also because they rarely receive remuneration for the increased carbon uptake on their land. What is needed here are new procedures in national and international emissions certificate trading and more research, the results of which will educate local communities and decision-makers as to the costs and benefits of sustainable land use.

Two additional options for increased land-based carbon dioxide removal

Accelerated rock weathering

Accelerated rock weathering, known as "enhanced weathering (EW)", is a chemical approach that makes use of the fact that rock naturally chemically weathers. This requires rainwater, for example, which always absorbs a certain amount of atmospheric carbon dioxide as it falls to the ground. When carbon dioxide reacts with water, carbonic acid is formed. When rain falls on the surfaces of stones or rocks, this carbonic acid attacks and dissolves the minerals of which they are formed. The dissolved material is washed away with groundwater and surface water. In a further step, acid-binding minerals such as calcium and magnesium react with the carbon dioxide dissolved in the rainwater. Carbonate minerals are formed in the course of this reaction, or, to put it simply, new rock is formed in which parts of the former atmospheric carbon dioxide is firmly bound. In nature, rock weathering is a very slow process. However, accelerated weathering can be achieved by mining, crushing and then field-spreading suitable rocks over large areas to increase the reactive rock surface. Certain types of construction waste and residues from cement production or mining could also be used as source materials. Enhanced weathering processes have as yet only been tested and researched in lab and small-scale field experiments. Knowledge as to potential environmental risks or co-benefits of large-scale applications is therefore still lacking. It is also still unclear where the required quantities of rock could be mined. According to the German National Academy of Sciences Leopoldina, in order to compensate for the unavoidable emissions in Germany, about 200 million tonnes of rock would have to be mined, ground and landspread annually. This would equate to roughly three quarters of the sand and gravel extraction for construction purposes in Germany in 2019. Experts note that the required logistic effort would likely be very high.

Direct carbon dioxide extraction from the ambient air

According to the Intergovernmental Panel on Climate Change, Direct Air Capture (DAC) methods of carbon dioxide fall into the category of "geochemical CDR methods". DAC requires technical systems that draw in the ambient air and filter out the carbon dioxide it contains, using a chemical binder medium (liquid or solid). These chemical media are subsequently stripped from the carbon dioxide through the application of heat (up to 900 degrees Celsius) and moisture or under pressure – a generally highly energy-intensive process. This regenerates the chemical media for reuse and the removed carbon dioxide is either stored deep underground (Direct Air Carbon Capture and Storage, DACCS) or used for the production of carbon-containing products (Direct Air Carbon Capture and Utilization, DACCU).

The advantage of the DAC method is that it has a much smaller land footprint than other methods. Moreover, it also lends itself to locations that are not suitable for farming or forestry, such as deserts or inner city areas. However, since air contains very little carbon dioxide, such systems need to filter vast quantities of air, driving up their energy consumption and causing much higher costs than if the carbon dioxide were captured in a power plant or a steel mill.

A sample calculation: according to the German Environment Agency, even with a highly ambitious climate policy, at least five per cent of Germany's greenhouse gas emissions would still be unavoidable in 2050 and would have to be offset by means of carbon dioxide removal. If one were to attempt to offset these unavoidable emissions through DAC methods, the energy required might amount to more than 100 terawatt hours per year. This would correspond to about one fifth of Germany's electricity generation in 2021 (518 terawatt hours). However, since DAC processes mainly require heat, waste heat from industrial processes or geothermal energy could also be considered as energy sources.

According to the International Energy Agency, 18 DAC demonstration plants were already in operation in Europe, the USA and Canada in September 2022. Taken together, they were removing about 10,000 tonnes of carbon dioxide from the atmosphere per year. The captured gas was subsequently used mainly in beverage production (carbonic acid) and only a small proportion was injected underground for permanent storage. At that time, a DAC facility capable of capturing one million tonnes of carbon dioxide per annum was under construction in the USA.

Industrial-scale usage of DAC will depend on whether future facilities can be operated with renewable energy and whether sufficient water will be available wherever moisture is needed for the separation of carbon dioxide and binder media. In countries like Germany, the situation is further complicated by the fact that geological storage of captured carbon dioxide is controversial at the societal level and the process currently lacks public support.

Conclusion

Solutions implemented far too rarely

The terrestrial carbon stores are much smaller than the oceanic carbon stores. Oceans store ten times as much carbon than is contained in terrestrial organisms and soils. Nonetheless, there are several reasons why the land carbon balance (soils and terrestrial vegetation) plays a key role in the current climate crisis.

Human societies have always contributed to the depletion of land carbon stocks through land-use change. This kind of depletion occurs wherever forests are cleared, be it by fire or otherwise. It also happens when wetlands are drained, natural grasslands are converted to arable land or soils are depleted by intensive agriculture. Each of these activities burns or results in the decomposition of organic matter, thus creating and releasing greenhouse gases. Carbon dioxide emissions from land-use change currently account for about one-tenth of all carbon dioxide emissions attributable to human activities. In addition, methane and nitrous oxide emissions from livestock farming and from the intensive use of fertilizers are on the increase.

Globally, humankind has so far converted 75 per cent of all original land areas and has destroyed 85 per cent of the wetlands that once existed. This has not only altered local climatic processes. It has also had the further effect of reducing the capacity of the remaining ecosystems to absorb and store carbon. The world's terrestrial vegetation and soils do however still function as a carbon sink, i.e. they absorb more atmospheric carbon dioxide and store the carbon it contains than they release through counteracting processes.

This characteristic means that terrestrial vegetation, and especially forests, has absorbed roughly 31 per cent of our carbon dioxide emissions since 1850 and stored them below ground and in its biomass. Scientists have also been observing a fertilization effect of the rising atmospheric carbon dioxide concentration, which leads to terrestrial plants showing improved growth and steadily taking up and storing more carbon overall.

Based on this knowledge, a number of solutions have been developed that can largely prevent further greenhouse gas emissions from land-use change, increase the size of the land carbon sink and compensate for anthropogenic emissions remaining after all emissions reduction options have been exhausted.

In essence, it is about protecting existing forests, wetlands and grasslands, restoring destroyed ecosystems and soils, practising agriculture and forestry in an environmentally friendly way, and producing enough biomass so that part of it can be devoted to bioenergy generation and the manufacture of goods.

Not all measures are without risk, and competition for land is fierce in some places. Properly implemented, however, known methods could achieve roughly 20 to 30 per cent of the greenhouse gas emissions reductions and carbon dioxide removal needed by 2050 to keep global warming to below two degrees Celsius.

But thus far these have been implemented on far too small a scale. The Intergovernmental Panel on Climate Change attributes this failure to a lack of investment and political, institutional and societal support. There is thus a clear disconnect between our lived reality and the scientific insight and recognition that humankind can only overcome the climate and biodiversity crises with the help of healthy and functional ecosystems.

4 Ocean-based CDR – research under massive expectations

> In the search for ways out of the climate crisis, attention is increasingly focused on ocean-based methods to boost the removal of CO_2 from the atmosphere. However, much of the knowledge about the potentialities, feasibility and impacts of ocean-based CO_2 removal (CDR) is theoretical. Marine research is now expected to deliver solutions as swiftly as possible, but faces criticism, as well as competition from businesses whose primary goal is to generate revenue from ocean-based CDR.

An ocean of opportunity – or harmful hype?

> Climate change is inflicting ever more loss and damage around the globe – and while policy-makers and businesses seek ways to reduce emissions, they are still reluctant to take radical action. New research on ocean-based CDR now faces a challenge: it must develop a comprehensive approach to this multi-faceted topic as swiftly as possible. But can this be achieved without commercial interests coming to the fore? A code of conduct will be needed to avert unwanted developments.

A tension-filled research area

Although policy-makers and scientists have been discussing the potential and feasibility of land-based CDR for more than 15 years, the notion that the ocean may also offer opportunities for targeted action to mitigate climate change has only recently gained traction. While scientific experiments on ocean fertilization were already being conducted in the late 1990s and early 2000s, research on ocean-based CDR methods was not scaled up until after the signing of the Paris Agreement in December 2015.

Critics attribute this development to the fact that land-based climate intervention approaches are increasingly encountering practical obstacles (land-use competition, local protests, etc.) and are therefore viewed with growing scepticism by society at large. Putting it bluntly, these land-based interventions are practically impossible to push through at the political level, or require major effort. Interventions at sea, by contrast, are less likely to encounter opposition from the public – at least, that is the hope; this applies particularly to techniques that support natural processes of carbon capture and storage. Critics also note that shifting the climate policy focus towards the ocean fits into the "blue economy" narrative which claims that the limits to land-based resources and development can be circumvented in future by upscaling the extraction of food, raw materials and energy from the sea. Arguably, the expansion of fish farming in marine aquaculture is evidence of this trend, as are the moves to commence deep-sea mining.

Weighing far more heavily, however, is the claim that the entire debate about CDR is merely a stalling exercise that shifts genuine, life-changing emission reduction measures into the future, invariably on the grounds that technical options for regulating atmospheric carbon dioxide concentrations will be available one day in any case. Critics therefore claim that the political debate about CDR is nothing more than climate policy hype backed by a raft of empty promises.

In response, others argue that the increasingly dramatic impacts of climate change amplify the urgent need for effective climate change mitigation actions, and so ocean-based carbon dioxide removal methods can no longer be dismissed out of hand. However, they point out that there is an equally urgent need to close the numerous knowledge and regulatory gaps in this area: most ocean-based CDR methods – other than the restoration of devastated coastal ecosystems – are comparatively new. As they have rarely been tested, there is a general absence of detailed data on their effectiveness, potential costs, risks and impacts on the environment and society. Critics also point to the legal aspect: it is already clear that the existing international conventions and national legislation pertaining to marine governance are inadequate as they can neither safeguard the reliability and transparency of research on ocean-based CDR nor properly regulate its use on an industrial scale.

Ocean fertilization

Phytoplankton need nutrients such as iron, nitrogen and phosphorus compounds in order to grow. However, there is a deficit of these nutrients in many ocean regions. Scientists have therefore developed the concept of ocean fertilization; this involves seeding the ocean's surface with iron to encourage phytoplankton growth. In theory, more phytoplankton would remove more carbon dioxide from the atmosphere and convert it into carbohydrate, which would then sink into the deeper ocean. Thirteen research experiments conducted at sea confirm that increased nutrient input does indeed lead to more phytoplankton growth. However, the scientists have been unable to find firm evidence of increased carbohydrate transport into the deeper ocean. What's more, there is still a lack of comprehensive data on the potential risks of ocean fertilization and its impacts on humans and nature.

For that reason, a regulatory mechanism was established to prohibit ocean fertilization for commercial purposes (e.g. sale of emissions allowances) in international waters, although it is still permitted for research. This regulatory mechanism is based on an amendment to the 1996 London Protocol, which updates and is intended to replace the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) in the long term. However, as only six countries have ratified the new version of the London Protocol thus far, it has not yet entered into force under international law.

4.1 > The international climate change conferences, which are held annually, look at which specific climate change mitigation actions are being planned and implemented by individual countries. Scientists are under growing pressure to identify carbon dioxide removal techniques that are particularly effective, equitable and sustainable.

Investors – the main drivers of research

For these reasons, and despite all the criticism, the number of research projects on ocean-based carbon dioxide removal is steadily growing. US investors are a driving force here: they have a commercial interest in ocean interventions for climate change mitigation and are willing to commission studies on this topic. The first research project funded by the German government to identify the most promising ocean-based carbon dioxide removal methods began in August 2021. At EU level, selected ocean-based CDR processes have been investigated in joint studies involving various research institutes since 2020, again with public funding.

The data gathered so far, however, do not provide an adequate basis for a comprehensive assessment of key factors such as carbon dioxide storage potential, technical feasibility and effectiveness, or of the costs, risks and possible positive impacts of these techniques. There is thus a concern among specialists and environmental activists that the intense pressure to take action, combined with burgeoning economic interests, could prompt decision-makers to endorse the use of ocean-based CDR before the numerous knowledge gaps have been closed. Furthermore, if research studies are commissioned and funded by companies, the possibility that investors will seek to influence the interpretation and assessment of the collected data cannot be ruled out.

A code of conduct for climate intervention research

Leading scientists in the US have therefore drafted a code of conduct to guide research on ocean- and land-based CDR. It consists of five key points which, the experts say, should be adopted and implemented as an ethical framework for any research project in this field. These five key points are:

- *Prioritize collective benefit:* The collective benefit to humankind and the environment must be the primary purpose of research conducted to develop and evaluate the potential for climate intervention technologies to moderate or reverse human-induced climate change.
- *Establish responsibility:* Governments and public agencies must clarify responsibilities for and, when necessary, create new mechanisms to govern and oversee large-scale climate intervention research activities that have the potential or intent to significantly modify the environment or affect society. These mechanisms should build upon and expand existing structures and norms for governing scientific research and, in the event of damaging outcomes, establish who would bear the cost.
- *Commit to open and cooperative research:* Research should be conducted openly and cooperatively, preferably within a framework that has broad international support. Research activities with the potential to affect the environment in significant ways should be subject to risk assessment, considering the risks and their distribution associated with both the activity itself and the ongoing limits to understanding if the experiment is not conducted.
- *Perform evaluation and assessment:* Iterative, independent technical assessments of research progress on climate intervention approaches will be required to meet societal goals. Assessing any intended and unintended consequences, impacts and risks will be critical to providing policy-makers and the public with the information needed to evaluate the potential for climate interventions to be implemented.
- *Engage the public:* Public participation and consultation in research planning and assessments, and in the development of decision-making mechanisms and processes, must be enabled to ensure consideration of the international and intergenerational implications of climate intervention strategies and activities.

4.2 > A diver collects research samples at a macroalgae farm off the East Coast of the United States. Scientists are attempting to identify species of macroalgae that are fast-growing, hardy and resilient.

For opponents of ocean-based CDR, this code of conduct is inadequate. They reject further human interventions in the ocean as a matter of principle and point to climate change, overfishing and marine pollution as indications that there has already been too much human interference in the marine environment.

In view of the predictable controversy surrounding the pros and cons of ocean-based climate intervention technologies, researchers are working to systematize the multiple issues and apply an integrated, trans- and interdisciplinary approach to research on this complex topic. In addition to the technological, environmental, economic, legal and regulatory aspects, a key question arising in this context is whether a national population or region affected by such measures would actually consent to and support relevant interventions aimed at offsetting residual emissions.

It is already clear that small-scale actions will not be sufficient to effectively halt climate change. If the ocean is to make a significant contribution to offsetting residual emissions (for reaching the 1.5-degree target: 420 to 1100 billion tonnes of carbon dioxide), a new carbon dioxide removal industry will need to be established and the appearance of the landscape in affected marine and coastal regions will change accordingly. In other words, using ocean-based CDR for effective offsetting of residual emissions will require massive intervention in the ocean's natural processes – across large areas and for a long time.

Many parallels and additional challenges

A comparison of land- and ocean-based climate intervention technologies reveals numerous parallels between them. In both spheres, experts distinguish between biological, chemical and geochemical CDR methods, with hybrid forms also possible. The key processes are similar as well. In essence, the restoration and expansion of vegetation-rich coastal ecosystems such as mangrove forests, salt marshes and seagrass beds are mirror images of land-based methods for the (re)forestation and restoration of carbon-rich woodlands, wetlands and grasslands. Techniques to boost the alkalinity of seawater are based on accelerated weathering of rock, while processes which involve large-scale algaculture for bioenergy production require a carbon capture and storage (CCS) component, analogous to BECCS.

However, the ocean poses a particular challenge: its sheer size, global currents and complex systemic interactions make it difficult to measure how much carbon dioxide it can naturally capture and store, and for how long. If ocean-based CDR is to be deployed, other challenges will arise: measuring and verifying the additional human-induced carbon dioxide that is captured, attributing it to specific processes or actions, and monitoring the duration of storage, as well as assessing the potential environmental impacts of each individual measure over long periods of time. How will this work? This is a key question for research, given that properly functioning and, ideally, standardized measuring and monitoring systems do not exist for most CDR methods at present.

The same applies to solutions aimed at limiting any potentially negative impacts of specific CDR methods to a small area of the sea. As the currents form a connecting link between all the ocean regions, the possibility that CDR interventions in a country's coastal waters may ultimately impact on areas thousands of kilometres away cannot be ruled out.

A wide range of ocean-based CDR methods are currently being researched. Most rely either on marine biology – in other words, the conversion of carbon dioxide into biomass by photosynthesis and storage of this biomass in the deep ocean – or on chemical and physical processes in which more carbon dioxide is dissolved in surface waters and then transported to greater depths by the ocean currents.

The carbon dioxide removal techniques discussed most frequently or intensively by scientists and climate policy-makers are described in the following pages. This overview looks at how each method works, its potential to store carbon dioxide and for how long, its technological development status, and whether it offers scope for upscaling. It also includes a cost-effectiveness analysis, identifies the benefits and disbenefits for people and nature, if known, and outlines the key social, legal and political frameworks.

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

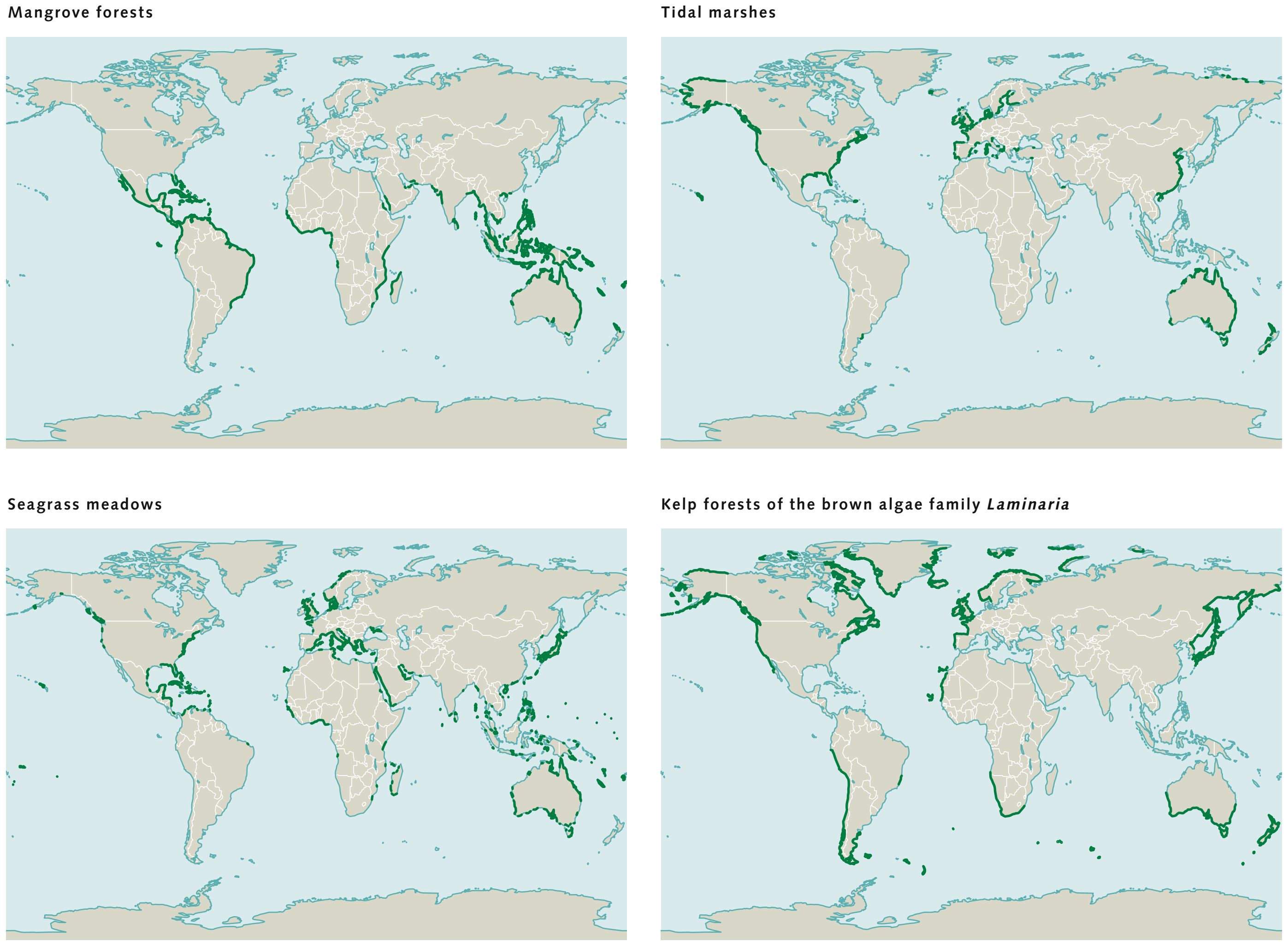
In the search for ways to increase the ocean's carbon dioxide uptake, it makes sense to first focus on the key players in the ocean's carbon cycle. In coastal areas, these include above all the vegetation-rich ecosystems in tidal and shallow waters (up to 50 metres of water depth), i.e. tidal marshes, 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.

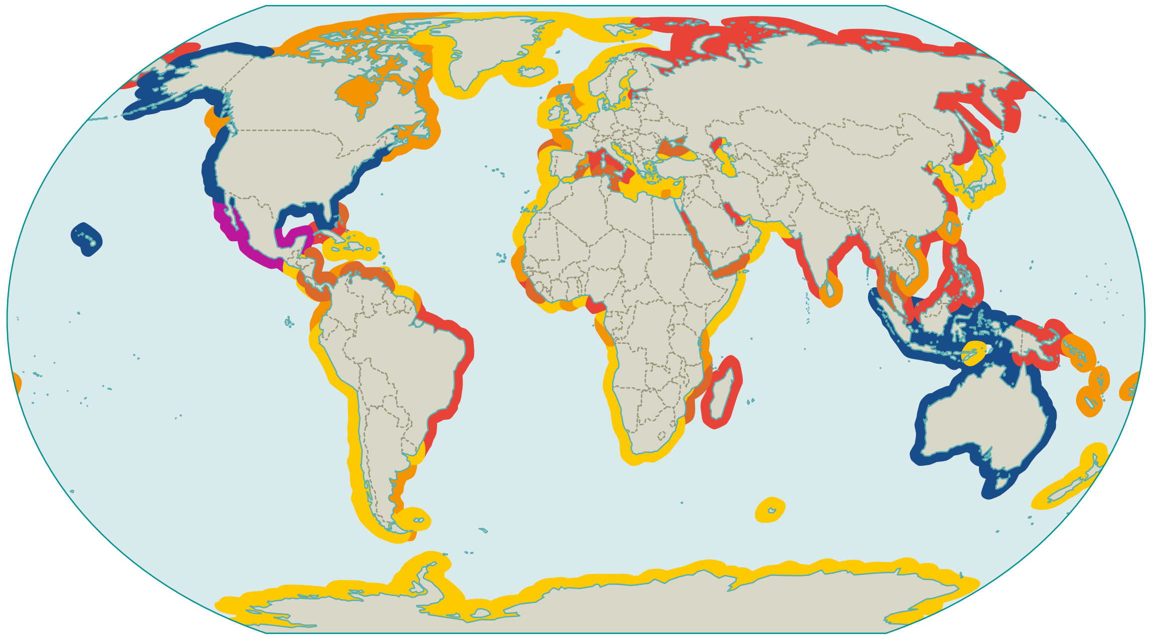
5.1 > Mangroves protect the coast from waves, sea-level rise and storm surges. But they cannot withstand all weather extremes. When Hurricane *Maria* swept across Costa Rica in September 2017, large parts of this mangrove forest died.

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

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.

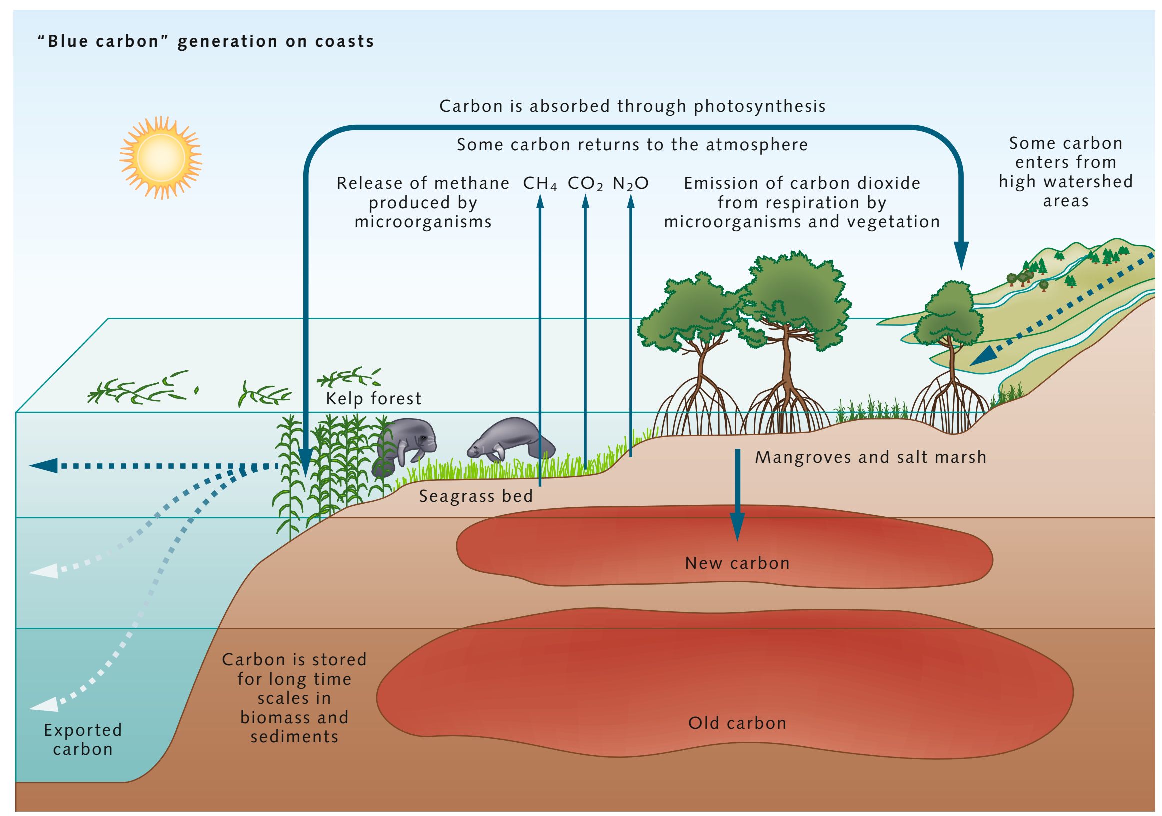
intact. In the Spanish Portlligat Bay, for example, there are seagrass meadows whose carbon stores are more than 6000 years old.

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.

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.

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

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.

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

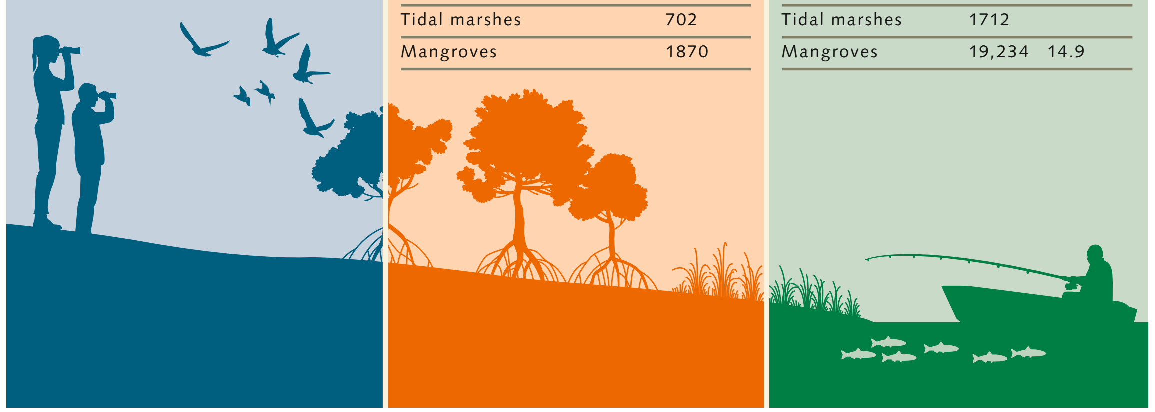
Recreation
BCEs are visited frequently by birdwatchers and fishers. In two popular Melbourne bays, seagrasses generate leisure and recreational effects for fishers worth 33.1 million Australian dollars (AUD) annually, while a visit to the tidal marshes and mangroves provides fun and entertainment worth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

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 (N_2O). 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.

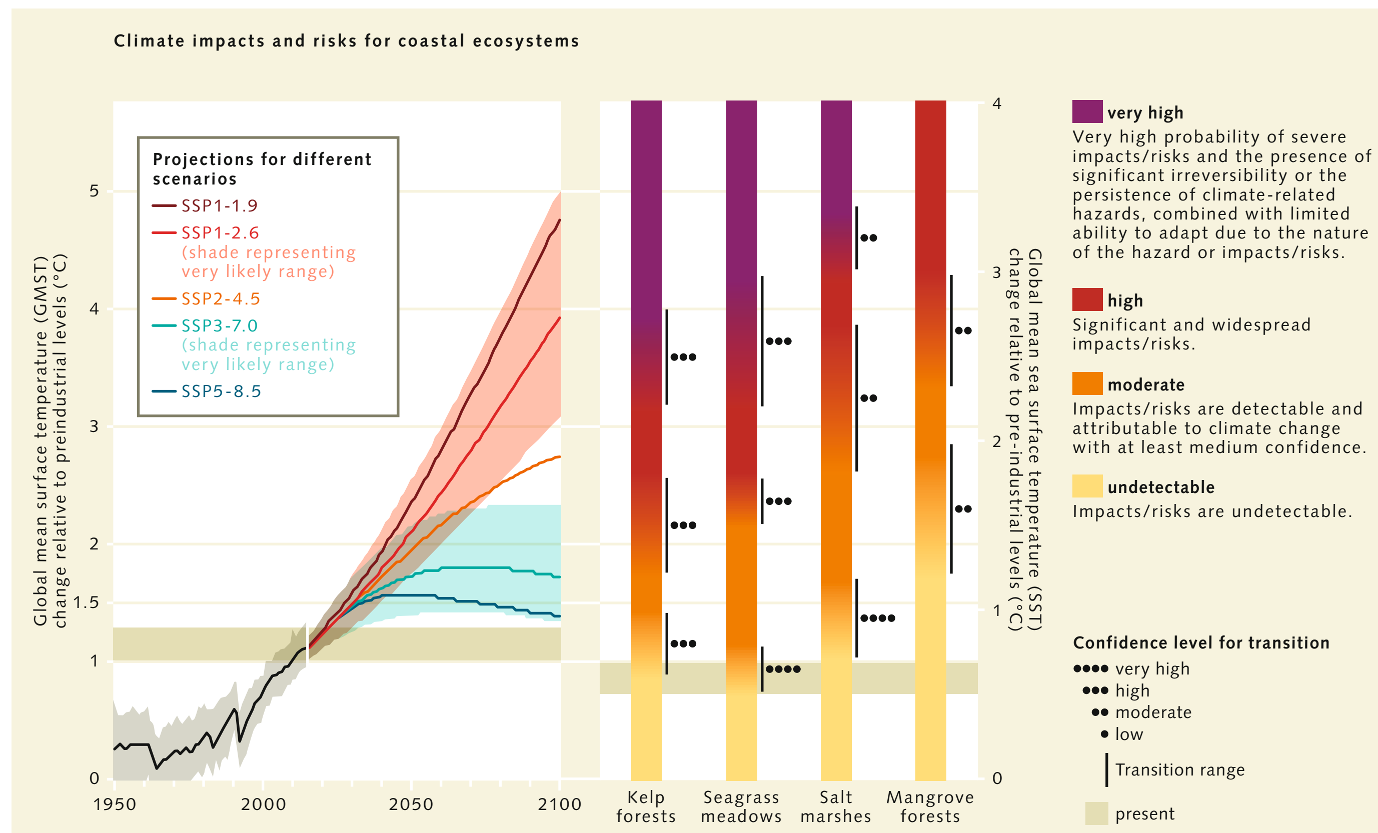
If large-scale spatial shifts are not possible due to space constraints and ecosystems decline in area or disappear, their carbon stores in the coastal sediments would also be at risk.

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

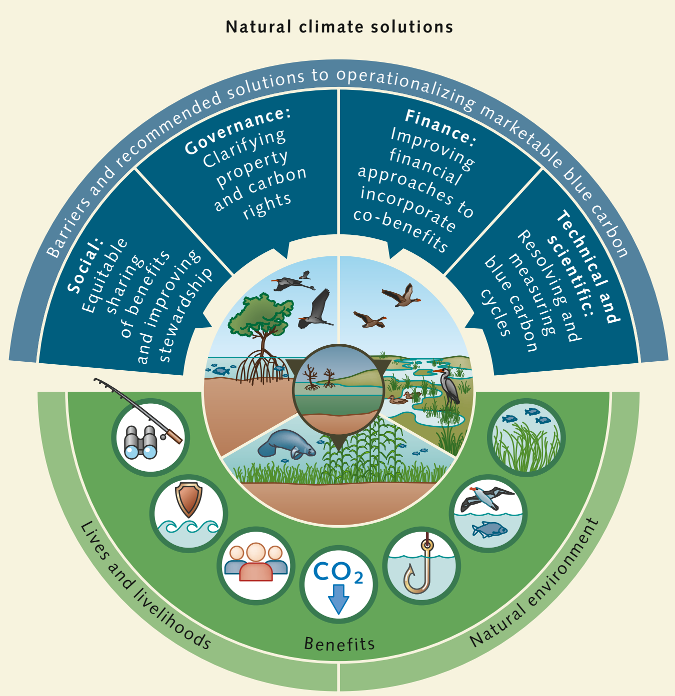
Many blue carbon projects have not yet been able to meet these requirements. A difficulty may be, for example, that it is hard to prove exactly how much additional carbon dioxide is being removed from the atmosphere. For this reason, the amount of blue carbon credits issued is still comparatively small. 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.

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

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.

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.

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.

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.**

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.

6 Artificial upwelling – the idea of greening the ocean

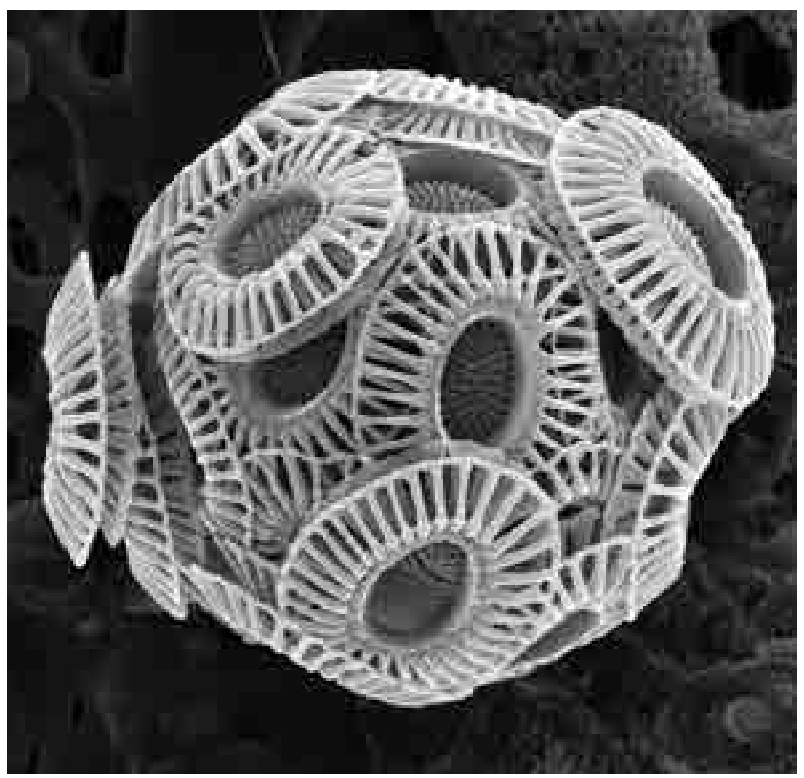
> Algae, zooplankton and fish are prime drivers of what is termed the biological carbon pump. This natural process needs nutrients to function properly. Such nutrients, however, are lacking in many places, notably in sunlit surface waters. Pumping up nutrient-rich deep ocean water could remedy this nutrient deficiency. Whether such a step would actually increase the ocean's natural uptake of carbon is uncertain.

Kick-starting the biological carbon pump

> Phytoplankton growth is limited on about 75 per cent of the ocean surface, because in those regions the light-filled surface waters do not contain enough nutrients. Deep ocean water, in contrast, tends to be rich in nutrients. This knowledge gave rise to the idea to pump up ("upwell") nutrient-rich water from several hundred metres below the ocean surface in order to increase algal growth in the sunlit upper layers and thus boost the performance of the biological carbon pump. Whether artificial upwelling will prove useful is uncertain. Research investigating the concept has been presenting scientists with extraordinary technical challenges.

The role of microscopic marine algae

Protecting and expanding the highly productive plant communities of coastal regions (Chapter 5) would be one possible biological method to enhance the ocean's uptake of carbon dioxide. However, there is a second approach that relies on the ocean's biology. Its basic idea is to boost the natural organic biological carbon pump of the ocean. This is driven by the biotic communities in the oceanic surface waters, especially by single-celled, microscopic algae, the phytoplankton, whose representatives are just 0.0001 to 0.5 millimetres in size.

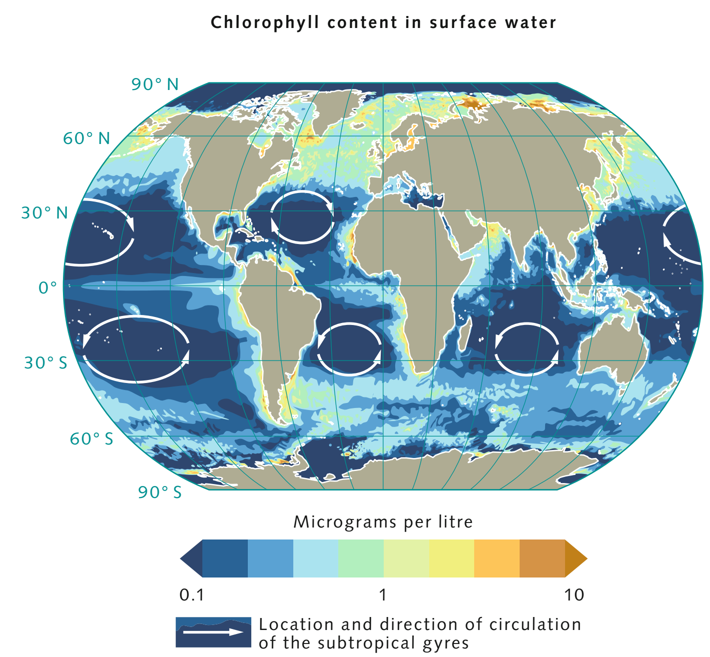


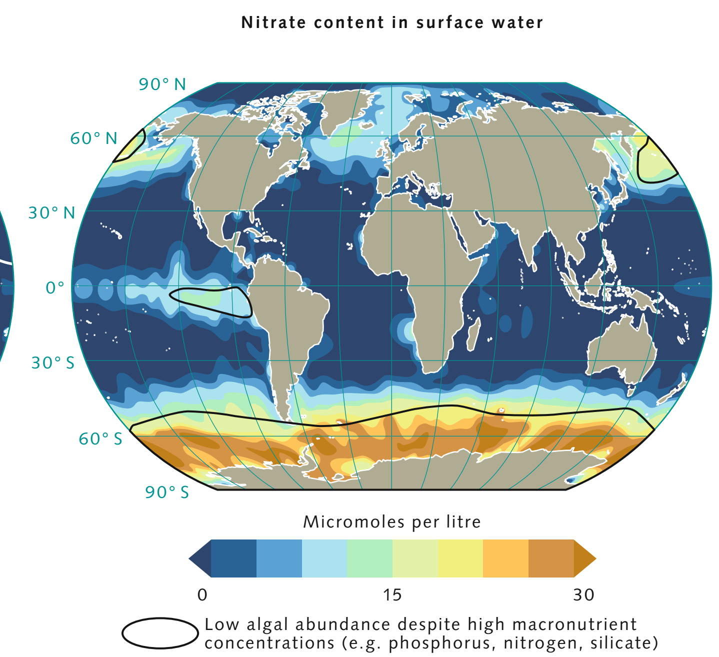
6.1 > The unicellular algae *Emiliania huxleyi* is one of the ocean's keystone species. It forms huge algal blooms and thus contributes significantly to the oceanic biological carbon pump. Its conspicuous shell consists of microscopic calcite discs, to which the unicellular organism owes its name „calcareous algae".

The most important groups of phytoplankton include the diatoms, the dinoflagellates, the haptophytes with their best-known subgroup, the coccolithophores, and the tiny picophytoplankton, which account for up to 80 per cent of the biomass in surface waters in the large nutrient-poor areas of the oceans. Together, the phytoplankton communities of the global ocean are currently responsible for about half of the global carbon dioxide uptake and carbon sequestration. It is estimated that they absorb about 50 gigatonnes of carbon per year. The unicellular marine algae thus have a critical influence on the carbon dioxide content of the global ocean and atmosphere and are important players in the ocean's carbon cycle.

Phytoplankton needs sunlight in order to photosynthesize, which is why the algae are only active in the sunlit oceanic surface waters, at depths of not more than 150 metres, depending on the water's turbidity. How fast the algae grow and what species occur together depends primarily on which nutrients the surface water contains and in what quantities. It is not limited by the availability of dissolved carbon dioxide, as this basic ingredient for photosynthesis is always available in sufficient quantities. Diatoms, for example, which bind a comparatively large amount of carbon and are responsible for about 40 per cent of marine biomass production, primarily grow in areas where the surface water contains both the macronutrients phosphorus and nitrogen as well as micronutrients such as iron and dissolved silicic acids (silicon dioxide, also called silicate).

Phosphorus and nitrogen (often in the form of nitrate) are needed for the development of algal cells. Both nutrients enter the sea via rivers, from the atmosphere, or are released during microbial recycling processes, for example in the sediment layer on the ocean floor. The





6.2 > The main nutrients of importance for algal growth, i.e. phosphorus, nitrogen (in the form of nitrate) and silicate, are unevenly distributed in the oceans. Therefore, only 25 per cent of the sea surface can be described as nutrient-rich areas. They are mainly located at higher latitudes as well as in the Earth's natural areas of upwelling.

nitrogen then needs to be converted into nitrate by cyanobacteria – otherwise it's no use to the phytoplankton. The algae need iron to form enzymes and proteins – especially those that are essential for photosynthesis. Important sources of iron for marine phytoplankton communities are Arctic and Antarctic glacial meltwater, sediment-laden streams and rivers, dust clouds that rise above deserts and subsequently discharge sand over the ocean, as well as deep sea hydrothermal processes (such as black smokers, i.e. deep sea vents), in which iron-rich water escapes from the ocean floor. If there is a lack of silicate in the water, diatoms are unable to build up their silica shells, which among other things protect the protozoa from being consumed by smaller copepods. Under these conditions, other, mostly smaller algae species grow instead of diatoms.

Globally, only 25 per cent of the ocean surface waters are considered to be nutrient-rich areas. These are mainly located in the higher latitudes (e.g. North Atlantic) and in the Earth's natural areas of upwelling. The remaining 75 per cent lack certain nutrients in the surface waters, so that algal growth is naturally limited. In deep ocean water, however, sufficient nutrients are available everywhere.

Artificial upwelling – modelled on the ocean itself

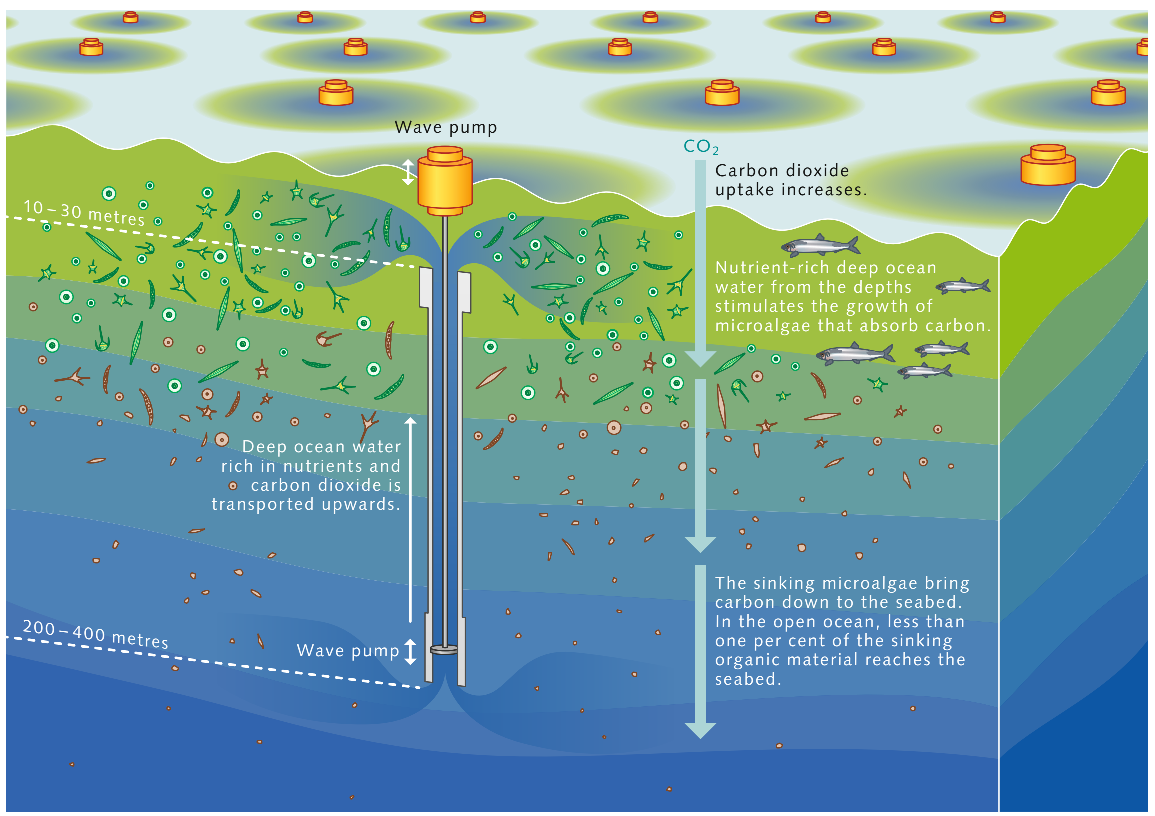
One must understand these connections to realize how the organic biological carbon pump could theoretically be cranked up. The plan is to pump nutrient-rich water from depths of 200 to 1000 metres up to the surface in nutrient-poor regions of the ocean where there is as yet not much algal growth, an approach termed "artificial upwelling". According to this idea, the function of deep ocean water brought up to the light-filled surface layer would be akin to fertilizer: Algal growth would increase, especially when it comes to diatoms, and in the course of photosynthesis the algae absorb more carbon dioxide from the water and incorporate the carbon it contains into their biomass. The carbon dioxide content of the surface water would consequently decrease, enabling the ocean to absorb new carbon dioxide from the atmosphere.

Increased algal growth in the surface waters would in turn mean more food for krill, copepods, true conchs and other free-floating organisms (zooplankton) as well as fish, and would lead to an increased transport of carbon-containing material in the form of particles, faecal pellets and carcasses to greater water depths, ideally deeper than 1000 metres. The carbon contained in the sinking material would thus be locked away in the depths of the ocean for decades or even centuries – until such time as one day the carbon-rich water masses rise back to the surface.

Until then, the carbon stored in the depths can no ,longer escape into the atmosphere in the form of carbon dioxide. However, only those residual amounts of biomass are actually removed from the carbon cycle that trickle down to the ocean floor undamaged and are permanently stored in its sediment. Their share corresponds to less than one per cent of the carbon originally absorbed by the algae. If the carbon originated from other sources (wood, whale bones, etc.), this proportion can be higher (for more detailed information see Chapter 2).

Artificial upwelling mimics the functionality of the large natural areas of upwelling off the western coasts of Peru, Namibia, California and Mauritania (subtropical Africa and America). Driven by winds, nutrient-rich cold deep ocean water rises to the sea surface there and allows life to flourish in the surface waters. This nutrient input from the depths is the reason why upwelling areas are among the most productive and fish-rich ocean regions in the world. However, in order to imitate this successful oceanic strategy using technological means and apply it in previously less productive marine regions, tens to hundreds of thousands of upwelling pumps with a total delivery volume of one million cubic metres of water per second would be needed. Only then would the artificially generated upwelling effect be roughly equivalent to that in the natural areas of upwelling.

It is questionable whether it would be expedient and economically viable to deploy that many pumps. In a simulation study conducted in 2022, researchers concluded that the additional carbon dioxide removal and consequent storage at greater depths would merely



6.3 > 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.

6.4 > The beauty and variety of forms of diatoms only become apparent when viewed through an electron microscope. Many thousands of species have been discovered so far. They all live in a “house made of glass”, or more precisely in a protective armour of hydrated silicate.

amount to approximately 150 million tonnes per year even if upwelling pumps reaching down to a depth of 500 metres were to be deployed to every square kilometre of surface across the tropical-to-subpolar ocean waters.

The envisaged ecosystem transformation

Artificial upwelling would have the greatest theoretical potential impact in nutrient-poor and consequently less productive marine regions such as the subtropical gyres. The biotic communities in their surface waters are perfectly adapted to the low nutrient status. For example, instead of many large diatoms, smaller species of algae grow in such regions; following their death they sink less quickly and also carry away less biomass (fixed carbon) into the ocean depths. The zooplankton is also comparatively small: It does not need large mouthparts to crack the diatoms' hard shells, and smaller organisms also need less food and energy to survive. After all, both are in short supply in the nutrient-poor surface waters of the subtropical gyres.

If the amount of available nutrients were to change permanently due to artificial upwelling, the biotic community of the surface waters would presumably adapt to this new situation over time. First, more diatoms would grow. These would be followed by larger zooplankton which is able to break down the diatoms' hard silicon shells. Large, nutritious zooplankton would in turn attract fish, which is why experts assume that artificial upwelling would boost fish stocks in the long term in the regions concerned. But just how well the envisaged adaptation processes would work in practice is the subject of current research projects.

Interplay of biological and physical carbon pump

The biological carbon pump is not the only process that determines whether or not artificial upwelling can in fact remove additional carbon dioxide from the atmosphere. In addition to high nutrient concentrations, deep ocean water also contains additional carbon dioxide, which has accumulated there by means of two processes: firstly via the biological carbon pump described above and secondly via the physical carbon pump.

The physical carbon pump is driven by sinking cold water masses in the polar regions. Since the solubility of gases is higher in cold water, i.e. the water can absorb more gases, the water masses that sink in the high latitudes and then slowly move at depth towards the equator contain a relatively high amount of carbon dioxide. If this cold, carbon dioxide-rich deep ocean water is pumped to the surface, it warms up. At the same time, its ability to dissolve gases decreases and the stored carbon dioxide outgasses back into the atmosphere. Therefore, if the oceanic carbon dioxide uptake is to be increased by means of artificial upwelling, the process must ensure that more carbon dioxide will be sequestered by algae and transported to great water depths than reaches the surface with the upwelled deep ocean water.

One of the arguments in favour of using artificial upwelling is that progressive climate change increases the stratification of oceanic water masses. As a result, the surface water and the water in the twilight zone below mix to a lesser extent, which is why the natural nutrient supply from the deep ocean decreases, and along with it, in the long term, biomass production in the sunlit part of the water column. Artificial upwelling could counteract this development to some extent.

Using computer simulations, researchers also discovered that the carbon dioxide removal potential through artificial upwelling increases with each degree of additional warming, regardless of the decreasing biomass production due to ocean warming, acidification and oxygen loss. Once again, this is due to the physical carbon pump. Model calculations indicate that the physical carbon pump would benefit threefold in a warmer world from large-scale deployment of artificial upwelling:

- Firstly, the upwelling of cold deep ocean water would lead to a cooling of the air layers near the surface and simultaneously reduce the temperature of the surface water.
- Secondly, a large proportion of today's deep ocean water was formed before the onset of industrialization. This means that these water masses so far only contain carbon from natural carbon dioxide sources and not yet from man-made emissions. For this reason, the deep water still has sufficient buffer capacities to absorb additional carbon dioxide and contribute to compensating for hard-to-avoid anthropogenic carbon dioxide emissions (for further explanations please refer to Chapter 2).
- Thirdly, the acid-binding capacity of deep ocean water – its alkalinity – is higher than that of the surface water in some marine regions. There, artificial upwelling would lead to an increase in alkalinity in the surface water, which would allow for an increased uptake of carbon dioxide, while also buffering the associated acidification (for further explanations please refer to Chapter 2).

However, it is not yet clearly understood which of the two carbon pumps is the more significant in terms of artificial upwelling, and how their carbon dioxide removal potential will change in the course of climate change. Research into the feasibility of artificial upwelling processes and their impacts and risks is still in its infancy.

The search for the optimal pumping technology

One open research question, for example, is which pumping technique would be the most efficient way to generate artificial upwelling. The methods discussed so far differ in pumping technique and upwelling mode. The critical factor for the pumping technique is where the pumps get the energy they would need to transport large masses of water to the ocean surface. German marine scientists have already gained experience with a "wave pump". Pumps of

6.5 > The Spanish research vessel *Sarmiento de Gamboa* at sea with a wave pump. The pump was deployed in November 2022 for testing and research purposes in the Atlantic Ocean south of Gran Canaria. The dark upwelling tube is initially wrapped around the yellow buoy and only unrolls when the bottom weight drops down into the ocean depths.

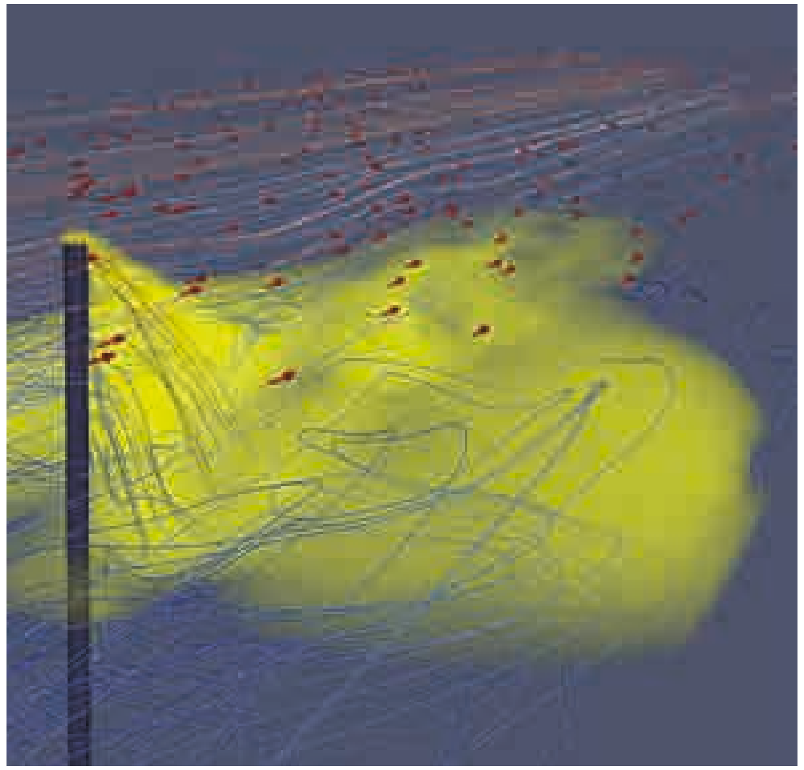
this type consist of a long upwelling tube and have a surface buoy at the upper end that rises and falls following the wave motion. This motion transfers to a pump in the upwelling tube which then lifts the deep ocean water to the surface using the force of the waves. A bottom weight keeps the tube upright in the water column.

When scientists in Germany used such a wave pump with a tube 30 metres in length and 0.4 metres in diameter off the coast of Gran Canaria, it generated an upward flow of about 35 cubic metres of water per hour. With wave frequencies and wave heights typical of oceanic regions in low to mid-latitudes, maximum flow rates of one to two cubic metres of water per second can be generated with larger dimensioned pumps of this type. However, to achieve a substantial climate-impacting throughput, at least one million cubic metres of deep ocean water per second would have to be pumped to the surface.

Higher pumping rates could be achieved using electrically driven propeller pumps. In Norway, such pumps are already in use in salmon aquaculture to pump oxygen-rich and warmer deep ocean water into the cages in winter. The salmon grow faster this way. However, propeller pumps have not yet been tested for artificial upwelling projects in the open ocean. Electrically powered pumps would only be an option if wind or solar power for their operation could be generated on-site.

Moreover, if artificial upwelling were to be used on a large scale, the maintenance effort would be considerable, because the pumps held vertically in the water column would be exposed to tremendous stresses around the clock. For example, one of the issues would be the varying current strengths depending on water depth. They would tug at the pump to varying degrees and put the material under constant stress, especially in ocean regions with strong currents, such as the subtropical gyres. Researchers from Germany experienced these impacts during the first test run of a newly developed wave-powered upwelling pump in November 2022. Three hours after the 200-metre-long pump was deployed, its bottom weight detached from its mount and sank. The wave pump then failed to operate.

6.6 > Researchers simulate the rise of deep water and its subsequent behaviour in the ocean's surface layer with the help of various flow models. This model illustration shows how the cold, nutrient-rich water (yellow) rises from the pump, then immediately sinks to medium depths and disperses.



Is it better to fertilize once or on an ongoing basis?

Apart from the pumping technique, a second important parameter is the upwelling mode. In this respect, experts distinguish between a one-time supply and a continuous supply of deep ocean water, which, according to initial test runs, has different effects on the marine ecosystem and the production of rapidly sinking biomass. For the first method (singular upwelling) the pump would be moored at sea, i.e. it would be stationary. The surface water would flow steadily past it and each individual unit of water would be enriched only once with upwelled nutrients. In contrast, with the second method (recurring upwelling) the pump would drift freely along with the current and could thus continuously supply one and the same body of water with nutrient-rich deep ocean water.

Initial results from experiments conducted as part of the EU research project *Ocean artUp* indicate that the

6.7 > In Norwegian salmon farms, electrically powered propeller pumps are used to create artificial upwelling. The aim is to supply the salmon with oxygen-rich and, during winter, warmer deep ocean water so that they grow more quickly.

biological carbon pump becomes more efficient when a body of water is continuously supplied with nutrients. This, in turn, would mean that the pumps would have to be deployed in a targeted manner and then allowed to drift freely along with the water masses – an approach that would entail many risks for humans and the environment and, on top of that, pose logistical and legal problems.

Simulations of artificial upwelling in flow models also suggest that the upwelled nutrient-rich deep ocean water does not disperse evenly at the ocean surface. Instead, due to its cooler temperature and resulting higher density, it probably sinks to medium depths, where low light levels limit photosynthesis by phytoplankton.

The success of artificial upwelling also depends on the nutrient concentration in the deep water. This can vary greatly depending on the area of the ocean where the pump is deployed and the depth from which the water is brought up. Which constellation of nutrients increases the carbon dioxide uptake of the sea most efficiently has not yet been sufficiently researched.

Impacts on marine ecosystems

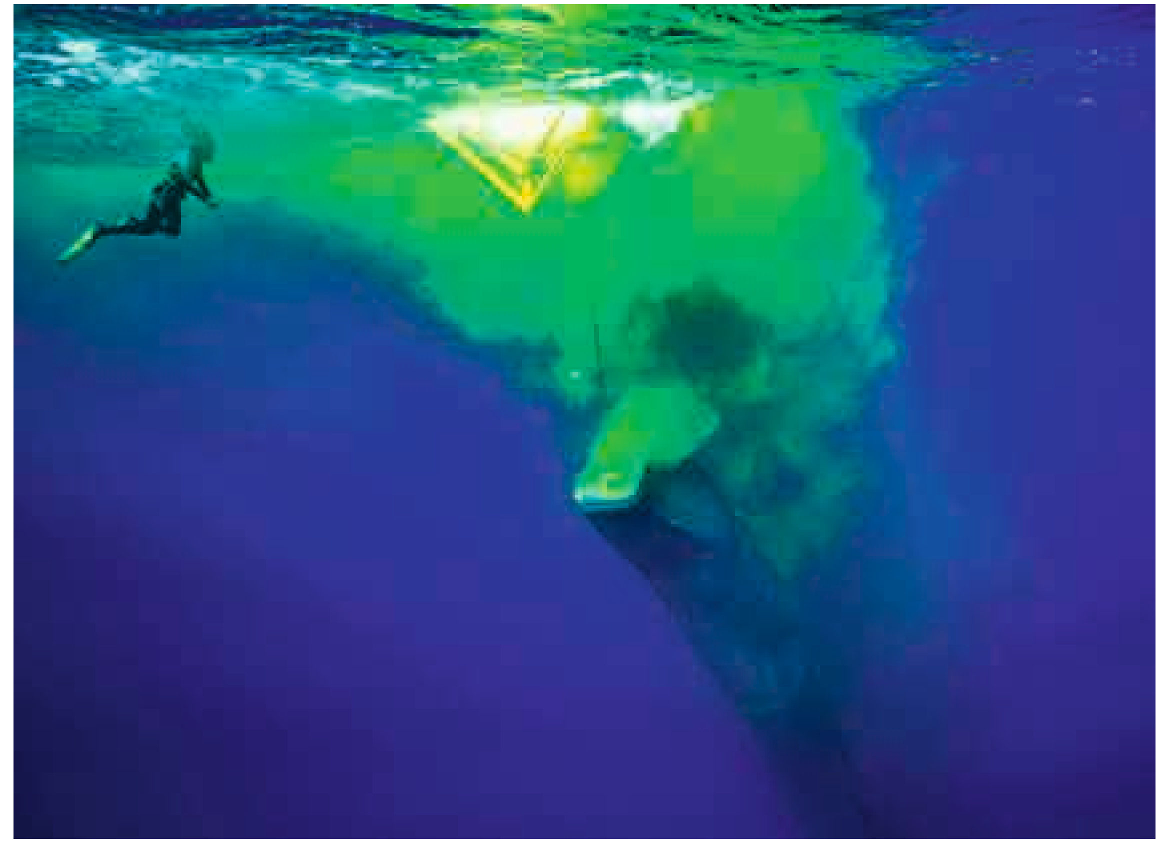
Artificial upwelling alters nutrient availability in surface waters and thus one of the pillars of marine life. Scientists have investigated how profound this change can be and what differences occur, using comparative experiments in the Humboldt Current (a natural upwelling area off the coast of Peru) and in a nutrient-poor marine region off the coast of Gran Canaria respectively. They focused on three parameters: the mixing ratio of nutrient-rich deep to nutrient-impoverished surface waters (low to high), the upwelling mode (recurrent or singular supply of deep ocean water) and the deep water's silicate content, which in turn is crucial for the growth of diatoms.

As expected by the researchers, all three parameters changed the algal growth and species community composition. The strongest algal blooms occurred when a lot of deep ocean water was brought up, this contained a lot of silicate and the surface water was fertilized just once. Under these conditions, the algal blooms even stored a particularly large amount of carbon in their biomass. Experts call this phenomenon carbon overconsumption.

However, to the research team's surprise, in the experiments off Gran Canaria the additionally formed algal biomass and its beneficial properties did not automatically lead to an increase in carbon transport to the ocean depths. Zooplankton and other marine organisms hardly capitalized on the additionally formed algal biomass. In other words, unlike in the Humboldt Current, whose biotic communities are accustomed to nutrient abundance, off Gran Canaria both the hoped-for transfer of fixed carbon in the food web and the accelerating effect on the downward transport of zooplankton feeding on phytoplankton failed to occur. Instead, the carbon-rich biomass formed in the surface water sank only slowly and was degraded by microorganisms before it could reach great depths.

One explanation for these observations could be the experiments' short duration. This gave the biotic community off the coast of Gran Canaria, which is accustomed to a lack of nutrients, insufficient time to adapt to the sudden increase in food supply. The marine organisms, the researchers reckon, were therefore unable to utilize the sudden food surplus and consume the well-armoured diatoms and other large algae species. This is an important finding, because the scientists expect similar results in the future for the use of moored upwelling pumps in nutrient-poor marine regions. The surface water would flow past these permanently installed pumps and only receive a one-time nutrient pulse, which will presumably present the plankton communities with the same problems as in the experiments off Gran Canaria.

Moreover, there are other unanswered questions, such as potential risks to marine life that may be associated with artificial upwelling, or the length of time it would take for the local ecosystem to fully adapt and be able to sequester the maximum amount of carbon and export it to the ocean depths after one or more pumps are put into operation. Experts suggest that increasing algal blooms could result in nutrient scarcity and reduced light penetration in the surface water, as well as increasing oxygen deficiency at mid-depths – where microorganisms would decompose the sinking biomass.



6.8 > In a wave pump test off Gran Canaria, the scientists poured a non-toxic bright green liquid made of seawater and the harmless fluorescent dye uranine into the upwelling tube in order to be able to observe how the deep water is distributed at the sea surface. Technical problems ultimately caused the experiment to fail.

It is also necessary to investigate the effects an increased transport of carbon-rich biomass might have on ecosystems in the deep ocean and how deep-sea communities react to possible changes in temperature and water mass stratification. Scientists involved in the German research mission *CDRmare* are conducting corresponding experiments, lab-based studies and computer simulations, the results of which will however only become available in the course of 2024.

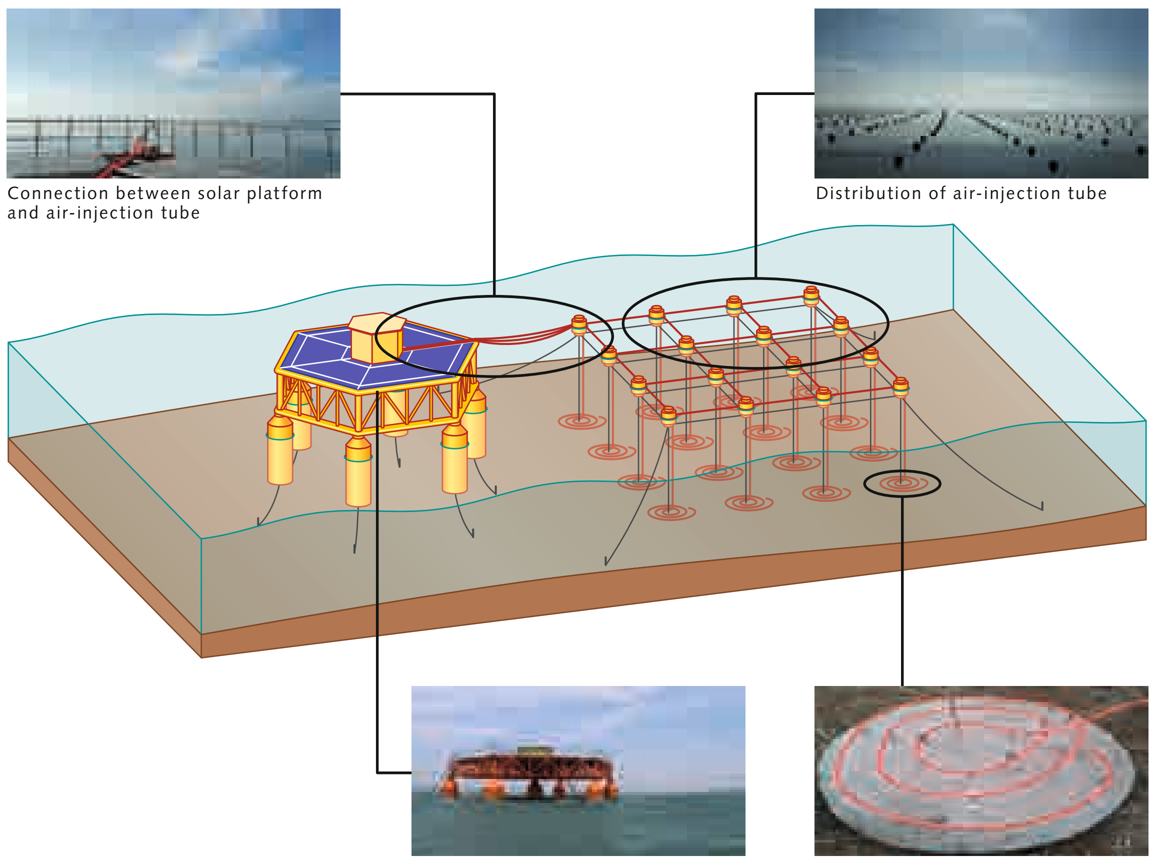
An unclear legal framework

The legal framework for the use of artificial upwelling has not yet been clearly defined at all. For example, the question arises as to whether the deployment of large numbers of upwelling pumps would violate currently applicable law or whether their deployment would even require a permit. Should permits be needed, then who would be allowed to issue these and under what conditions? Consideration must also be given to the fact that artificial upwelling constitutes an activity at sea that legally falls within the regulatory framework of international maritime law, but in substance aims to increase the ocean's potential to sequester CO_2 and thus pursues an objective of climate law. The international law of the sea does not yet take such new marine use plans into account.

For this reason, legal scholars are currently reviewing the legal framework for large-scale upwelling operations to increase the ocean's carbon dioxide uptake. Relevant conventions and principles in this context include the international London Protocol and the German Sea Pollu-

6.9 > With this system, consisting of a solar-powered platform, air-injection tubes and numerous nozzles, Chinese scientists succeeded in transporting nutrient-rich deep water to the sea surface in an over-fertilized marine bay. As a result, not only did the farmed macroalgae grow better, but the issue of eutrophication also diminished.

Schematic diagram of an artificial upwelling system



tion Act (*Gesetz über das Verbot der Einbringung von Abfällen und anderen Stoffen und Gegenständen in die Hohe See* – Law on the prohibition of dumping wastes and other substances and objects into the high seas). In addition, the experts are analysing the extent to which artificial upwelling operations could be regulated under international law, what decision-making powers rest with individual nations, and how artificial upwelling measures could be integrated into international marine environmental protection and climate law without compromising other forms of marine use and environmental and species protection concerns. The legal scholars aim to determine what changes would need to be made to the legal conventions and principles in order to create an appropriate regulatory framework for the governance of artificial upwelling (for more on legal frameworks please refer to Chapter 9).

Growth-aid for macroalgae

In view of the comparatively low carbon dioxide removal potential, the many and large knowledge gaps and the enormous technical and logistical effort that would be required to implement artificial upwelling on an industrial scale, it is considered rather unlikely that these processes will actually be used on a large scale one day to strengthen the ocean's biological carbon pump. In contrast, the use of artificial upwelling appears much more useful when it comes to the question of supplying sufficient nutrients to kelp farms in coastal waters.

This assertion is based, among other things, on experiments conducted by Chinese researchers in the Yellow Sea in the period of 2018 to 2020, more precisely in Aoshan Bay in the Chinese province of Shandong, a centre of Chinese macroalgae production. So many macroalgae are now grown in that region that the amount of nutrients in the surface water is no longer sufficient and diseases and deficiencies are therefore spreading among the farmed algae populations. In contrast, the bottom water and porewater in the seabed are far too nutrient-rich because these coastal waters have been over-fertilized for a long time. For the farmed macroalgae at the sea surface, however, these surplus nutrients are out of reach.

This observation gave the scientists the idea of using artificial upwelling to transport the nutrient-rich deep ocean water to the surface. They used a moored floating solar platform to provide power to an air-injection system that forms a large-scale rising bubble plume for two hours each day. The results confirmed the scientists' working hypothesis: Macroalgae growing in the immediate vicinity of the upwelling site had produced more than four times as much biomass as macroalgae harvested at a greater distance. At the same time, the macroalgae had taken up lots of phosphorus and nitrate from the depths and improved the water quality of the over-fertilized marine bay.

Used in the right place, artificial upwelling techniques have the potential to increase algal growth and thus the oceanic uptake of carbon dioxide, and also contribute to improving the environmental status of over-fertilized coastal waters. However, it appears more than questionable at the present time that this method will ever actually be used to enhance phytoplankton growth and thus boost the ocean's biological carbon pump.

Conclusion

Artificial upwelling – the verdict: "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.

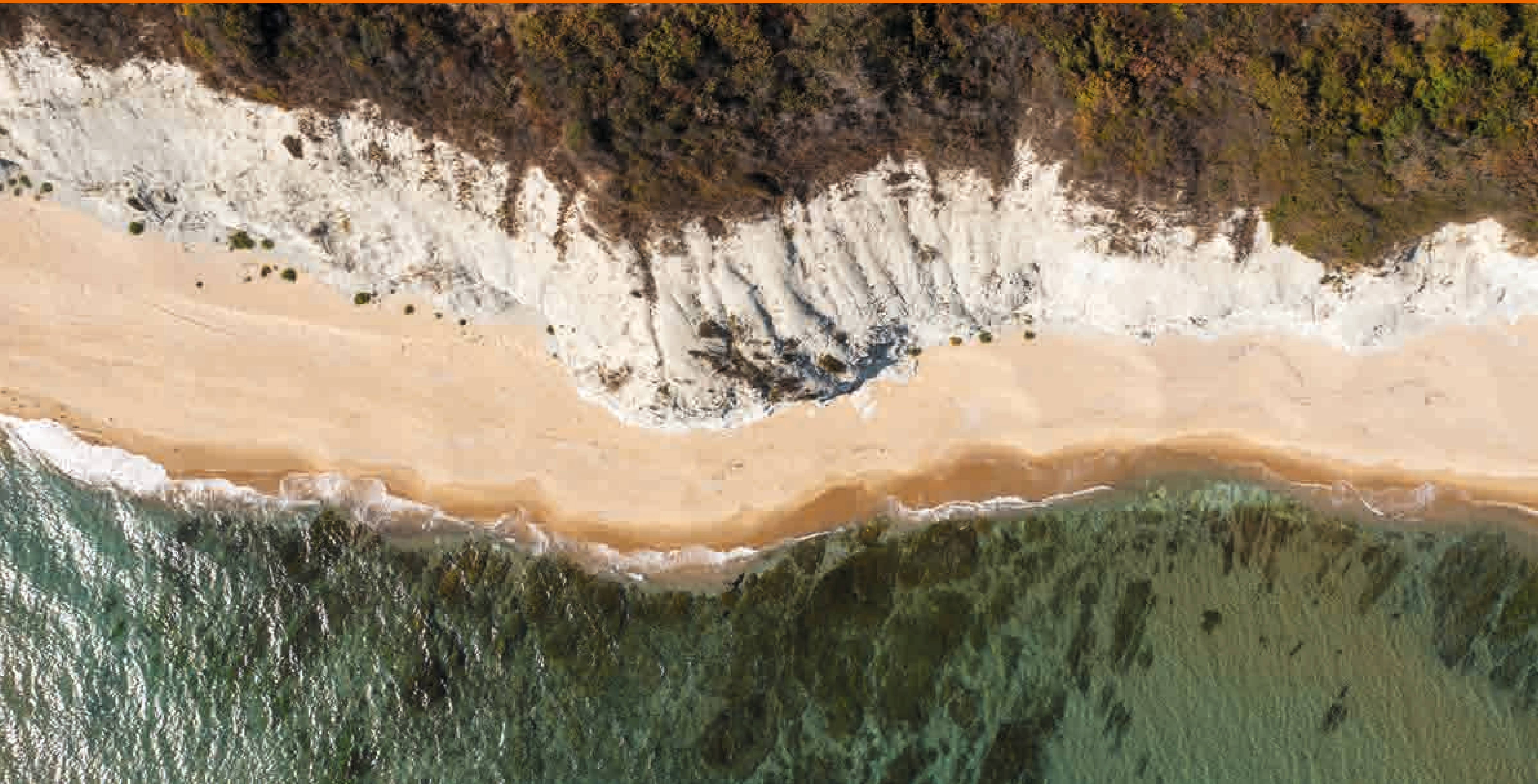
This would store a certain proportion of the now newly formed biomass in the depths of the ocean and lock away the carbon it contains for several decades to centuries.

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 be met under very specific conditions, which is why the potential for additional carbon dioxide removal is rather low.

There is also a high degree of uncertainty as to the technical means by which artificial upwelling can be generated on a climate-relevant scale and what risks the processes entail for the marine environment – especially for the numerous biotic communities at mid-depths and in the deep ocean. Uncertainties also surround the regulatory framework that would be required for large-scale deployment, precisely because the use of many 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 artificially generated nutrient input from the depths increases the growth of the macroalgae and helps them to absorb more carbon dioxide and bind more carbon in their biomass.

7 Targeted interventions in marine chemistry

> Complex processes allow the ocean to absorb carbon dioxide from the atmosphere, chemically bind much of the carbon it contains, and store this carbon in its water masses. However, the more carbon dioxide the sea absorbs, the more acidified its waters become. This process could be reversed through a targeted boost of its natural acid-binding capacity. As yet, however, little is known about the impacts that could result.



Alkalinity enhancement – an approach in its infancy

> The amount of carbon dioxide the ocean can absorb without substantially acidifying depends on the alkalinity of its surface waters. This term refers to the amount of acid-binding mineral components that were previously dissolved by the weathering of rocks and discharged into the sea. This then raises the question: Could a deliberate input of minerals help to increase the ocean's carbon dioxide uptake without disrupting its chemistry and life in the ocean?

The laws of marine chemistry

The ocean is a gigantic carbon repository. Today, its water masses already contain more than 50 times as much carbon as the Earth's atmosphere, and in recent years it has absorbed one-fourth of the carbon dioxide emissions produced by humans, thus significantly retarding the progress of global warming.

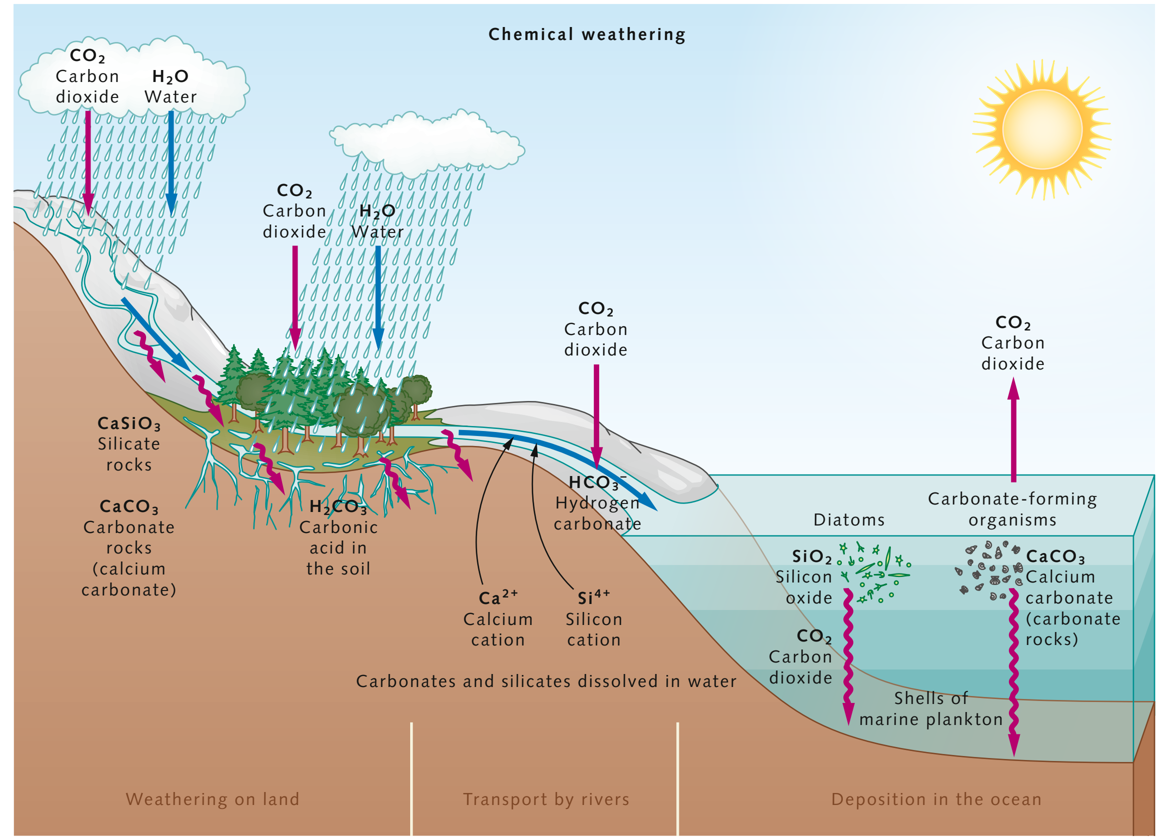
Carbon dioxide uptake by the ocean occurs at the sea surface, and is made possible by the constant exchange of gases between the surface waters and the atmosphere. The exchange balances out pressure differences that exist between the carbon dioxide dissolved in seawater and that in the atmosphere. When the concentration of carbon dioxide in the atmosphere increases, the ocean responds by absorbing more carbon dioxide.

7.1 > In September 2009, hundreds of fishers participated in a protest against the increasing acidification of the ocean off the southern coast of Alaska. The cold Alaskan waters absorb particularly large amounts of carbon dioxide from the atmosphere and are thus severely affected by acidification.

When carbon dioxide dissolves in seawater, a large proportion of the gas undergoes a series of chemical reactions. The dissolved gas, which could otherwise escape back into the atmosphere at any time, is chemically bound rather quickly in the seawater in the form of hydrogen carbonates and carbonates. When this has occurred, outgassing back into the atmosphere is no longer possible. At the same time, as a result of the reactions, the concentration of dissolved carbon dioxide in the surface waters decreases and the ocean is able, to some degree, to take up more carbon dioxide from the atmosphere.

However, as a consequence of this reaction chain, protons, or hydrogen cations, are released, a result that contributes to the acidification of the ocean. The amount of these that are released depends upon the acid-binding capacity of the water, which is also known as its alkalinity. The alkalinity of seawater is primarily determined by the abundance of acid-binding components of mineral origin in the water (hydrogen carbonate, carbonate and others), which were previously dissolved over many millions of years by the weathering of rocks on land, and transported by rainwater through brooks and rivers into the seas. Some rocks are also weathered directly at or in the sea. The slowly eroding chalk cliffs on the coast of Germany's island of Rügen in the Baltic Sea provide a striking example. With a bit of luck visitors to this site can directly observe how rain, wind and waves wash chalk residues (friable limestone) from the cliff walls and disperse the highly reactive minerals within the coastal waters.

When the amount of such acid-binding dissolution products of rock weathering in the water is high, a large proportion of the acidifying protons are not even released in the first place, but are immediately bound by the introduced minerals as part of the chain reaction. In this case,



7.2 > 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.

the acidification of the water is buffered. If the water contains a lesser amount of minerals, however, its acid-binding capacity is limited. The number of free protons increases and the water becomes increasingly acidified, which causes deterioration of the conditions for many marine organisms (as set out in detail in Chapter 2).

The idea – to accelerate natural weathering

The weathering of rocks and the resulting dissolution of the minerals they contain in the sea are natural processes that proceed comparatively slowly, and that influence the Earth's climate over time periods of thousands of years or more. It is estimated that they remove 1.1 billion tonnes of carbon dioxide from the atmosphere annually. As a long-term average, this is roughly the same as the amount of carbon dioxide that is introduced into the atmosphere through volcanic activity and through mineralization processes in the Earth's mantle and in the ocean. In order to increase the removal of carbon dioxide to offset unavoidable residual carbon dioxide emissions by human societies, the natural weathering processes would have to be accelerated by a factor of around five. An example calculation: If humans could increase the alkalinity of the upper 50 metres of the world ocean by 0.25 per cent, or five millimoles per cubic metre of water, the change in marine chemistry would result in an uptake of one billion tonnes of carbon. That corresponds to around 3.7 billion tonnes of carbon dioxide, which is one-tenth of the carbon dioxide that was emitted globally from fossil sources in the year 2022.

According to modelling studies, a targeted increase of ocean alkalinity through accelerated natural-rock weathering would indeed be possible. It would require the introduction of additional acid-binding minerals into the ocean. This approach is known as ocean alkalinity enhancement.

Limestone
Limestone is a sedimentary rock comprised primarily of the minerals calcite and aragonite, which are both forms of calcium carbonate ($CaCO_3$). The overwhelming majority of limestones are of biogenic origin, which means that they were formed and deposited by living creatures such as mussels or corals. Limestone can also, however, be precipitated directly out of the water by chemical processes.

The shellfish trick of the native North Americans

Native peoples on the west coast of North America have been using a natural form of alkalinity enhancement for thousands of years to boost their shellfish production. They have developed a special technique for breeding called clam gardening. The shellfish breeders construct walls in marine bays from debris and rocks along the low-water line. When surf water flows over this wall at high tide, silt, sand and gravel sediments are trapped behind it, settle to the bottom, and over time form a kind of terrace. Native clams then colonize the sediments on the terrace.

To encourage growth, the indigenous people have been scattering broken shells on the terraces and working them into the sediment for generations. The shells are composed of calcium carbonate, an acid-binding mineral. This raises the pH value of the pore waters, which especially benefits the acid-sensitive juvenile clams. Furthermore, the calcareous shell remains serve the young clams as a kind of storehouse for building material.

The results are impressive. Four times as many native butter clams *(Saxidomos gigantea)* and more than twice as many clams of the species *Leukoma staminea* grow on the terraces that have been spiked with clam shells than on a natural stretch of coastline. In addition, the shellfish grow faster, which is due not only to the addition of calcium carbonate, but also to other effects related to the terraced gardens.

Shellfish harvesters in other parts of North America are now also using alkalinity-enhancing methods to prevent production losses related to acidification. The amount of additional carbon dioxide that the clam gardens of the natives remove from the atmosphere, however, has not yet been measured.

7.3 > Native shellfish species grow faster and with greater densities in west-coast native clam gardens than on other stretches of coast without the artificial terracing and additional limestone input.

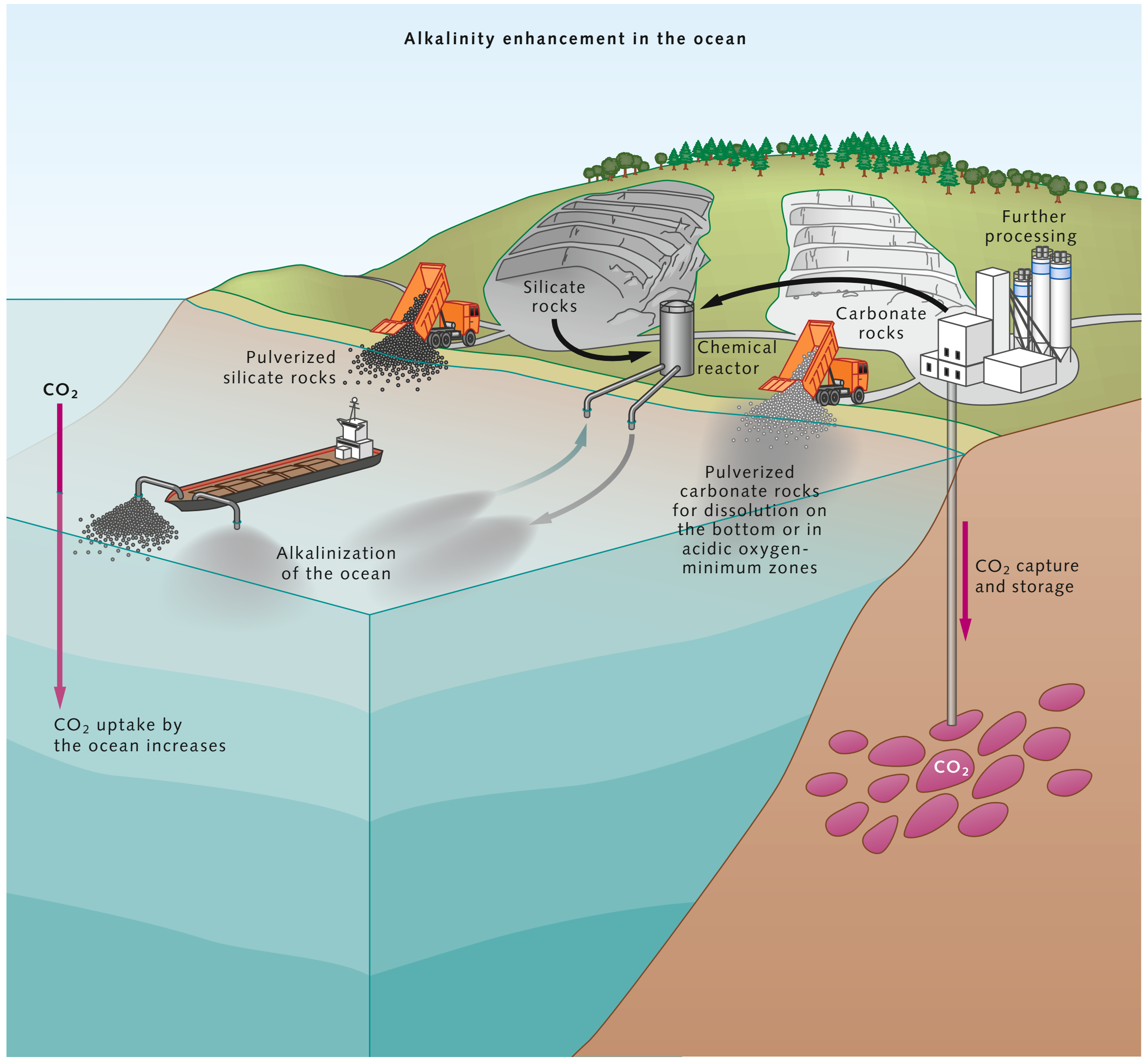
An intervention of this kind into the marine chemistry would have the advantage of enabling the ocean to absorb more carbon dioxide without additional acidification. At the same time, high acidification, which already affects a number of marine regions and which is harmful to many marine organisms, could be reversed, facilitating a recovery for many coral reefs and shellfish beds. Field experiments for testing the reduction of ocean acidification have already been carried out in the Australian Great Barrier Reef as well as on the coast of Florida. In these studies, researchers were able to demonstrate that calcite formation increased in both mussels and stony corals when the acidification level of the surrounding water was reduced by a targeted boost in alkalinity.

The entire ocean as a carbon reservoir

As a result of increased alkalinity, the surface waters are able to absorb more carbon dioxide, which is chemically bound and eventually stored, primarily in the form of hydrogen carbonate. The hydrogen carbonates, along with the weathering products dissolved in the surface waters, are dispersed throughout the ocean by marine currents (physical carbon pump), and are transported to very great water depths. The result is that the entire ocean becomes an immense reservoir for the carbon introduced at the surface. Depending on the water depths and current directions, decades, or even centuries will pass before the carbon-rich water returns to the sea surface through natural pathways.

In the upwelling areas of the world ocean, there is still water rising to the sea surface whose alkalinity has not yet been elevated by human activity. It therefore still possesses the full uptake potential for a targeted increase in alkalinity and the resulting carbon dioxide absorption. And even when water masses return to the surface that already contain stored carbon dioxide released by humans, in the form of dissolved carbon dioxide or hydrogen carbonate, the hydrogen carbonates will still remain in the water for as long as 100,000 years. This means that the carbon bound up in them could not be emitted back into the atmosphere in the form of carbon dioxide.

7.4 > Discoloured seawater enriched in carbon dioxide spreads over corals growing in a shallow-water area on Australia's Great Barrier Reef. In this initial field experiment on ocean acidification, researchers were able to demonstrate that acidification inhibits coral growth.



7.5 > 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.

Only the dissolved carbon dioxide would be able to escape.

The offsetting effect of lime formation

How long the additional hydrogen carbonates remain dissolved in the ocean depends on a number of chemical and biological processes: The elevated alkalinity reduces the acidity of the water, which inhibits the dissolution of calcareous sediments on the seabed and therefore improves conditions for calcareous species to secrete their calcite shells. Thus, fewer calcareous sediments are dissolved and more calcareous shells tend to be produced.

The formation of calcium carbonate is the reverse process of weathering. This chemical reaction consumes hydrogen carbonates dissolved in the water, thus reducing the alkalinity of the seawater. But at the same time, the process of limestone formation releases carbon dioxide, which again increases its concentration in the surrounding water. This dissolved carbon dioxide could escape into the atmosphere again if it comes into proximity with the sea surface. This means that through the formation of calcium carbonates, the carbon formerly stored in the ocean water is again transformed into a greenhouse gas and becomes relevant with regard to the climate.

In the ocean, however, calcite is produced not only by clams, corals and calcareous algae. It can also be precipitated directly from the water as a secondary mineral through a chemical reaction. If water masses are alkalinized too often, or if too many acid-binding minerals are introduced at once into a water body, it can lead to an oversaturation of the seawater. As a result, depending on the initial material, secondary minerals such as carbonates or silicates can precipitate. Solid limestone or silicate particles thus form spontaneously. When carbonate minerals precipitate, carbon dioxide is released. Experts thus assume that the precipitation of secondary minerals promoted by mineral supersaturation can limit the effectiveness of alkalinity enhancement as a carbon dioxide removal method, and may even completely cancel it out in some conditions.

They therefore draw two important lessons from the laws of marine chemistry: For one, in proposals for the targeted enhancement of seawater alkalinity, careful consideration would have to be given to deciding which minerals could be introduced at what locations in the sea, at what quantities, and in what form (as rock powder or alkaline solution), in order to avoid exceeding critical threshold values and to prevent supersaturation and the resulting carbonate precipitation. It is known, for example, that in marine regions where winds, waves and currents thoroughly mix the surface waters, critical oversaturation is less likely to occur than in regions where the introduced mineral remains near the surface for an extended time at high concentrations. Good mixing conditions would be found in coastal areas or in the open ocean.

Secondly, alkalinity enhancement measures cannot be repeated indefinitely as a way to increase natural carbon dioxide uptake by the sea. Presumably they would "only" be effective for several decades to a few centuries. Nevertheless, experts say, application over this time frame could be quite sufficient to offset residual emissions, and thus stabilize the climate.

Methods of alkalinity enhancement

A variety of approaches by which the alkalinity of seawater could be increased are presently being developed. These include possibilities such as the mining on land of naturally occurring minerals like limestone and chalk, or siliceous rocks such as basalts and olivine, then crushing them to increase their total surface area to enhance weathering (chemical reactions), and then spreading the rock powder on beaches or directly on the sea. Residual materials rich in calcium or magnesium, or waste products from cement production could also be used for the same purpose. These may include synthetically produced minerals such as quicklime (calcium oxide), slaked lime (calcium hydroxide), periclase (magnesium oxide), brucite (magnesium hydroxide) and sodium hydroxide. Brucite and sodium hydroxide, for example, are produced during

7.6 > Basalt is formed from cooling lava and is generally dark in colour. This basalt rock comes from the Cascade Mountain Range in the US state of Washington.

Electrochemical procedures to accelerate marine chemistry using electricity

The dissolution of minerals in seawater takes time. It can require as long as several months for alkalinized seawater to exert its chemical effect and absorb additional carbon dioxide from the atmosphere. Some experts are developing electrochemical procedures to accelerate this process. They employ an electrochemical cell through which seawater is passed. The cell contains two electrodes. When an electric current is applied to the cell, the electrodes become a positively charged anode and a negatively charged cathode. The anode attracts bases, while the cathode attracts acids, resulting in an "acid current" and a "base current". Both of these currents can be used to influence the carbon dioxide concentration in seawater. Depending on the approach, the objective is either to increase the alkalinity of the seawater or to remove carbon dioxide directly from the seawater.

Two examples – how electrochemical methods can be applied

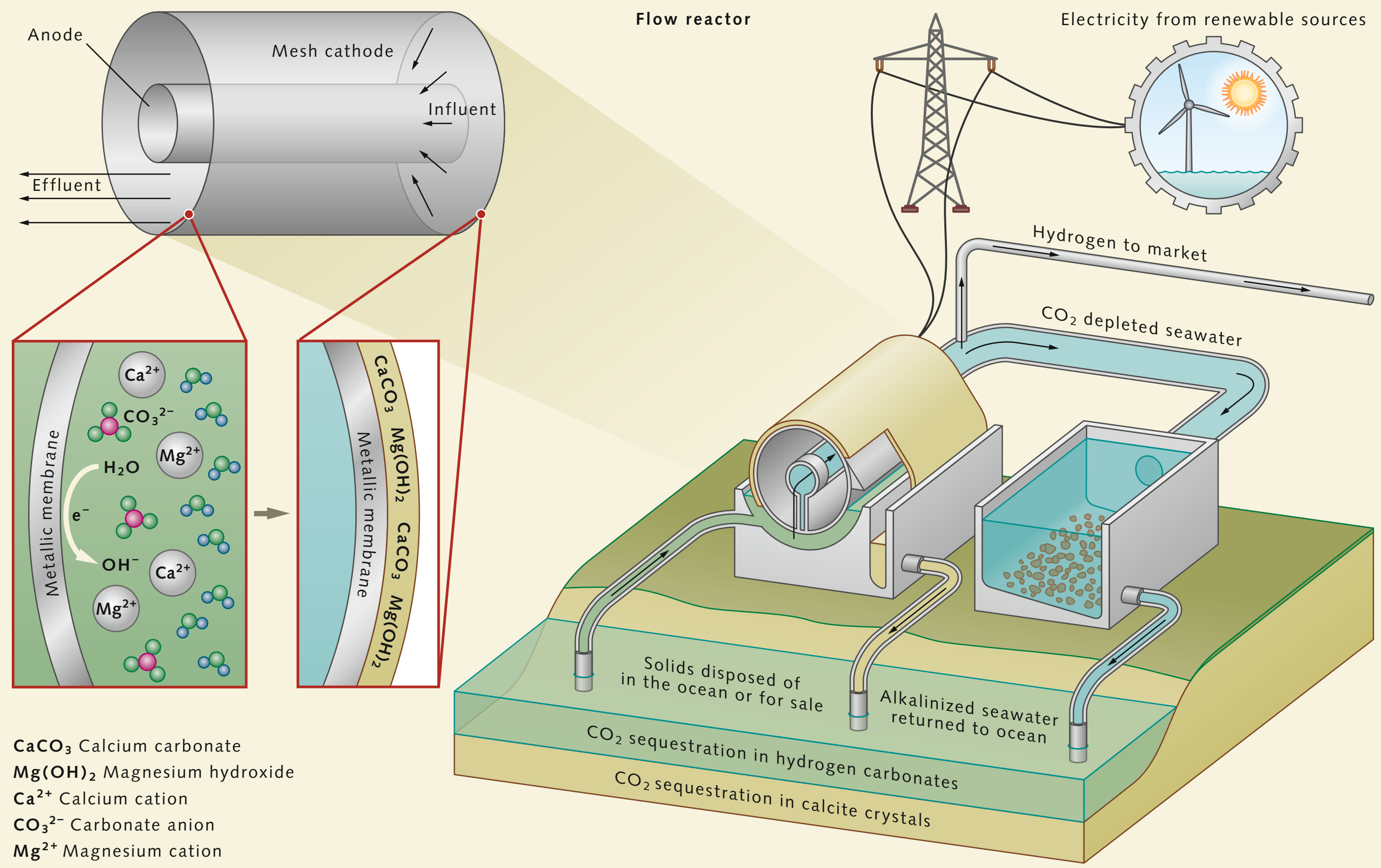
Scientists at the University of California have developed an electrochemical cell method by which the dissolved carbon dioxide in seawater reacts with and ultimately mineralizes the calcium and magnesium cations present in the water. The result is that carbon dioxide is chemically fixed through the formation of new rock material. The total carbon content of the water is thereby reduced, allowing it to absorb additional carbon dioxide from the atmosphere when it is reintroduced into the sea.

To achieve this chemical bonding, the seawater is passed through a machine called a flow reactor. In the machine the water flows across a network of electrodes that electrically charge it and electrochemically increase its alkalinity. In this state, the dissolved carbon dioxide and mineral components in the water can react instantly with one another. One result of this reaction is the formation of various solid materials such as calcium carbonate – $CaCO_3$ –, magnesium carbonate – $MgCO_3$ – and magnesium hydroxide – $Mg(OH)_2$ –, which can be further processed as mineral raw materials. Another result is water depleted in carbon dioxide, which is reintroduced into the sea. Hydrogen, which is in demand as a renewable fuel, is also produced in the process.

The researchers have calculated the scale at which this technology would have to be applied if the goal were to remove ten billion tonnes of carbon dioxide per year from the ocean and thus indirectly from the atmosphere. Worldwide, it would require the installation of around 1800 systems. The costs for the construction and operation of these flow reactors would reach several trillion US dollars. The necessary electricity would also have to come from renewable energy sources.

Researchers at the Massachusetts Institute of Technology (MIT) in Cambridge, Massachusetts have discovered a much less expensive solution. They channel seawater into an electrochemical cell where it is strongly acidified by protons from a bismuth electrode. This acidification causes the breakdown of the carbonates and hydrogen carbonates present in the water and frees up the carbon dioxide bound to them. This is then drawn off and collected. However, the acidified water has to be neutralized before it can be pumped back into the sea. This is achieved by passing it through a second cell with a reversed electrical charge, allowing the protons from the first pass to be recovered. This slightly basic water can then take up new carbon dioxide from the atmosphere. Here, the cost per tonne of carbon dioxide removed is 56 US dollars.

In contrast to the former method, however, the carbon dioxide removed is not bound in solid rock, but is gaseous and thus highly volatile. So it still must be further processed or stored in such a way that it does not escape back into the atmosphere. The second process can be conveniently integrated into existing seawater desalination plants where the necessary water intake and outlet installations are already in place. But before the MIT experts can build their first demonstration system there are several issues that need to be addressed. One of these is mineral precipitation that occurs during the process and contaminates the electrical terminals and electrodes of the cells.



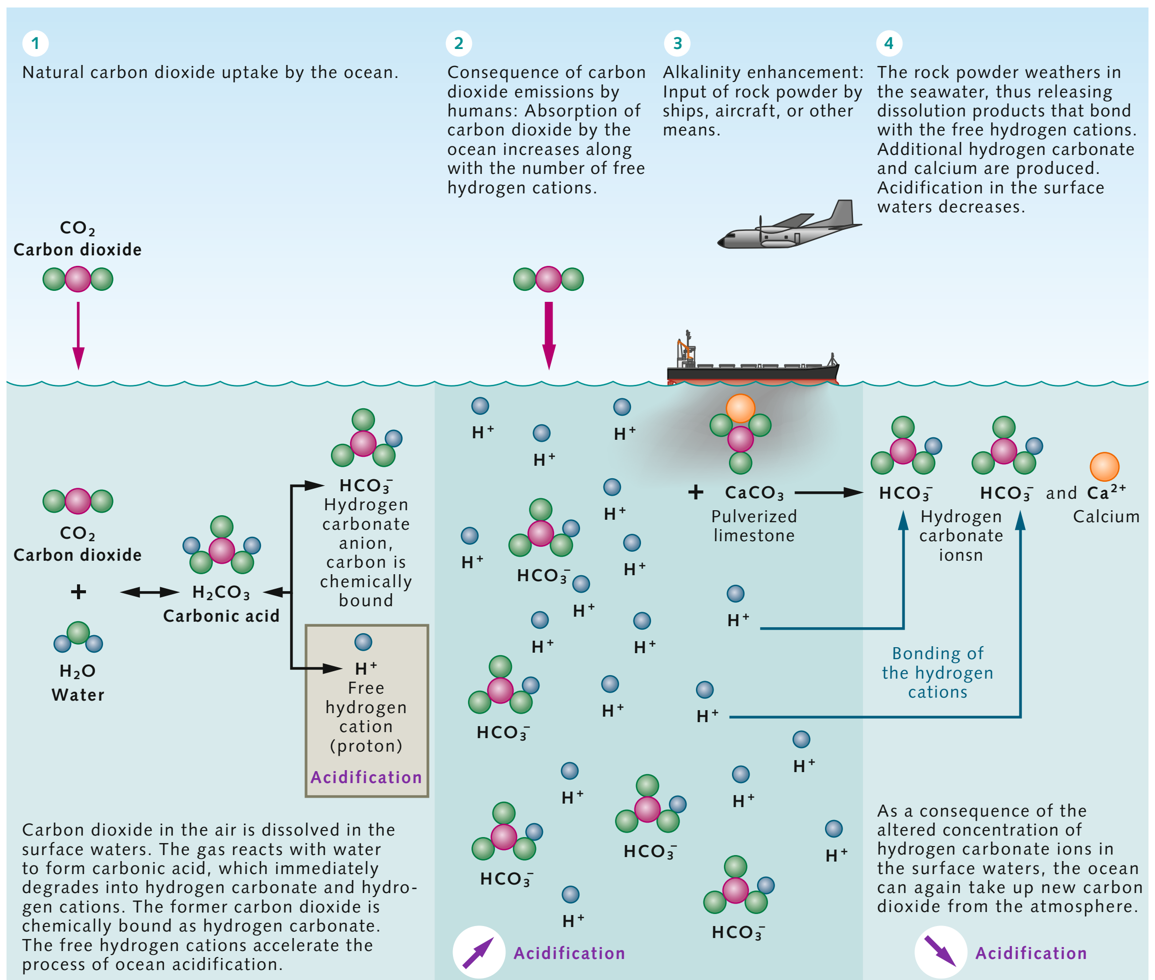
$CaCO_3$ Calcium carbonate
$Mg(OH)_2$ Magnesium hydroxide
Ca^{2+} Calcium cation
CO_3^{2-} Carbonate anion
Mg^{2+} Magnesium cation

7.7 > A flow generator forms the core of an electrochemical approach that has been developed by scientists in the US state of California. In the generator, carbon dioxide dissolved in the seawater reacts with and mineralizes calcium and magnesium cations. This decreases the total carbon content of the water so that it can absorb new carbon dioxide from the atmosphere when it is released back into the sea.

the manufacture of green hydrogen and could subsequently be used for alkalinity enhancement. The minerals would be distributed on the sea surface using ships or aircraft. On beaches, spreading vehicles or even manual efforts would be employed.

A second approach would involve the installation of chemical reactors on the coasts, on ships, or on platforms in the sea. Under the controlled conditions in these reactors, the calcium- or magnesium-rich rock powder would weather very rapidly after adding water rich in carbon dioxide, thus creating an alkalic solution. This would then be fed into the sea or sprayed onto its surface. In this way, the concentration of hydrogen carbonate in particular, as well as the amounts of calcium, magnesium or silicate, depending on the weathered rocks used, would be increased. These compounds are already present at high concentrations in seawater today, so the changes in these caused by targeted mineral input would be proportionately small. However, the potential impacts of altered mineral concentrations on marine ecosystems still need to be investigated.

But whether additional carbon dioxide can ultimately be removed from the atmosphere through alkalinity enhancement in the ocean, and how much might be removed, also depends on the amount of overall emissions produced by the work involved in the process. It is estimated that the extraction potential of alkalinity-enhancing processes is 100 million to one billion tonnes of carbon



7.8 > Complex ocean chemistry: The chemical reactions through which the input of limestone powder and its subsequent weathering contribute to reduce ocean acidification are illustrated schematically here. The reactions shown would occur in carbonate-undersaturated waters such as oxygen-depleted regions just below the sea surface.

dioxide per year. If these were to be applied ocean-wide – not limited to particularly suitable areas – the removal potential could even exceed one billion tonnes of carbon dioxide per year.

Studies indicate, however, that the effectiveness of the processes also depends on the marine regions and the time of year in which they are applied, because the chemical and physical preconditions differ regionally and are also subject to seasonal changes. Strong surface currents can rapidly transport the injected minerals into regions where the alkalinity of the water is already higher and additional carbon dioxide uptake is hampered. Or strong mixing of the surface waters by winds and waves leads to displacement of the minerals to deeper waters, resulting in a merely minimal change to the alkalinity of the surface water. Specialists are also cognizant of the fact, based on climate simulations, that the effectiveness of alkalinity enhancement declines with increasing global warming. In a world that warms by more than four degrees Celsius by the year 2100, a much greater volume of minerals would have to be input into the ocean to effect the additional uptake of a given amount of carbon dioxide than would be needed if global warming were limited to well below two degrees Celsius.

Mineral requirement – several kilograms of lime per person per day

Estimates to date assume that to increase surface-water alkalinity to a level that would be effective with respect to climate, something between one-half tonne and five tonnes of mineral products would have to be employed for every tonne of carbon dioxide that is fixed. For basalt rocks, for example, the removal proportion would be around three to one. This means that three tonnes of basalt rock would have to be weathered in the sea in order for the ocean to remove an additional tonne of carbon dioxide.

The following calculation illustrates how great the additional mineral requirement could be for a large-scale programme of alkalinity enhancement: If we assume that the Federal Republic of Germany still has residual emission levels of 60 to 130 million tonnes of greenhouse gases per year by the year 2045, that would represent 0.7 to 1.5 tonnes for each of its 83.2 million inhabitants. For Germany's population to compensate for these residual emissions solely through ocean alkalinity enhancement, each person would have to dissolve 6.5 to 14 kilograms of basalt, or five to eleven kilograms of limestone in the sea every day. Extrapolated for Germany's total population, this would result in an additional basalt demand of 200 to 416 million tonnes or a limestone demand of 150 to 312 million tonnes per year. If, on the other hand, the compensation process were to be divided among several carbon dioxide removal methods, the mineral demand would be proportionately smaller.

At this point, the good news is that both limestone and silicate rocks like basalt and olivine are present in sufficient amounts underground. The latter, in fact, are the most abundant rocks in the Earth's crust. It is not yet clear, however, how much energy and other investments would be required to extract the rocks on an industrial scale, process them and transport them to the coast or subsequently out to sea – and what greenhouse-gas emissions would be produced by each of the individual steps. A study in 2013 concluded that 100 universal bulk carriers with capacities of 300,000 dry-weight tonnes each would be needed, and that they would have to be in practically constant operation in order to distribute one billion tonnes of rock powder onto the ocean annually. At the time of the study, this demand would have corresponded to around four per cent of the total global shipping capacity.

Old and new input materials

It is known that limestone does not dissolve in seawater because the surface water of the ocean, as a rule, is chemically supersaturated with carbonates. Acidic and oxygen-deficient water masses, which occur, for example, in some deep areas of the Baltic Sea, are an exception to this rule. Often, the water within surface sediments is also very acidic, so that limestone can also be dissolved there. By contrast, seawater everywhere is undersaturated with

Green hydrogen
For the production of green hydrogen, water is split into its mole cular components hydrogen and oxygen using electric power from renewable energy sources (electrolysis). This ensures that the hydrogen production is climate neutral.

silicates, which means that silicate rocks would generally dissolve. In order to increase the alkalinity of the ocean as rapidly as possible, the silicate rocks would have to be very finely pulverized and distributed in shallow coastal waters, or dissolved in seawater in chemical reactors at high energy input.

Naturally occurring calcareous and silicate rocks or artificially produced minerals (quicklime, slaked lime, etc.), however, are not the only options. Researchers are now also testing synthetically produced ikaite for its suitability and its weathering properties. Ikaite is a very rare form of hydrated calcium carbonate that only forms in nature at temperatures below 15 degrees Celsius in seawater. If it should prove to be feasible, therefore, it could only be applied in marine regions with correspondingly cool water masses.

Mesocosms
The mesocosms used in the experiments are transparent, hose-like tubes that are filled with seawater and float in the surface waters. Organisms in the tubes are thus exposed to the same environmental conditions (temperature, light, etc.) as the organisms in the sea, but can be studied individually because there is no exchange of water between the sea and the tubes.

Laboratory and field studies of risks and side effects are lacking

To date, the greatest part of our knowledge about the chemical and biological consequences of alkalinity enhancement comes from modelling studies (computer simulations). Robust laboratory or field studies on the local, regional and global impacts of industrial-scale mineral input are lacking. For this reason, very little is known as yet about the possible risks and side effects of large-scale mineral input.

It is a well-known fact that the mining of minerals in quarries often leads to land-use conflicts and impacts on local ecosystems, as well as increased volumes of traffic accompanied by increased noise and dust pollution. Furthermore, it is also known that silicate rocks contain certain nutrients (silicon, iron) and heavy metals (nickel, chromium, zinc). The former would influence the growth of diatoms and thus impact the marine nutrient cycle, while some experts are optimistic that a boost in algal growth could stimulate the biological carbon pump, allowing the ocean to absorb additional carbon dioxide. Heavy metals, for their part, could have a toxic effect and thus cause damage to the ocean's ecosystems. There is some optimism, however, that the potentially harmful side effects of alkalinity enhancement could be avoided through the production of purely synthetic minerals.

As part of a German research mission that comprises various laboratory and mesocosm experiments, scientists are currently studying the extent to which the input of mineral materials or the weathering of rocks on the seafloor would impact coastal ecosystems in the North and Baltic Seas, and the threshold values to which the negative effects of alkalinity enhancement on marine communities could be avoided. This involves analyses of how phytoplankton, zooplankton, and other selected organisms that live on or in the seafloor react to the increased mineral input. Is there a risk, for example, that copepods or fish larvae might mistake the mineral particles for food, eat them, and then starve to death with a full stomach? This cannot presently be ruled out.

There is also evidence that the mineral type and composition would determine which marine organisms might benefit from an increase in alkalinity and which may tend not to. For example, if minerals rich in calcium are input, it becomes easier for the carbonate-forming organisms to form their skeletons and shells. Under these conditions, they would have a growth advantage, while diatoms would not receive much benefit. If, on the other hand, the material input contains silicates, diatoms would have the upper hand because they need these minerals to build their silicon-rich shells. The advantage of carbonate formation in the first case, however, would bring with it a critical disadvantage. When animals use the introduced minerals to construct their skeletons or shells, carbon dioxide is released into the seawater rather than removed.

The scientists will ultimately use numerical models to project their local research results to regional and global scales, and to simulate the application of measures to increase alkalinity in German territorial waters and other marine areas. With this approach they hope to identify risks, delineate critical threshold values, test concepts for monitoring and control procedures, and derive appropriate possible courses of action at the local, national and international levels.

7.9 > Limestone is mined in large quarries like this one. It is evident that the possibility of environmental damage on land must also be taken into account when considering whether alkalinity enhancement of the ocean would be worthwhile as an approach to combat climate change.

7.10 > Scientists have moored a mesocosm in the ocean off the coast of Gran Canaria. Several years ago, in its hose-like tubes, they studied the reactions of micro-algae and zooplankton to increasing ocean acidification. They are now using it to investigate the possible consequences of an alkalinity increase.

Much development work also awaits the researchers regarding the measurement and monitoring of carbon dioxide uptake by the ocean as a result of alkalinity enhancement. The application of this approach only makes sense if the desired effects can be measured and unambiguously attributed to the mineral input. In this context, scientists refer to the verification and attribution of a change – in this case, a change in alkalinity and increase in the carbon content of the ocean. Measuring these, distinguishing them from natural fluctuations, and attributing them to specific interventions is an immense scientific challenge for which no reliable method is yet available.

Further exacerbating matters is the fact that, unlike with projects for the restoration of seagrass beds or mangrove forests, the effects of increasing alkalinity cannot be confined within a specific marine region. The world ocean is a contiguous global system. Changes in one ocean region lead to interactions with other interconnected areas. That is especially true for the parameters of marine chemistry. For this reason, it is believed that a local input of minerals would result in impacts that not only extend far beyond the boundaries of the marine area originally targeted, but that could also last for very long periods of time. What these effects might be is presently being studied.

Legal framework

From a legal point of view, distributing acid-binding minerals in the form of rock flour or alkaline lye on the ocean would constitute an additional input of substances into the sea. Such activities are regulated internationally, primarily by the London Convention of 1972 – also known as the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter – and its 1996 supplement, the London Protocol. However, the Convention on Biological Diversity may also apply.

The scope of the London Protocol was expanded in 2013 such that marine CDR procedures can be regulated under the authority of the treaty. However, these changes will not take effect until they are ratified by a sufficient number of signatory states, which has not yet happened. Presently, an amendment to the London Protocol lists only iron fertilization as a CDR method that can be regulated. According to experts, however, procedures to enhance the alkalinity of the ocean could also be regulated under the Protocol. For this to happen, the Protocol would have to be amended to include them (more on this in Chapter 9).

In Germany, the use of procedures for alkalinity enhancement of the oceans is prohibited under current law. Similarly, the determining factors here are found in the provisions of the German Act on the Prohibition of Dumping Waste and Other Substances and Objects into the High Seas. Accordingly, it is prohibited for scientists at German research institutes to carry out field experiments related to this subject, both in national waters and on the high seas. This legal framework will need to be revised if society decides to increase the carbon dioxide uptake of the ocean through the input of acid-binding minerals. The fact is that comprehensive knowledge about the risks and side effects of such operations cannot be gained without field experiments.

Conclusion

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

Mineral-rich dissolution products from the natural weathering of rocks enable the 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 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 quite 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, initial studies are being carried out on the possible environmental impacts and risks, about which very little is yet known. Specialists are also working on electrochemical methods of alkalinity enhancement. These require a high input of energy but, in contrast to other methods, could be applied without the massive input of rock material.

The true potential for carbon dioxide removal using alkalinity-enhancement methods is also difficult to quantify. According to calculations, if the presently known methods were to be applied worldwide, an additional 100 million to more than a billion tonnes of carbon dioxide could be removed from the atmosphere. However, this would be countered by new greenhouse gas emissions generated in the activities of quarrying, transporting and processing the rocks. As a consequence, potential methods for targeted alkalinity enhancement in the ocean are still subject to large uncertainties.

8 Injecting carbon dioxide deep beneath the sea

> When carbon dioxide is captured during industrial activities or is removed directly from the atmosphere, the question of appropriate storage arises. Because underground land-based storage sites harbour risks and provoke protests from local communities, the search for storage options in rocks deep beneath the sea is intensifying. The technology for this already exists and has been employed for decades in various pilot projects.

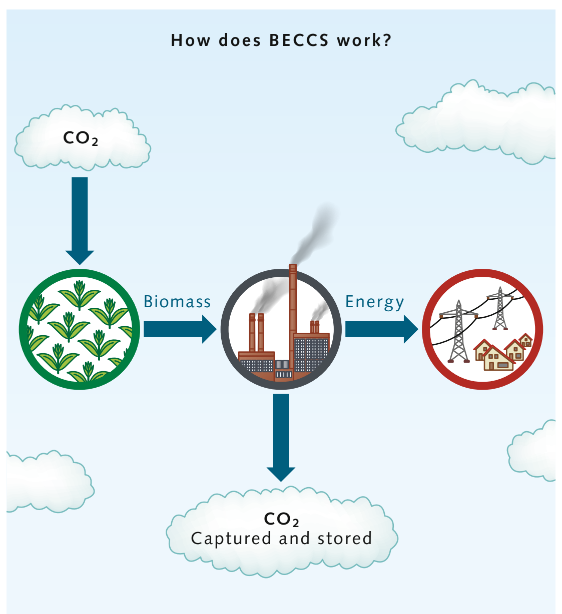
Gas storage in sandstone layers and basalt rocks

> Rock layers at depths of 1000 to 4000 metres underneath the seabed are potential storage sites for carbon dioxide. These can be depleted oil or natural gas fields, or rocks whose pore spaces are presently filled with saltwater. Two approaches are currently being investigated. In one, carbon dioxide is injected into deep-lying sandstone formations, a method already used in the North Sea. In the second approach, the gas is injected into the reactive and porous upper basalt layer of the ocean crust in the hope that it will mineralize there relatively quickly.

Carbon dioxide capture – a technology with a disposal problem

Theoretically, unavoidable residual emissions can be offset by direct removal from the atmosphere of the same amounts of the greenhouse gas carbon dioxide that were originally released. The technology used for this removal is collectively referred to as Direct Air Capture (DAC). However, all the methods for doing this are bound by the requirement that the extracted carbon dioxide be further processed or safely stored. This applies to all carbon dioxide released, including that captured on-site from steel and concrete plants, waste incinerators, or other large emission sources (often referred to as point sources), to avoid its escape into the atmosphere. This technological option for preventing carbon dioxide emissions is termed Carbon Capture and Storage (CCS).

Process emissions
"Process emissions" refers to the release of greenhouse gases that are not a result of the use of fossil fuels and raw materials for producing energy, but are generated by the process-related use of carbonaceous source materials in making certain products. In Germany, process emissions are produced primarily in the glass, lime and cement industries. These make up one-fourth of the industrial emissions.



8.1 > In BECCS, plant biomass is used to generate electricity or heat. CO_2 released in the process is separated and stored or permanently reprocessed.

CCS is not limited to reducing heavy-industry greenhouse emissions from fossil sources. The technology is also a key component of energy and heat production in biomass-fired cogeneration plants with subsequent carbon capture and storage (Bioenergy with Carbon Capture and Storage, BECCS), one of the most important land-based carbon dioxide removal methods to date. Without CCS this process would be just as inconceivable as direct removal of carbon dioxide from the air or water (Direct Air Carbon Capture and Storage, DACCS) would be.

In early 2023 there were 35 plants in operation worldwide for the capture or removal of carbon dioxide. Their combined removal capacity was 45 million tonnes of carbon dioxide per year. This is almost exactly the amount of carbon dioxide that companies in Germany emitted in the course of their industrial processes in the year 2021. Additional removal plants are presently planned or being built. According to the International Energy Agency (IEA), more than 200 new plants have been announced to begin capture or removal operations by the year 2030. Their additional removal capacity adds up to more than 220 million tonnes of carbon dioxide per year.

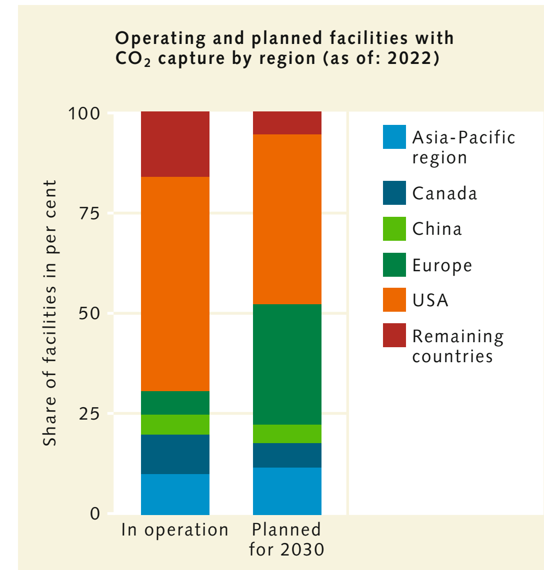
There are now a number of technical methods that can be employed to capture carbon dioxide from gas streams. The most thoroughly tested and widely used capture methods are chemical absorption and physical capture. In chemical absorption, the carbon dioxide reacts with a binding chemical, from which it must then be separated at a great expense of energy. In physical separation, on the other hand, the carbon dioxide either accumulates on a hard surface (for example, on activated carbon) or it is dissolved in a liquid solvent.

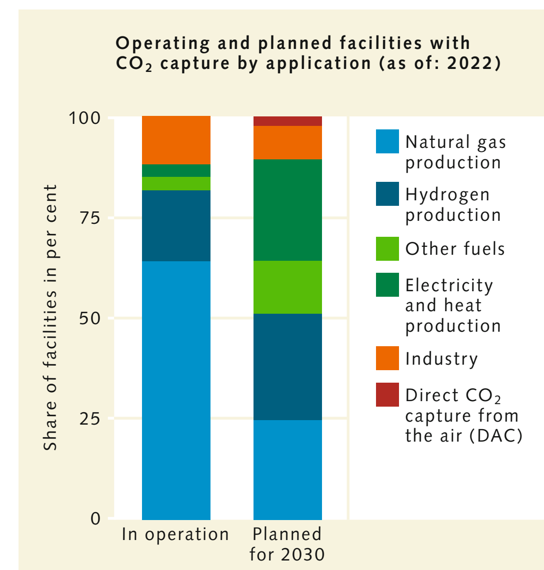
Both chemical and physical capture processes are employed in the course of natural gas production, which currently accounts for around two-thirds of the carbon dioxide captured worldwide. In many places, the natural gas extracted from underground contains not only methane fuel but also carbon dioxide, in proportions ranging from less than three per cent to as much as 80 per cent – the latter, however, only in rare cases. This carbon dioxide must be separated out before the natural gas can be pumped into pipelines as almost pure methane. When the gas is eventually burned carbon dioxide emissions are again produced.

Capture systems are also used in other emission-intensive industrial processes, such as energy and heat generation from fossil fuels and biomass, fertilizer and steel production, refineries, and waste incineration. Furthermore, carbon dioxide capture will be necessary over the long term in the production of blue hydrogen and bioethanol fuel. In the future, greater amounts of carbon dioxide will arise due to the increasing use of direct air capture methods. The world's first DAC plant will begin operations in 2024, and should remove more than a million tonnes of carbon dioxide per year.

CCS will also play a key role in the decarbonization of the cement and lime industries. The production of one tonne of cement clinker (calcium oxide), the main component of cement, generates around 0.8 tonnes of carbon dioxide as a process emission, regardless of the fuel used. If the huge emissions from the cement and lime industry are to be avoided – globally, they amount to over two billion tonnes of carbon dioxide each year – it is important that demand for cement clinker be drastically reduced. But it is also essential to capture those emissions that cannot be prevented, and then to permanently store the gas or use it productively.

The Norwegian cement producer Norcem is presently installing the world's first cement CCS system at its factory in Brevik. It should begin operations in 2024, and will be able to capture 400,000 tonnes of carbon dioxide annually. The gas obtained will then be liquified and transported by ship to a carbon dioxide terminal operated by the *Northern Lights Project* on the western coast of Norway. From there, the liquified gas will be pumped 100 kilometres through a pipeline in the North Sea and ultimately injected into a sandstone formation 2600





8.2 and 8.3 > Carbon dioxide capture facilities currently operate mainly in the USA, and are mostly associated with the production of natural gas.

metres below the sea floor. Large-scale CCS projects are also being planned by cement producers in the USA and Great Britain.

In view of the ambitious plans for facilities to implement carbon dioxide capture and removal, new underground storage capacities will need to be developed worldwide. Hundreds of these development projects are presently planned. The International Energy Agency (IEA) projects that, by 2030, it will be possible to store more than 420 million tonnes of captured carbon dioxide deep underground annually. This storage capacity corresponds roughly to the amount of carbon dioxide that, according to current estimates, can be captured in 2030 and subsequently needs to be safely stored.

Underground carbon dioxide storage

The pore spaces in rock layers at depths of 1000 to 4000 metres are particularly suitable for carbon dioxide storage. These are found either in depleted oil and natural gas fields or in rocks whose pore spaces are filled with saltwater. In order to be useful for storage, however, the rock layers must be overlain by an impermeable cover or barrier layer. This generally consists of fine clay or salt rock and prevents the escape of stored carbon dioxide from the reservoir rocks.

Whether the barrier is effective or not depends on the local geological conditions. The necessary conditions were not present in Algeria in 2004, when the oil companies BP and Statoil began to inject carbon dioxide from natural gas production into rocks at a depth of 1.9 kilometres. Seven years after beginning the *In Salah CCS Project*, after the operators had injected 3.8 million tonnes of carbon dioxide, the work was discontinued. Geophysical and geochemical control measurements had reinforced the suspicion that injected carbon dioxide might be able to escape from the reservoir rock into the 300-metre-thick barrier layer through pressure-induced cracks and faults in the subsurface. The risk of leakage was too great.

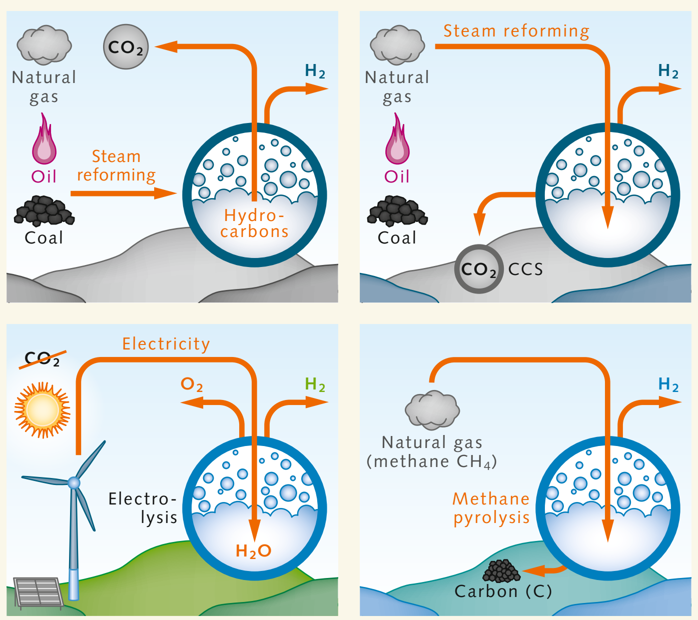
Specialists have learned from the debacle, however, and have incorporated some of the measurement methods

The colours of hydrogen

Hydrogen can be produced in different ways. The most common method currently used is steam reforming, by which methane is broken down to produce carbon dioxide and hydrogen. If the carbon dioxide is ultimately released into the atmosphere as a greenhouse gas emission, the hydrogen is termed "grey". But if the carbon dioxide is stored or reprocessed, the hydrogen can be referred to as "blue". Grey and blue hydrogen are both used in industrial processes and for power production.

Blue hydrogen should be replaced by "green" hydrogen over the long term. This is produced by the process of electrolysis, which means that an electrical current is used to split water into its molecular components, hydrogen and oxygen. If the electricity used comes from renewable energy sources, the process is climate-neutral and the hydrogen produced is termed "green".

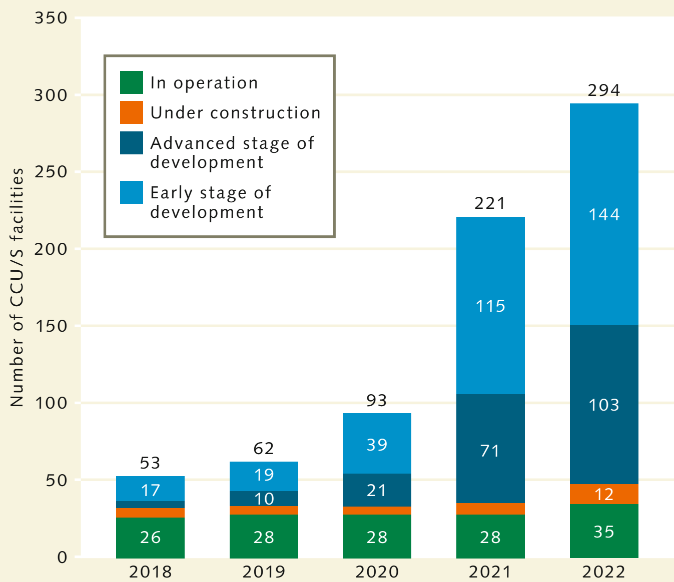
Another option for making climate-neutral hydrogen is methane pyrolysis using energy from renewable sources. In this method, methane is split into hydrogen and solid carbon. Solid carbon is a granulate that can be safely stored in old mine shafts, for example, and used again later. The climate-neutral hydrogen produced by methane pyrolysis is called "turquoise" hydrogen.



8.4 > The four methods for producing hydrogen are distinguished by their source material, the energy source, the necessary production steps, and ultimately by the balance of emissions.

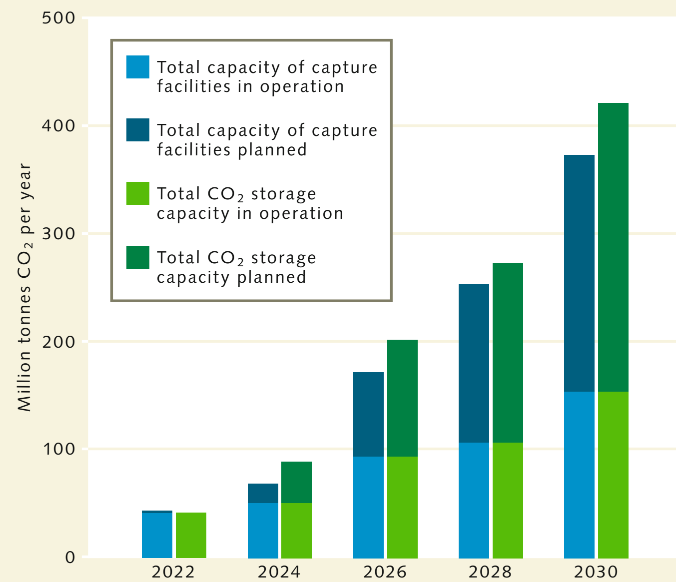
8.5 > High-purity carbon powder is formed during pyrolysis when methane (natural gas) is heated to over 1000 degrees Celsius and split into its elemental components, carbon and hydrogen. The powder is used in the production of many products, from modern building and construction materials to high-tech applications such as energy storage.

Trends in the number of projects for CO_2 capture from 2018 to 2022



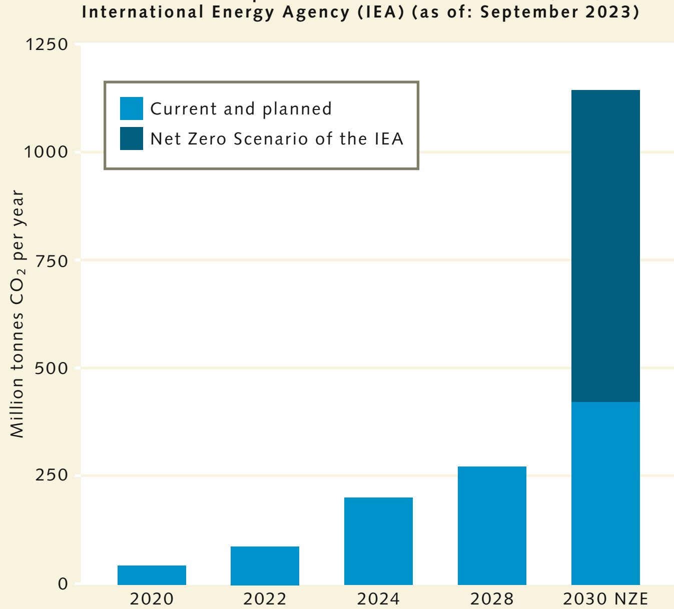
8.6 > Worldwide, the number of facilities planned, under construction or in operation for capturing carbon dioxide rose continuously during the period from 2018 to 2022.

Comparison of current and planned CO_2 capture capacity vs. storage capacity for the years 2022 to 2030 (as of: September 2023)



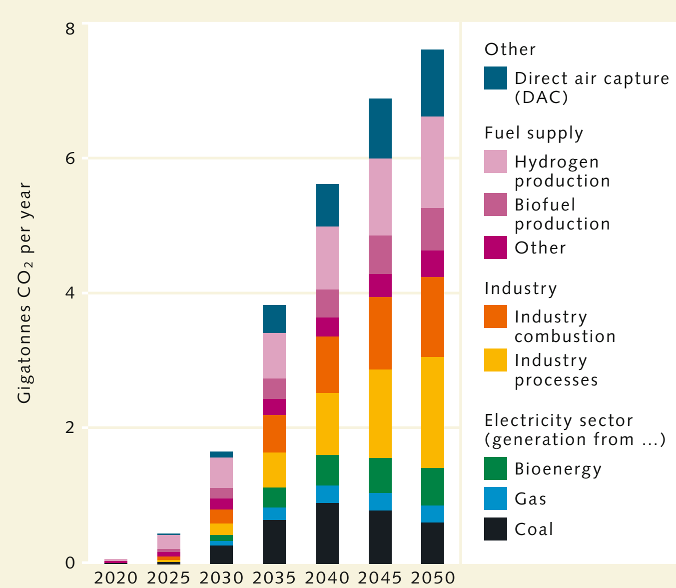
8.7 > The number of planned development projects for geological reservoirs has also increased significantly. Projections indicate that sufficient storage capacities will be available for captured CO_2 in 2030.

Current and planned CO_2 storage capacity for the years 2020 to 2030 compared to the Net Zero Scenario (NZE) of the International Energy Agency (IEA) (as of: September 2023)



8.8 > There is a large discrepancy, however, between the planned and operational CO_2 storage capacities vs. those that would be necessary for a Net Zero Scenario in the year 2030, according to calculations by the IEA.

Global CO_2 capture 2020 to 2030 in the Net Zero Scenario (NZE) of the International Energy Agency (IEA)



8.9 > According to calculations by the IEA, an estimated 7.6 billion tonnes of CO_2 will have to be captured in the year 2050, of which some 40 per cent are energy and process-related emissions by the industrial sector.

8.10 > This facility captures carbon dioxide from the ambient air and produces fuel from it. It was developed by the Canadian company Carbon Engineering, which is also involved in building the first large DAC plant in the USA.

employed at that time into their manual of relevant preliminary exploration and monitoring methods for geological carbon dioxide reservoirs. When all pressure thresholds are strictly observed in carbon dioxide injection today, at least 99 per cent of the injected carbon dioxide remains in the appropriate rock formations. It is also known, however, that certain geotechnical risks increase during the process of carbon dioxide injection. Pressure changes in the subsurface can trigger earthquakes or cause the land surface to rise. It is also conceivable that, as a result of carbon dioxide injection, pore waters from the deep subsurface could rise up and salinate or otherwise pollute groundwater layers.

For these reasons, plans to inject captured carbon dioxide on land, particularly in densely populated regions, are commonly met with rejection and protests from the local populations. In addition to the lack of public acceptance, however, the high costs and significant energy expenditure for carbon dioxide capture have also contributed to the fact that such processes have only been applied on a large scale in relatively few industrial projects.

A controversial method gaining momentum

Recently, however, attitudes have changed in politics and business. Under increasing pressure to effectively reduce their own emissions, more and more countries and companies are planning to implement CCS. The government of the USA, for example, in its infrastructure law of November 2021, has included more than 12 billion US dollars to be spent for CCS projects and related activities. Of that total, 2.5 billion US dollars are earmarked for search and validation of storage sites, eight billion US dollars for hydrogen production plants – including those for blue hydrogen – and the Department of Energy wants to invest

Carbon dioxide utilization – new ideas with the long-term goal of a circular economy

Captured carbon dioxide can be used either directly or it may undergo various biological or chemical processes prior to being used as a raw material or ingredient in the manufacture of various products (Carbon Capture and Utilization, CCU). Currently, according to the International Energy Agency (IEA), about 230 million tonnes of carbon dioxide are directly utilized worldwide every year. Almost 130 million tonnes are used to make synthetic urea for fertilizers. Oil companies inject an estimated 80 million tonnes into the subsurface in order to extract oil reserves more quickly and as completely as possible (Enhanced Oil Recovery, EOR). The remaining carbon dioxide is utilized in the food and beverage industries or is pumped into greenhouses to enhance plant growth. Carbon dioxide can also be used as an extinguishing agent or refrigerant.

There are some relatively new proposals to use captured carbon dioxide as a carbon source in the production of synthetic fuels for ships and aircraft, for carbon-based feedstocks in chemical industry, or for plastics and construction materials. If these prove to be feasible on a large scale, products containing carbon from captured carbon dioxide could replace materials formerly made from fossil-sourced carbon. The ultimate goal of these ideas would be to establish an added-value chain and circular economy for carbon, in which carbon from coal, oil or natural gas is no longer needed.

For the production of chemicals and fuels from carbon dioxide, the gas must be synthesized with hydrogen. In this way, methanol and other hydrocarbons can be produced that will ultimately be useful in chemical industry or as synthetic fuels. A pilot project for this purpose is being planned at a refinery in Schleswig-Holstein, for example. If chemical industry implements the CCU projects it has already announced, the sector could see an estimated five million tonnes of captured carbon dioxide being used worldwide for fuel production in 2030. However, almost half of the proposed projects are still in the early development stage, and in many locations the pipelines and other infrastructures for transporting hydrogen and carbon dioxide are not yet in place.

Emissions balance – the devil is in the details

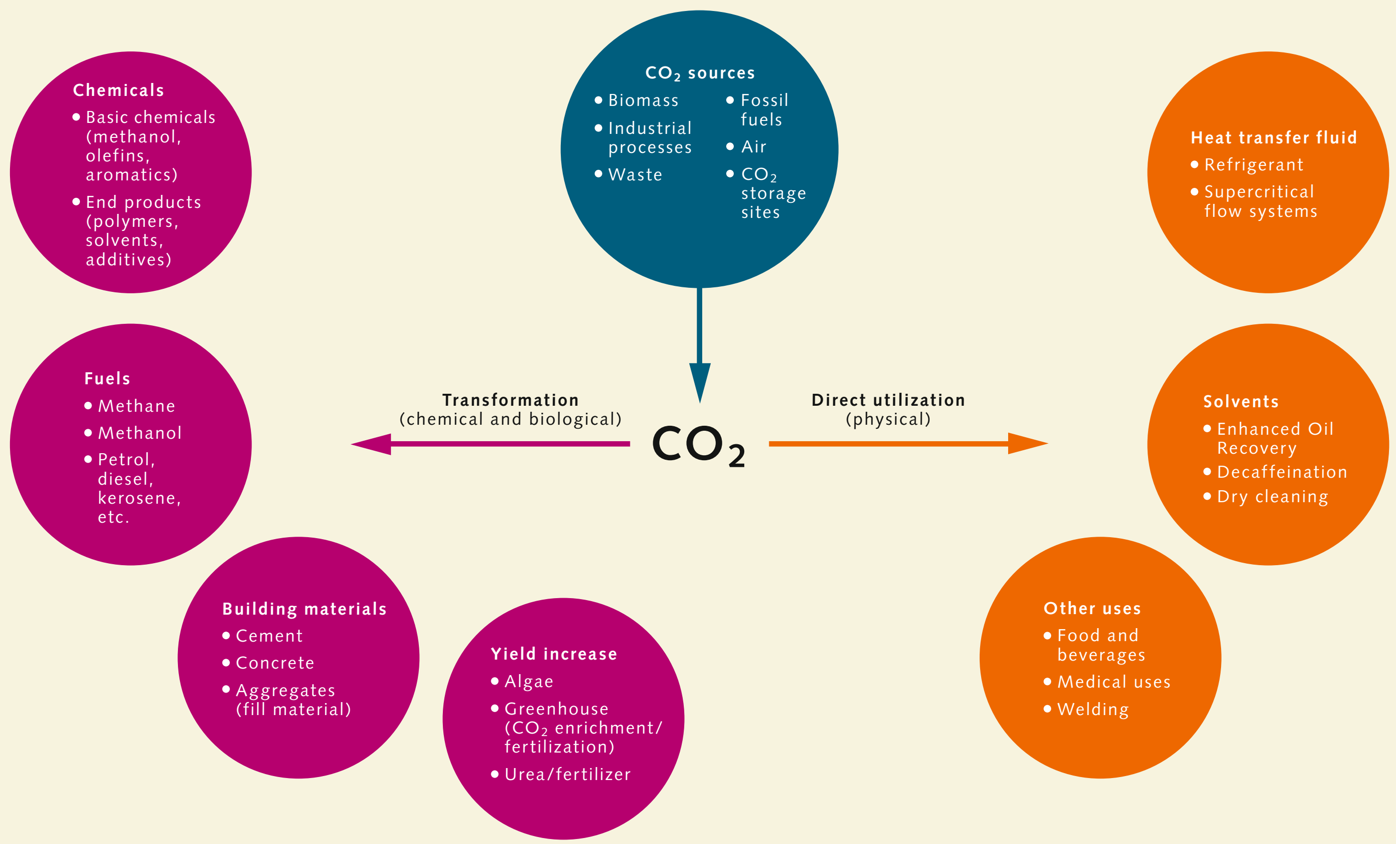
The emissions balances for the various carbon dioxide processing methods are highly complex. The products that are made can only be considered climate neutral if the carbon dioxide used originates from the atmosphere, if green hydrogen is used, and all of the production processes are powered by energy from renewable sources. But even under these conditions, the reprocessing of carbon dioxide can only be designated as permanent removal in a few exceptional cases.

This status requires that the manufactured products be used or recycled over a climate-relevant time period (longer than 100 years), and they must also retain the carbon they contain for that long. However, these two conditions are very rarely met.

As a rule, CCU products only last for a few weeks or months, and during their use or disposal the carbon they contain is released again in the form of carbon dioxide. This is the case, for example, when the synthetic fuel product is burned in ship motors or airplane turbines. The climate balance of the fuel is only neutral if an equivalent amount of carbon dioxide was removed from the atmosphere to make the fuel as was emitted during its production and combustion.

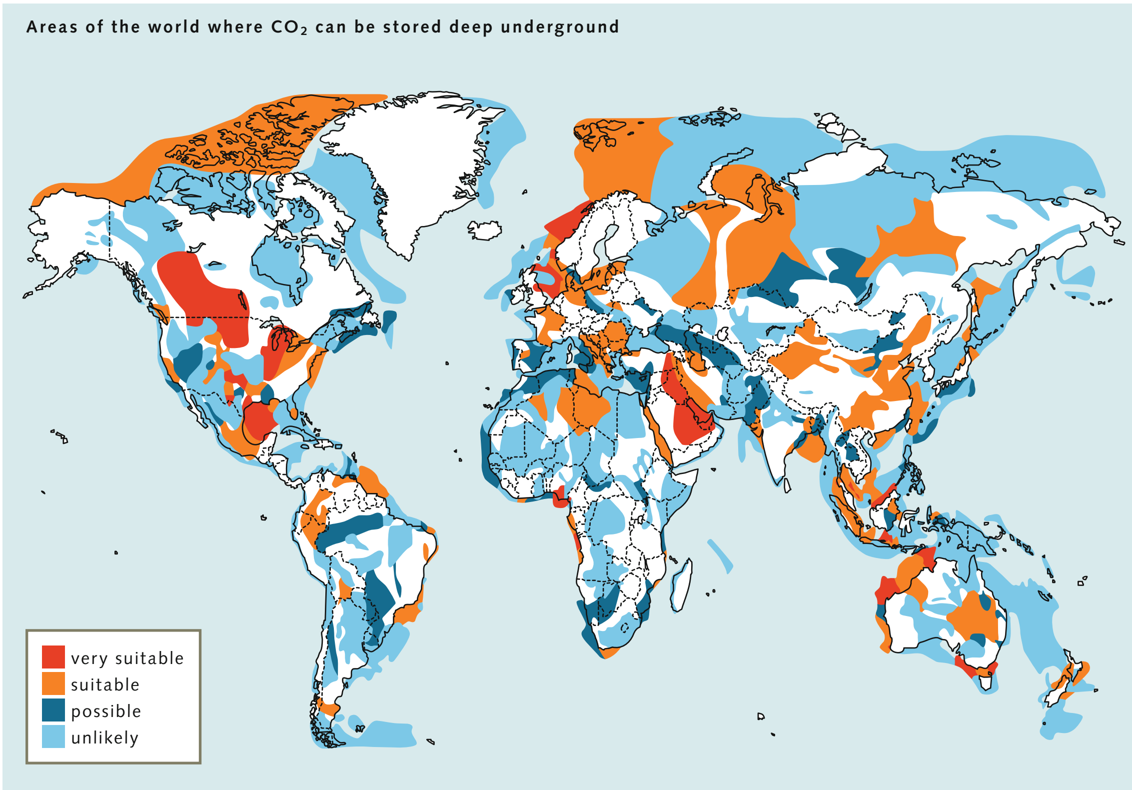
If the carbon dioxide used in CCU products originates from oil, natural gas or coal, there will even be new emissions created in the long run. This means that only a few of the yet known and applied CCU technologies actually do result in the removal of carbon dioxide. In its development scenario for achieving carbon dioxide neutrality by 2050, the IEA assumes that only about five per cent of the captured carbon dioxide will actually be reprocessed in 2030. The greatest share of the greenhouse gas must therefore be stored underground.

Possible uses of CO_2 excluding the production of fossil fuels (figure after IEA 2019)



8.11 > Captured carbon dioxide, and particularly the carbon it contains, can be used in a large variety of applications. However, to achieve a positive climate effect, the gas or carbon must be processed in such a way that it can no longer escape into the atmosphere.

8.12 > Rock formations with large pore volumes overlain by impermeable barrier layers are especially well suited for the underground storage of carbon dioxide. These conditions are only present in some regions of the world.



more than 200 million US dollars in the development of new storage technology. Canada has introduced tax incentives for CCS projects, Denmark has committed to CCS subsidies of five million Euros, and Norway has pledged investments equivalent to 100 million US dollars. That money will be spent for the construction of three large hydrogen production plants. The European Union is already funding four CCS projects with money from its Energy and Innovation Fund, including a BECCS project in Stockholm, Sweden, a cement factory in France, a facility for producing hydrogen in Finland, and a factory for producing hydrogen, ammonia and ethylene in Belgium. Seven additional CCS projects have reached the second round in this funding competition.

According to new government plans, Great Britain aims to capture around 20 to 30 million tonnes of carbon dioxide in its industrial sector starting in the year 2030, and to inject the bulk of the gas underground in at least two storage projects (*East Coast* and *HyNet*). The governments of Japan, China, Malaysia, Indonesia and Australia are also supporting the search for and development of geological carbon dioxide storage and the associated infrastructures. In Australia the oil companies Chevron Australia and Exxon have already been operating the *Gorgon CCS Project* since 2019. This involves natural gas retrieved from offshore reservoirs and transported to land through a pipeline. The carbon dioxide it contains is then separated out and injected beneath Barrow Island off the northwest coast of Western Australia.

The oil-producing countries of North Africa and the Middle East are also pursuing CCS expansion plans. Three facilities for carbon dioxide capture are already operating in the region – one each in the United Arab Emirates, Saudi Arabia and Qatar. New storage projects are in the planning stage. The future outlook for CCS has never been better than it is now, according to the annual report for 2022 by the Global CCS Institute. Overall, however, the think tank draws a sobering conclusion: Global efforts to

reduce greenhouse gas emissions, including investments in CCS, are still woefully inadequate.

Environmental and climate activists sharply criticize government support for CCS, especially for projects promoted by oil- and gas-producing companies to capture and store carbon dioxide from the burning or processing of fossil resources. The critics argue that such projects are examples of "greenwashing" and serve only to unnecessarily delay the phaseout of fossil-fuel use. The CCS opponents say that if all the green energy needed to capture carbon dioxide from fossil sources in a climate-neutral way were fed directly into the power grid, it would probably be sufficient to end the generation of electricity from coal, oil and natural gas. Other experts point out that CCS is indispensable if carbon dioxide removal methods such as BECCS and DACCS are to be employed at industrial levels. They assert that efforts in the search for storage sites, along with infrastructure and technological development, would thus have to continue.

According to the German Energy Agency (dena) around 34 to 73 million tonnes of carbon dioxide would have to be captured and stored in deep rock layers annually in the Federal Republic of Germany for the country to achieve its goal of greenhouse-gas neutrality by 2045. Because political obstacles make the technical storage of carbon dioxide on land practically impossible in many places, experts are now increasingly considering storage in the geological subsurface beneath the seas.

This could be feasible with the help of two approaches. In the first, compressed or liquified carbon dioxide would be injected into deep-lying sandstone formations, a procedure that is possible in all marine regions where these very common formations are found. By the second method, liquified carbon dioxide or carbon dioxide dis-

8.13 > At this liquefied natural gas plant on Barrow Island, Australia, carbon dioxide is captured during natural gas processing and injected underground some distance away at a depth of two kilometres.

8.14 > Since 1996, in the *Sleipner Project* of the Norwegian oil company Equinor, around 0.9 million tonnes of carbon dioxide have been captured annually during natural gas processing and subsequently stored deep beneath the North Sea.

Mechanisms for storing carbon dioxide in the deep subsurface

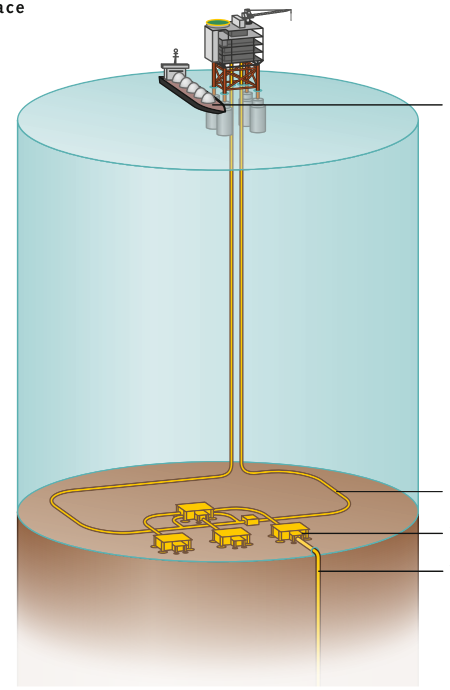
Structural trapping
An impermeable cap rock prevents the carbon dioxide from escaping upward from the reservoir rock.

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.



8.15 > 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.

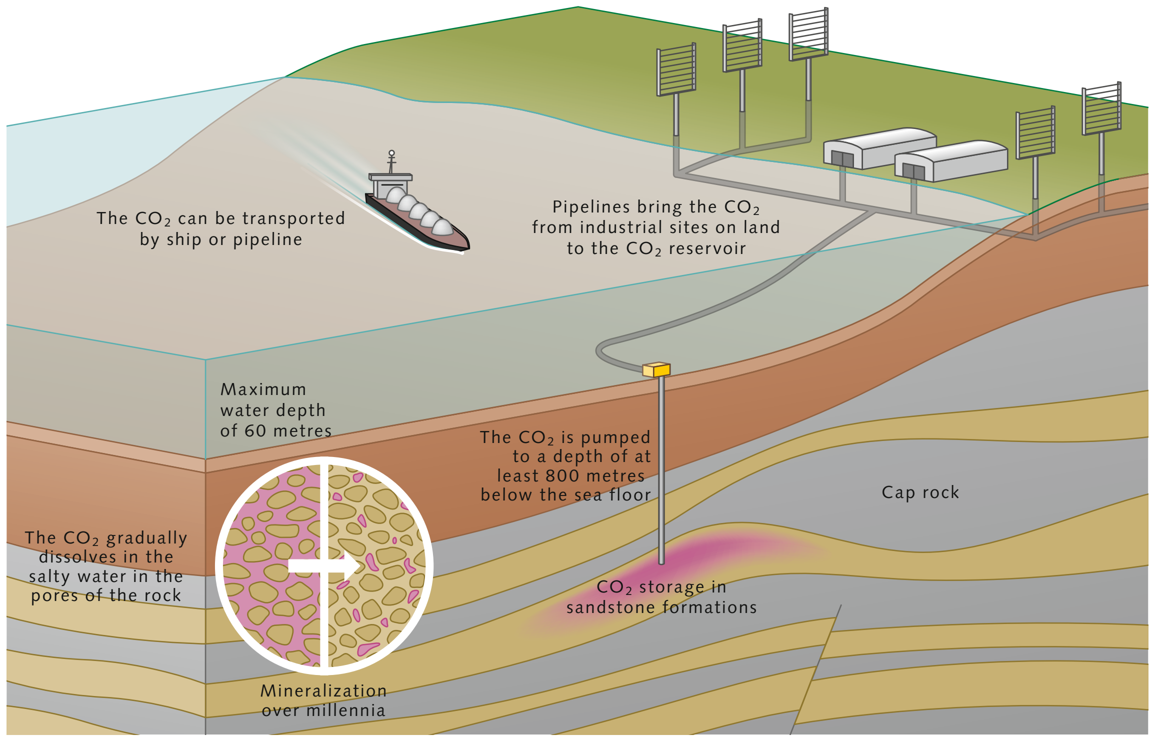
solved in seawater would be injected into the highly reactive, porous upper basalt layer of the ocean crust or into rocks called flood basalts. The former are found primarily at the mid-ocean ridges. The latter can also occur near the coasts.

Carbon dioxide storage in sandstone formations

Sandstone formations that can be considered feasible to use as geological carbon dioxide reservoirs are found both on land and in the deep subsurface below the ocean floors (800 metres and deeper). Compared to other rocks, these sedimentary rock layers are more permeable and contain pores between the individual sand grains through which the injected carbon dioxide can disperse. A prerequisite for permanent storage in this case is also that the reservoir rock is capped by a suitable trapping layer composed, for example, of clay or salt. This kind of layer seals the reservoir rock and prevents the injected carbon dioxide from escaping upwards.

If a storage site fills these and some other geological requirements, the captured carbon dioxide can be compressed, liquified if appropriate, and injected through one or more boreholes into the storage formation. There, the carbon dioxide disperses into the rock pores that are filled with saline water. Geologists refer to this salty pore water as formation water. Because the injected carbon dioxide is lighter than the formation water, it tends to rise in the reservoir rocks. It collects at the highest point below the sealing cap rock and remains there as long as the cap rock is truly impermeable.

Over time, the carbon dioxide dissolves in the formation water. The resulting solution is heavier than water, and the carbon dioxide no longer rises towards the surface. Finally, the carbon dioxide dissolved in the water reacts with minerals contained in the sandstone and is converted to dissolved bicarbonate. In this form, the introduced carbon no longer has any harmful climate impact, even if the dissolved bicarbonate should escape into the sea. How fast the carbon dioxide is converted into bicarbonate depends upon how many reactive minerals are present in the reservoir rock. The bicarbonate eventually precipitates to form solids in which the introduced carbon is permanently bound. However, it can take



8.16 > Captured and compressed carbon dioxide can be transported to the injection site via pipeline or ship.

many thousands of years for this process to be completed.

Carbon dioxide storage projects in the North Sea

The North Sea has many areas that could be considered suitable for the storage of carbon dioxide in the deep subsurface. Calculations indicate that around 150 to 190 billion tonnes of carbon dioxide could be stored in underground sandstone formations if the Norwegian and Barents Seas are included. As a shelf sea, the waters of the North Sea are not especially deep. Its maximum depth in German waters is just 60 metres, which would make the construction or installation of injection facilities on platforms and the seabed comparatively easy.

Some North Sea countries are already injecting carbon dioxide deep into the sea floor or will soon begin to do so. It began with the Norwegian oil company Equinor (formerly Statoil) in 1996. After the Norwegian government introduced a national carbon dioxide tax in 1991, the company stopped releasing the carbon dioxide contained in the natural gas into the atmosphere, and began separating it on-site on the offshore production platforms and injecting it into sandstone formations deep below the platforms. Since 1996, in what is known as the *Sleipner Project*, around 0.9 million tonnes of carbon dioxide have been pumped into the subsurface every year.

Furthermore, in the *Snøhvit Project* in the Barents Sea, the company has been discharging around 0.7 million tonnes of carbon dioxide deep below the sea since 2009. This shows that the storage of carbon dioxide in the deep subsurface of the North Sea has been technically possible for decades. Furthermore, specialists have gained a high level of experience and knowledge in carrying out these kinds of storage projects in deep-lying sandstone formations.

Other companies and countries have begun to follow Equinor's example because increasing prices for carbon dioxide emission allowances are gradually making a profitable business out of its storage deep underground in the ocean. Capturing one tonne of carbon dioxide,

transporting it by pipeline to the marine area, and pumping it into the subsurface costs an estimated 80 to 200 Euros, depending on the location of the site. In the year 2022, the allowance for emitting the same amount of carbon dioxide into the atmosphere cost around 80 Euros. Numerous new projects for storing carbon dioxide in the subsurface of the North Sea are presently being planned and implemented, for example off the coast of Rotterdam (The Netherlands), in the Danish and British zones of the North Sea, and below Norwegian waters. In each case, sandstone formations are investigated that are either saturated with saltwater (for example, *Sleipner* and *Snøhvit*) or from which natural gas and oil have previously been extracted.

Because industrial emission sources like cement plants or waste incineration plants are not usually located at the same place as possible utilizers of the captured carbon dioxide or near storage sites, this carbon dioxide must be transported. In the *Sleipner Project* in the Norwegian North Sea, the carbon dioxide is captured and injected directly on-location at the natural gas production site at sea, while in the *Snøhvit Project* in the Barents Sea the carbon dioxide is transported from a processing plant on land to the injection wells through pipelines on the sea floor. Transport by pipelines or ships is also planned for the storage of carbon dioxide in the Norwegian *Northern Lights Project* in the North Sea, and in further projects off the coasts of The Netherlands, Denmark and Great Britain.

CCS today is planned and implemented cooperatively

Although CCS projects in the past were primarily planned and implemented for an individual facility for the capture of carbon dioxide with its own downstream transport and storage system, in recent years, regional alliances of companies have been forming to develop and use joint transport and storage infrastructures (such as pipelines, port facilities, intermediate storage facilities, storage sites). A prominent example is the CCS project of the Port of Rotterdam, in which many of the companies that operate there are taking part. A similar association has formed in Houston, Texas. There, 14 companies are currently working on the construction of a large CCS infrastructure, mostly oil-producing companies and the chemical giant Dow. They want to capture carbon dioxide in their refineries and plants in the Port of Houston, feed it by pipeline into the Gulf of Mexico and inject it deep into the subsurface there.

Other companies are planning cross-border carbon dioxide transportation networks, on land and in the sea, in order to transport the greenhouse gas from the capture plants at point sources to the final storage sites. In the future, the oil company Santos, for example, wants to transport captured carbon dioxide from the northern Australian city of Darwin for injection into the maritime territory of the neighbouring island state, the Democratic Republic of Timor-Leste, through a pipeline previously used for natural gas.

8.17 > Outside the port of Rotterdam, captured carbon dioxide will be injected into a depleted gas field under the North Sea beginning in 2026. This, however, will be mostly to store carbon dioxide from fossil sources, which only prevents additional emissions. There is no actual removal of CO_2 from the atmosphere.

In Europe, the companies Wintershall Dea and Equinor want to build a carbon dioxide pipeline extending from Wilhelmshaven on the German North Sea coast into the Norwegian North Sea. Parallel to this, specialists in other projects are investigating whether it would be feasible to deploy tankers with load capacities of 30,000 to 70,000 cubic metres to transport captured carbon dioxide cost-effectively from more distant sources to storage facilities off the coasts of Norway and other shelf-sea states.

The risks of storing carbon dioxide in sandstone formations beneath the sea

Based on the experience gained from ongoing carbon dioxide storage projects and on research from the past two decades, scientists know very well the risks associated with the injection of carbon dioxide into sandstone formations beneath the seas. These include four main hazard issues, as follows:

- a portion of the carbon dioxide injected into the subsurface rises along faults or through the boreholes and escapes at the sea floor (leakage);
- very salty formation water, as well as heavy metals or other materials that it may contain and are harmful to the environment, escape at the sea floor and impact local ecosystems;
- pressure changes within the reservoir rocks reactivate existing geological faults and trigger earthquakes, which could endanger the stability and functionality of infrastructures located on the sea floor;
- marine mammals are disturbed or possibly harmed by noise that is made during the search for suitable storage formations, in construction of the facilities, or in subsequent monitoring of the storage site.

Which of these risks actually develops into a problem and to what degree depends on the local conditions, which must be thoroughly investigated in advance of any carbon dioxide storage project.

When carbon dioxide or formation water escapes from the seabed

As a rule, the sea floor of the shelf sea is not a tightly sealed surface. On the contrary, natural gas seeps out of the seabed in some places. In the North Sea, around one and up to a maximum of 70 tonnes of natural gas is released per year per seepage site. The origin of this gas is not always evident. It can either be formed by microorganisms living within the sea floor or it may rise along natural faults from gas reservoirs deep in the subsurface. In addition to this, in the North Sea natural gas escapes through old wells at a rate of one to 19 tonnes per leakage site per year.

As yet, there are no known carbon dioxide leaks at modern wells that were specially drilled for the purpose of carbon dioxide storage. Likewise, in the Norwegian storage projects, which have been operating for many years, no carbon dioxide has yet been released at the sea floor. However, in choosing storage sites, the possible existence of faults and other sediment structures in the subsurface through which the carbon dioxide and possibly formation water could rise to the surface has to be investigated. At the same time, it must be determined whether old wells are present and, if so, whether they are properly sealed.

In the preliminary stages of a carbon dioxide storage project beneath the sea, it is also crucial to chemically analyse the formation water in the selected reservoir formations. Based on the results, it will be possible to assess the environmental risks that could arise if the formation water should escape from the sea floor, along with the heavy metals or other environmentally harmful substances it might contain.

CO_2 release experiments on the sea floor of the North Sea show that escaping carbon dioxide is immediately dissolved in the near-bottom seawater, thus changing the chemical properties of the water. The seawater in the vicinity of the discharge site becomes acidified, which affects the living conditions, especially for mussels and other carbonate-forming creatures. The area affected by the acidification is comparatively small (approxmately ten to 50 square metres), if roughly an equal amount of carbon dioxide is released as the natural gas seeping from the North Sea leakage sites mentioned above.

When carbon dioxide storage sites in the marine realm are rigorously surveyed and selected, it is expected that only a very small amount of carbon dioxide would be able to escape from the storage facility when it is properly operated. It is presumed that more than 99 per cent of the stored carbon dioxide would remain underground over the long term.

Nevertheless, leakage must be prevented to the greatest extent possible. Effective early-warning and monitoring systems are necessary to detect deviations from the expected storage performance in a timely manner so that appropriate countermeasures can be taken. In recent years, great progress has been made in the research, testing and commercial application of monitoring technology. Monitoring technologies for the offshore sector in particular have been tested and further developed. In experiments by the specialists carrying out the testing, carbon dioxide was released on or in the sea floor to determine the effectiveness of a particular technology or method in detecting the escaping carbon dioxide. In one experiment in the British North Sea, sensors were able to detect carbon dioxide released at the very low rate of six kilograms per day in the sediment and in the water column.

On the whole, according to experts, a wide range of monitoring technologies is now available that can be used on a large scale for carbon dioxide storage. However, advances in technology are still possible and desirable, for example in the areas of sensor technology, data management and intelligent autonomous systems, including autonomous underwater vehicles. To date, these have limited autonomous decision-making capabilities, and can only travel along preprogrammed routes. What is needed, however, are fully autonomous underwater vehicles capable of acting intelligently in real time in response to sensor readings. Work is already underway to develop the required technology. If this could be implemented in the near future, the costs of monitoring storage sites would be reduced.

Engineers are also placing great hopes in fibre-optic-based monitoring systems. These would use fibre-optic cables with multiple sensors attached. The cables can be laid on the land surface, placed in the ground along pipelines or on the sea floor, and run directly into deep boreholes, so that both the injection and the storage of carbon dioxide can be closely monitored. Depending on the sensors selected, various parameters can be recorded in close temporal succession. Free carbon dioxide or carbon dioxide dissolved in water can thus be directly identified. The fibre-optic cables will also be used to determine the pressure, temperature and gas saturation in the pore spaces as well as seismicity and deformation in the subsurface. If the optical fibre is used as a geophone, seismic measurements can also be obtained. All that is currently lacking is informative long-term experience in the application of such monitoring cables, especially regarding the durability of the fibres and sensors in a harsh environment. For this reason, the application of these methods and others is being tested and further developed in a joint European research project. According to experts, their use in combination with conventional monitoring methods is already practical today. Over the long term, the cables could even completely replace conventional monitoring technology. The costs for the construction and use of such fibre-optic cables are comparatively low.

When carbon dioxide injection triggers motion in the subsurface

When carbon dioxide is injected into reservoir rocks, the pressure in the rock formation is increased. This can activate existing faults in the formation. This means that at some locations, cracks in the rock can expand or rock layers can be displaced relative to each other. As a result of such movements in the subsurface, paths could be created through which the stored carbon dioxide and the formation water rise and eventually escape at the sea floor.

In marine regions where earthquakes already occur naturally, pressure changes in the reservoir rocks could cause changes in the subsurface tension. This could then trigger earthquakes, which would endanger the stability of wind turbines or pipelines. A carbon dioxide pilot reservoir at Nagaoka, in the province Niigata, Japan, withstood

8.18 > For the exploration and monitoring of carbon dioxide reservoirs beneath the sea, airguns must be employed. The noise they produce likely poses a great danger and causes stress for harbour porpoises and other marine organisms.

a strong earthquake with an intensity of 7 with no damage. However, drawing conclusions about other storage sites is only possible to a limited extent, because the individual site-specific conditions need to be considered.

Whether on land or at sea, potential sites for storing carbon dioxide deep underground must be thoroughly examined. Their geological characteristics, possible leakage paths, and the locally prevailing pressure and temperature conditions must be investigated before a decision can be made on their feasibility for carbon dioxide storage.

Noise pollution for whales, fish and other animals

In the search and exploration for suitable carbon dioxide storage sites in the marine subsurface, the same geophysical methods are used as those employed in the search for oil and natural gas reserves. These include, among others, active seismic methods in which, for example, airguns are towed through the water by ships. These send out a series of sound waves that penetrate deep into the substrata and are differentially reflected by the rock layers. Through the transmission and reflection of the sound waves, scientists are able to map the form and structure of the subsurface.

The drawback to airguns is that their sound waves have an impact on marine life that is not yet well understood, especially on noise-sensitive North Sea inhabitants such as harbour porpoises. Because harbour porpoises depend on acoustic signals for orientation, as well as for communication and in searching for food, underwater noise influences their behaviour and, over the long term, could drive them out of their native habitat. Very high sound levels at certain frequencies can also injure and possibly even permanently harm the animals. The same is true in other shelf seas for the native marine mammals and other animals.

Based on this knowledge, and considering the already generally increasing noise levels in the coastal seas, it is essential to recognize the risks of high-intensity noise for marine organisms and to develop appropriate protection measures. The risks of increased noise produced during the search for storage sites must be considered, as well as sounds caused by injection and monitoring. In the same vein, noise levels must be taken into account in marine spatial planning – for example, in determining whether or not otherwise suitable rock strata underlying marine protected areas should be permitted for carbon dioxide storage.

Low-noise monitoring methods that are available include, for one, passive seismic techniques. These involve the placement of highly sensitive devices on the seabed that silently record both naturally occurring seismic events and those caused by carbon dioxide injection. A consideration here, however, is that where passive seismic measuring devices are placed on the seabed they need to be protected from destructive activities. Fishing and the anchoring of ships and boats may have to be prohibited in these areas.

Mounting claims upon the North Sea

With shipping, wind parks, fisheries, pipelines, and natural gas production, the German North Sea and many other marine regions are already being intensively utilized by human societies. But most of the areas are also important habitats for diverse marine species that must be protected and preserved through the designation of marine protected areas. To avoid conflicts with marine conservation and other uses, potential carbon dioxide storage sites need to be integrated into marine spatial planning.

To date, however, marine spatial planning for German waters only takes into account the use of the seabed, the water column, and the air space above it. Furthermore, an expanded use of the marine subsurface at different depths is not mentioned in the revised specifications that came into force in 2021. But the debate is under way among experts on how carbon dioxide storage can be integrated into Germany's marine spatial planning.

Carbon dioxide storage in reactive basalt rocks in the upper ocean crust

In addition to the Earth's sandstone formations, iron- and magnesium-rich rock layers are also viewed as possible carbon dioxide storage sites. Scientists refer to these as "mafic" or "ultramafic" rocks, terms derived from the element symbols "Ma" for magnesium and "Fe" for iron.

Magmatic rocks are particularly rich in iron and magnesium. This is especially true for basaltic volcanic rocks, either solid or unconsolidated. They are widely distributed, occurring on land (e.g. in India, Australia, Canada, and South Africa) as well as in the sea floor. The Earth's upper oceanic crust, for example, is composed of basaltic rocks.

If you imagine dark cobblestones when you hear the word basalt, then you do actually have basalt rock in mind. The rocks of the upper 100 to 400 metres of ocean crust, however, have little to do with the dense, fine-grained rocks that are used to pave marketplaces or driveways. By contrast, these rock layers are highly porous, and in places are riddled with millimetre-sized bubbles and cracks.

This open-pored structure develops early in the formation of the six- to eight-kilometre-thick ocean crust. The crust is generated in areas called spreading zones, such as the Mid-Atlantic Ridge. These are zones on the Earth where two tectonic plates move slowly apart while hot magma from inside the Earth flows out between them. When it comes into contact with cold seawater, the surface of the magma abruptly cools and solidifies. In the process, the structure of the rock near the surface is fundamentally altered. In many places, bubbles, fissures or shrinkage cracks are formed. This creates a network of tiny hollow spaces and pathways, which from then onwards pervade the upper part of the basalt rock.

Seawater circulates through this subsurface network of pores. The upper 400 metres of basalt rock is like an extensive conduit system for fluids (liquids and gases). It constitutes the largest water-bearing rock formation (aquifer) on earth, directly beneath the ocean. Its pore spaces thus offer sufficient storage volume for the injection of enormous amounts of liquified carbon dioxide or carbon dioxide-rich water, according to specialists.

There is a distinct advantage to storing carbon dioxide in basalt rocks rather than in porous sandstone formations. Because of their chemical composition, alkaline basalt rocks react relatively quickly when they come into contact with carbon dioxide-rich solutions. The magmatic rocks contain minerals such as olivine, plagioclase, pyroxene and volcanic glass. These, in turn, contain the primary components calcium, magnesium and iron, among others.

If seawater is enriched with carbon dioxide or if injected carbon dioxide slowly dissolves in the pore waters, the water is acidified and becomes "sparkling water". When water in this state comes into contact with the basalt rock, the acid in the water corrodes the basalt surface, dissolving out the iron, magnesium and calcium components. These then react with the dissolved carbon dioxide to form carbonates, which initially remain dissolved in the water. But as the dissolution reaction continues, the water will eventually become oversaturated, and the carbonates will precipitate out to form carbonate minerals such as calcite, dolomite or ankerite. These, simply put, are mineral rocks in which the former carbon dioxide is tightly bound, in the best-case scenario, for many millions of years.

Scientists refer to this process as the mineralization of carbon dioxide. It proceeds much more rapidly and thoroughly in mafic rocks than in sandstone formations, where the injected carbon dioxide remains for a very long time as a separate phase (liquified carbon dioxide) or dissolved in the formation water. A further positive aspect of basalt rocks is that natural mineralization can be technically accelerated through the systematic input of more carbon dioxide.

Successful project on Iceland

The amount of carbon dioxide that can theoretically be stored in the upper ocean crust has not yet been thoroughly investigated, and any estimates of its capacity are therefore fraught with huge uncertainties. Currently, however, experts believe that the theoretical mineral carbon dioxide storage capacity of the mid-ocean ridges of our planet is many times greater than the amount of carbon dioxide that would be released by the burning of all the Earth's fossil resource deposits. And potentially suitable rock layers are found not only on the mid-ocean ridges but also in areas known as flood-basalt provinces, which often form underwater plateaus with high porosity or a high proportion of vesicles.

Since 2014, captured carbon dioxide dissolved in water has been injected into the upper ocean crust as part of the *CarbFix Project* in Iceland. The volcanic island lies directly on the Mid-Atlantic Ridge, so that young, still-warm and thus quite reactive basalt rocks can be accessed through comparatively shallow boreholes. The mineralization rates are correspondingly high. Because of the high reactivity of Iceland's hot crust, around 98 per cent of the injected carbon dioxide mineralizes and is thus per-manently bound in the subsurface within two years. *CarbFix* has said that by April 2023 it had injected more than 90,000 tonnes of carbon dioxide into the Earth's crust, although the process has consumed a great deal of geothermal energy and large quantities of fresh water.

An example calculation: In order to dissolve one tonne of carbon dioxide in water using the *CarbFix* procedure, a pressure of 25 bars and a water temperature of 25 degrees Celsius are required. Given the present state of research, it is difficult to estimate the amount of additional energy required for the water injection. This uncertainty factor is not of crucial importance in Iceland because the availability of renewable geothermal energy is practically unlimited. But this is far from the case in other regions. Experts therefore advise that for future storage projects in which these injection methods are considered, the costs and the availability of large amounts

8.19 > Iceland is an island where the young, reactive rocks of the upper ocean crust rise above the sea surface – recognizable by the black basalt rocks of these steep coasts.

8.20 > This pipeline is part of the *CarbFix Project* in Iceland. Since 2014, captured carbon dioxide dissolved in water has been injected into the upper ocean crust there.

of water and energy need to be taken into account during the planning stage and must be included in cost-benefit assessments.

Large basalt deposits in the deep sea

Because there are only a few places in the world where the ocean crust rises out of the water above sea level (e.g. on Iceland and the Azores), science is turning its attention to greater water depths where there are tens of thousands of kilometres of mid-ocean ridges with young, reactive basalt crust in which carbon dioxide could be stored.

This idea is reinforced by the fact that high pressures exist at greater water depths. The pressures can help to facilitate dissolution of the injected carbon dioxide in seawater that is circulating in the basalt crust, resulting in denser and heavier water – or they can promote the liquification of the carbon dioxide. The density increase is such that at a pressure of 280 bars or greater (water depths below around 2800 metres) carbon dioxide would be heavier than the seawater at a comparable depth, and no longer able to rise out of the sea floor. Thus, carbon dioxide leakage from the subsurface would be improbable, but there would be a residual risk depending on the local temperature and pressure conditions.

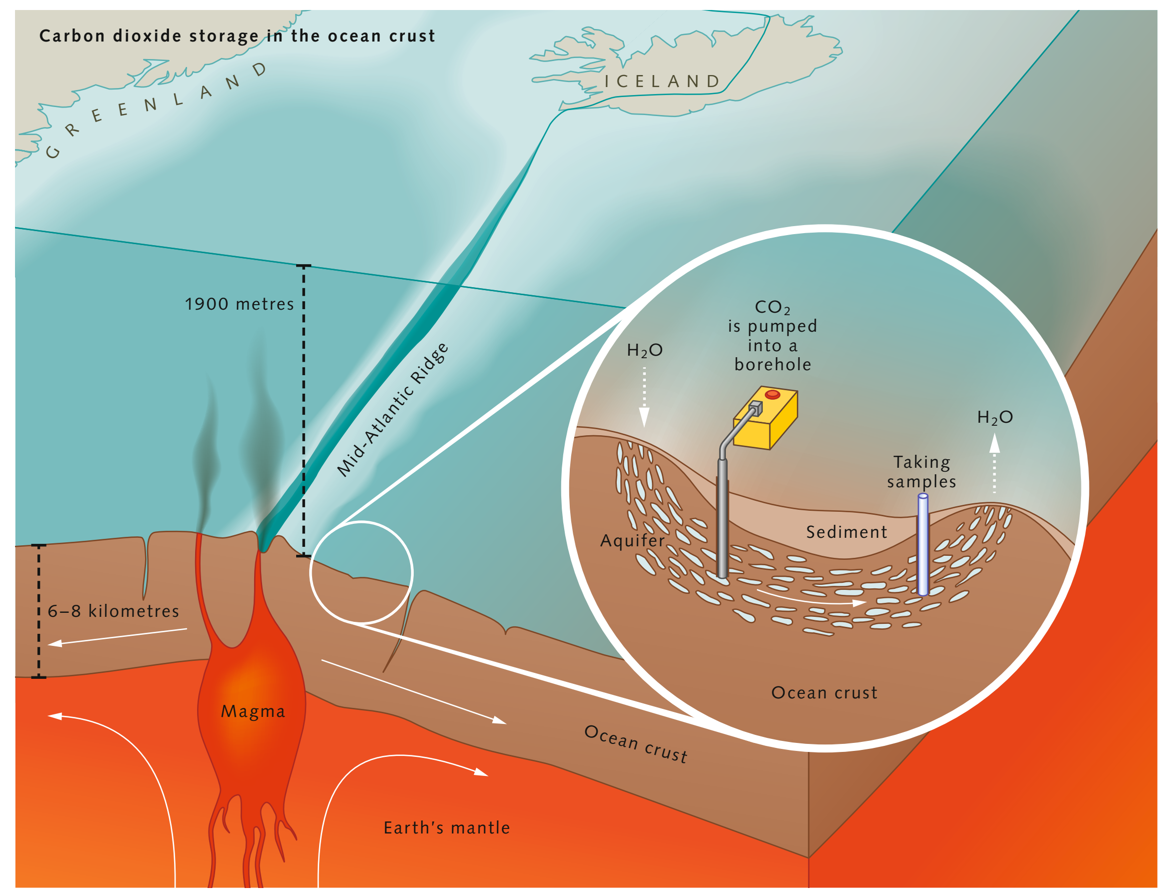
In order to be able to completely rule out the possibility of leakage over time, only basalt layers that lie beneath a layer of sediment several hundred metres thick should be selected as carbon dioxide reservoirs in the future. At large distances from the coasts, this sediment layer consists predominately of very fine clay material, which provides an effective seal for the basalt layer.

Their typically large distance from any coasts would represent still another advantage for storage at mid-ocean ridges. If the injection of carbon dioxide into the upper basalt layer of the ocean crust should trigger small earthquakes, which cannot be ruled out, their occurrence in the depths of the ocean would not endanger people or infrastructures. On land, by contrast, they would present a risk.

Carbon dioxide storage in the deep-sea subsurface, however, would also have certain disadvantages. In the cooled basalt crust, injected carbon dioxide would mineralize at a significantly lower rate than in warm rocks such as those on Iceland. In addition, many aspects of working in the deep sea would be very costly and would be pushing the limits of technical feasibility.

Due to this complex situation, the objectives of potentially storing carbon dioxide in the upper part of the ocean crust must be carefully weighed. The most cost-effective method would certainly be to dissolve carbon dioxide in seawater and inject it into the ocean crust at shallow water depths and low concentrations with high mineralization rates – as is already being done on Iceland. The few areas where a mid-ocean ridge rises above sea level, however, are generally located far from the industrial centres where large volumes of carbon dioxide are produced. The greenhouse gas would therefore have to be transported over long distances in liquified form before it could be injected into the basalt rocks.

If, on the other hand, the liquified carbon dioxide were to be injected directly into the pore spaces of the basalts at greater water depths, there would be additional advantages beyond the larger number of potential storage sites. It would also be possible to store large amounts of carbon dioxide within a short time, which, due to the ambient pressure and temperature conditions, would automatically remain in the reservoir rocks, even though it would mineralize very slowly there. The rate of mineralization, in turn, could be increased by mixing the carbon



8.21 > To test whether carbon dioxide storage in the deep sea is a technically feasible and economically viable process, scientists are conducting a deep-sea research experiment on carbon dioxide storage on a cooled flank of the Mid-Atlantic Ridge.

dioxide with seawater to dilute it – then again, with this approach it would take significantly more time to inject a given amount of carbon dioxide, because the ocean crust on the ridge flank is colder than at *CarbFix* on Iceland, for example.

Research intensifies to fill gaps in knowledge

The range of options for storing carbon dioxide in the upper basalt layer of the ocean crust is currently being examined in a number of research projects. The researchers want to find out:

- whether all theoretical prior considerations on carbon dioxide storage in the upper oceanic crust are correct and appropriate, and whether carbon dioxide injection into the deep sea floor is actually feasible;
- what concentration and amount of carbon dioxide should be injected into the basalt rocks to achieve optimal reaction processes;
- how fast injected carbon dioxide would disperse and mineralize in the rocks;
- what procedures could be used to reliably monitor the storage site over the long term and what costs they would entail;
- whether there are possible pitfalls in the conceptual considerations that have not yet been taken into account and
- whether carbon dioxide storage in the deep sea would be a more sustainable, effective, and long-term cost-effective option compared to storage on land or in the deep sandstone formations beneath the shelf seas.

These research projects are being carried out at *CarbFix* on Iceland, on the Vøring Plateau off the coast of Norway, in the Cascadia Basin off the west coast of Canada, and on Reykjanes Ridge a few hundred kilometres south of Iceland. The different project teams are working closely together and sharing scientific data on the structure, composition and geochemical processes taking place in the basalts. This knowledge is critical to determining, with the subsequent help of computer models, how much carbon dioxide can be stored at which sites in the upper ocean crust, the costs that will be incurred in the process, and what technical environmental problems, risks and damages might be involved. A concrete search for suitable sites can only begin when these numerous questions have been answered, and when society makes the conscious and informed decision to store carbon dioxide in the upper ocean crust.

The legal framework for storage of carbon dioxide under the sea

Injecting carbon dioxide into the basalt layer of the upper ocean crust or into deep-seated sandstone formations involves intervention into the ocean floor, and thus into a legal landscape that is governed by the provisions of international maritime law. Experts also point out that, under certain conditions, CCS projects in the sea could result in the escape of carbon dioxide and formation water from the sea floor and cause harm to marine ecosystems. The legal framework for carbon dioxide storage in the subsurface beneath the sea must therefore also pay particular attention to the requirements of marine environmental protection.

The provisions of international maritime law
From the perspective of international maritime law, the initial question that arises is whether states are allowed to store carbon dioxide in the seabed and, if so, where they can do it. Answers to this question are provided by the United Nations Convention on the Law of the Sea (UNCLOS). It divides the sea into different zones within which the rights of the coastal states are precisely defined.

These include:

- the internal waters and territorial seas of a state,
- the contiguous zone,
- the exclusive economic zone (EEZ),
- the continental shelf,
- the high seas and „the Area“ (the sea floor in international waters).

8.22 > On Iceland, the path of the Mid-Atlantic Ridge can be observed with the naked eye. This rift exists because the Eurasian and North American tectonic plates are moving away from each other here.

Because the internal waters and territorial seas are subject to the sovereignty of the individual coastal states, these can freely approve CCS projects there and regulate them as they wish. The legal situation becomes more complex when extended to the exclusive economic zone (EEZ), which borders on the territorial sea, and the continental shelf. These are zones in which the coastal state is only assigned particular, although exclusively sovereign, rights and jurisdictional powers. These include, among others, the exclusive right of a coastal state to drill into the marine subsurface and to construct tunnels on its continental shelf. According to experts, this also infers the exclusive right of the coastal state to subject the storage of carbon dioxide on its continental shelf to its national law, to regulate such storage under its own laws and to enforce the national provisions.

No state possesses exclusive rights in the zones designated as high seas and deep-sea floor (or simply “the Area”). At sea, both in the water column and on the seabed of international waters, the principle of freedom of the high seas is in effect. An exception to this is the research and exploitation of mineral resources on the sea floor. These activities are subject to regulation and oversight by the International Seabed Authority (ISA), which is based in Kingston, Jamaica.

The storage of carbon dioxide in the marine subsurface of the high seas, on the other hand, falls under the regime of the high seas. This gives every state the basic right to inject and store carbon dioxide in the subsurface in international waters.

Aspects of marine protection under international law
By signing the UN Convention on the Law of the Sea, all Parties have committed to protecting and preserving the marine environment. The provisions laid out in the Con-

vention apply to all marine zones and are chiefly aimed at preventing pollution of the sea. There is now an overwhelming consensus that the precautionary principle should apply. This means that the requirements for marine environmental protection are in force when the mere possibility of pollution is present.

For a long time, it was questionable whether the injection of carbon dioxide into the marine subsurface should be considered as pollution of the seas or dumping of substances. However, these questions were resolved at the international level in 2006. Since that time, the Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter – which specifies the standards of the Convention on the Law of the Sea – has permitted the underground storage of carbon dioxide on the continental shelf of a coastal state and in other areas of the marine subsurface, provided permission is given by the appropriate authority under the relevant national law.

In order to meet the requirements of the precautionary approach, the signatories agreed to develop specific guidelines for the application of Carbon Capture and Storage. A new annex to the London Protocol now specifies three conditions that must be met when issuing the required storage permit:

- *First,* carbon dioxide may be introduced into subsurface rock formations, but not into the water column.
- *Second,* the stored gas must consist mostly of carbon dioxide.
- *Third,* the addition of other substances to the carbon dioxide intended for storage, with the purpose of disposing of these as well, is prohibited.

The London Protocol requires the Parties to meet these three requirements before the issuance of a storage permit. Moreover, the approval of carbon dioxide storage does not absolve the Parties from making further efforts to reduce the need for undersea storage.

Where the injection of carbon dioxide into the seabed is allowed, the responsible state authority must require a listing of all other substances contained in the carbon dioxide stream. Otherwise, it cannot issue a permit. Among other things, the listing must contain information on the composition, form, total amount, origin, properties, toxicity, stability and bioaccumulation potential of all substances. If the required list is incomplete or not sufficiently accurate, such that a full assessment of the risks to human health cannot be made, the injection cannot be approved.

In addition, the London Protocol requires the signatories to draw up a national action list. This should describe how the carbon dioxide stream in question and its components can be tested, for one, with respect to possible impacts on human health and the marine environment. Secondly, threshold values must be established for every substance so that a decision can be made in each individual case as to whether these are met and whether the injection of carbon dioxide can therefore be permitted. If the thresholds are not met, conditions can be imposed or the injection may be prohibited altogether.

The London Protocol also makes stipulations for the selection of the storage site. Among others, the physical, chemical and biological parameters of the water column and the marine subsurface must be evaluated, as well as any special aspects of the site and the economic and operational feasibility. When assessing the potential impacts of carbon dioxide storage, not only must the impacts of injection into the marine subsurface be considered, but also any possible disposal alternatives on land.

The impacts of carbon dioxide storage, and any work associated with it, on human health, the marine environment and other uses in the ocean should be assessed as conservatively as possible, and should also take into account contingencies such as accidents. If the assessment indicates that the impacts are too hazardous, approval should be refused. However, refusal is not mandatory.

If approval is granted for the undersea storage of carbon dioxide, the London Protocol requires the establishment of a monitoring and surveillance programme. This is to ensure that the previously assumed conditions and impacts are actually valid. Permits issued are to be reviewed regularly based on the monitoring results. If the actual developments do not correspond to the prior assumptions, the approval may be revoked.

The signatories to the London Protocol have also adopted a framework for risk assessment and risk management in relation to carbon dioxide storage in the marine subsurface. This specifies the application or implementation of monitoring requirements, and is intended, among other things, to assist official decision-making under conditions of scientific uncertainty. With respect to site selection the framework requires, for example, that storage capacity, storage security, sustainability and potential leakages as well as their effects be documented.

In the assessment of consequences for the marine environment, the sensitivity of native species and the impacts on human health, among other things, should be analysed, and the related temporal and spatial scope must be indicated. With the aid of control measurements within the storage reservoir, in the overlying marine subsurface, and at the seabed, leakages should be recognized in a timely manner and their occurrence avoided through preventive measures, but there should also be advance planning for reaction measures in case of an emergency. Even after shutdown of the borehole, the storage site should continue to be directly monitored over the long term. With growing certainty over time that carbon dioxide is not escaping from the deposit, the frequency of the measurements can be gradually decreased.

May states export carbon dioxide for offshore injection?

Whether carbon dioxide injection into the seabed is permissible at all must be distinguished from the question of whether international law allows sequestered carbon dioxide to be exported to other states for storage. Under Article 6 of the London Protocol the signatories are prohibited in principle from exporting waste and other substances to other states for dumping or incineration at sea or in the sea floor.

Article 6, however, was amended in 2009 with specific regard to the cross-border export of carbon dioxide for the ultimate purpose of storage. Because the amendment has not yet been ratified by a sufficient number of states, it has not yet entered into force. In 2019 the signatories to the Protocol therefore agreed that Article 6 can be applied provisionally.

The provisional application of an agreement in international law, however, requires a corresponding declaration by the individual state. Such a declaration has so far only been submitted by Norway, The Netherlands, Denmark and South Korea. Finland and Belgium are currently preparing these (as of: September 2022). If Germany wanted to export captured carbon dioxide to one of these two states, it would also have to submit the appropriate declaration. Moreover, if applied provisionally, the amended Article 6 of the London Protocol requires the conclusion of a specific agreement between the exporting and importing state.

Based on this legal framework, experts conclude that the signatories to the London Protocol have established all of the legal requirements for the storage of carbon dioxide in the marine subsurface and also that it may be exported for this purpose. Final decisions on the legitimacy of storage and possible carbon dioxide transport, however, will continue to be made at the national level.

How the legal framework will be applied at the national level for member states of the European Union currently also depends on the EU Carbon Capture and Storage Directive. This allows the geological storage of carbon dioxide in the territories of the EU member states, in their Exclusive Economic Zones (EEZ), and in their continental shelves, as defined by the UN Convention on the Law of the Sea. However, every storage project must be approved by the appropriate national authority.

In August 2012, the German government transposed this EU directive into national law in a very restrictive manner, in part in conjunction with the German Carbon

Capture and Storage Act (German: *Kohlendioxid-Speicherungsgesetz, KSpG*). The Act currently presents a two-pronged obstacle to carbon dioxide storage projects in the German North and Baltic Seas. Firstly, it contains a clause stating that proposals for approving carbon dioxide storage must have been submitted by the end of the year 2016. Secondly, the federal legislature grants Germany's federal states the right to exclude certain areas from possible carbon dioxide storage.

The federal states of Mecklenburg-Western Pomerania, Lower Saxony and Schleswig-Holstein have exercised this right to exclude all marine areas under their authority from subsurface carbon dioxide storage. By doing so, they have virtually imposed a ban on underground carbon dioxide storage in the coastal area of the German North and Baltic Seas.

Article 44 of the Carbon Capture and Storage Act requires that an evaluation report be produced every four years on the application of the Act and the national and international experience acquired with regard to Carbon Capture and Storage (CCS). In the current second evaluation report produced in 2022, the authors concluded that the applicable German legal framework at that time prevented the actual application of CCS in practice. At the same time, the report points out that CCS and CCU technology could contribute in varying degrees to Germany achieving its goal of greenhouse-gas neutrality by the year 2045.

The importance of procedures for carbon capture and storage, or subsequent processing, is currently (as of: summer of 2023) being discussed in the debate on a German carbon management strategy. This strategy shall include the determination of potential areas of application for CCU and CCS technology as well as the development of economic and regulatory frameworks for its rapid and large-scale implementation.

In this context, Germany's federal government recommends an expansion and adaptation of the Carbon Capture and Storage Act such that it provides a suitable legal basis for CCS and CCU, from the source of the carbon dioxide to its transport and ultimate permanent storage or use. This legal framework is urgently needed. A draft amendment to the German Climate Change Act stipulates that the storage of carbon dioxide deep underground should become an integral part of national climate policy and that, for the first time, storage targets should be set for the years 2035, 2040 and 2045 (as of: June 2023). The goals of climate protection, which include greenhouse-gas neutrality by 2045 and net carbon dioxide removal after 2050, should also be enshrined in the Act.

Pressure for action also comes from a new initiative of the EU Commission. In March 2023, the Commission announced its intention to establish by the year 2030 geological capacity for long-term storage of 50 million tonnes of carbon dioxide. The plan is part of the new Net-Zero Industry Act of the Commission, in which CCS is identified as a bridging technology for sustainable development.

In the proposed legislation, the Commission would require European Union member states to publish timely data on areas where carbon dioxide storage sites could be approved, and to report annually on the progress made in developing carbon dioxide storage projects in their territories. The necessary exploration and development work would be undertaken and financed by oil- and gas-producing companies. Simply put, this means that oil and gas producers are held accountable by policymakers. The companies rather than the states should explore more geological reservoirs to ensure the necessary storage capacity for at least 50 million tonnes of carbon dioxide per year.

The reactions to this proposed legislation were divided. While proponents of CCS welcomed the initiative, critics pointed out that it is much more important to fundamentally restrict the generation of greenhouse gases. All efforts should therefore be directed toward appropriate technologies and changes in behaviour rather than relying on CCS.

One thing is certain: the political and societal debates on CCS will continue in the coming months and years, and will very probably lead to new regulations and laws, particularly in Germany.

Conclusion

Carbon dioxide storage beneath the sea – a controversial practice on the horizon

Carbon dioxide can be captured either directly from the air or from exhaust streams. Both approaches are now playing an increasingly important role in the development of climate policy. Their application is hoped to offset residual emissions from industry and agriculture that are difficult to avoid, or to prevent their release in the first place. Moreover, carbon dioxide removal methods like widely-discussed combined electricity and heat production in biomass-fired cogeneration plants can similarly only contribute to offsetting emissions if the carbon dioxide produced during combustion is captured and then further processed into durable products, such as carbon fibres, or is safely stored. Carbon capture and storage (CCS) technology is therefore of vital importance in achieving the goal of greenhouse-gas neutrality by the year 2050.

The number of capture facilities operating worldwide is steadily increasing, but it is uncertain where the carbon dioxide that is removed can be permanently stored. Experts agree that most of the gas cannot be further processed over the long term, but instead must be stored, preferably underground in rock layers that are sealed by an impermeable cap rock to prevent the carbon dioxide from escaping upwards. On land, there is strong resistance to such storage plans in many locations because the injection of carbon dioxide could increase the risk of earthquakes and of groundwater pollution.

Experts are therefore now directing their search for suitable storage rocks more toward the marine subsurface. The two most promising candidates here are sandstone formations and the porous upper basalt layer of the ocean crust. The technology for carbon dioxide storage in sandstone formations has been implemented successfully since 1996, mostly in Norwegian waters. To date, carbon dioxide has only been injected into the upper ocean crust in Iceland, because the basalt rocks there rise above sea level and are thus easily accessible. In contrast, there is still much that is not known about the storage potential of basalt rocks in the deep ocean subsurface. This is now being studied in various research projects.

One fundamental difference, however, is already known: Carbon dioxide injected into sandstone may linger for many thousands of years in the pore waters of the rock before it mineralizes and is safely bound in solid form. In the more reactive basalt rocks, on the other hand, the processes that facilitate mineralization operate much more rapidly.

Carbon dioxide injection beneath the sea is not without its risks. Reservoirs must be thoroughly investigated, carefully selected, and ultimately monitored for an extended time and in an environmentally responsible manner (noise). Furthermore, under some circumstances the injection of carbon dioxide may also conflict with other kinds of marine utilization in the area.

Legally, carbon dioxide storage under the sea is regulated, for the most part, by new guidelines in the Protocol to the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol). For example, it establishes what may be injected and how the monitoring of the storage site should be ensured. The final decision on approval of proposed projects, however, rests with the national authorities who are responsible for implementing the London Protocol at the national level.

9 Key principles and rules for the use of marine CDR procedures

> There is no longer any doubt that humanity must remove carbon dioxide from the atmosphere if it is to achieve its climate targets. However, this removal must meet exacting requirements: neither nature nor people should be harmed, and the removal should be permanent and have a positive climate impact at the same time. Initial propositions, principles and regulatory approaches have already been developed, but the debate has only just begun.

How to regulate increased CO_2 uptake by the ocean?

> Humanity faces a dilemma. Having ignored the threat posed by climate change for decades, we now need solutions more urgently than ever. Ocean-based methods to remove carbon dioxide from the atmosphere may help us to offset a proportion of our residual emissions. However, implementing the corresponding measures in a controlled, fair and responsible manner is a mammoth task. As the conservation and management of the oceans are only possible on a collective basis, clearly defined international rules and principles are essential.

Unaccustomed dynamics

Right now, the increasingly dramatic impacts of climate change are creating unaccustomed parallels between political and scientific processes. To take two examples: in Germany, the government is already consulting an array of experts on amending the legal frameworks to enable deep subsea storage of carbon dioxide, while marine scientists are in the process of assessing the suitability of geological formations beneath German waters as potential storage sites and developing appropriate monitoring systems. Meanwhile, one of the topics being discussed at the international level is which removal and storage options may be eligible for certification, although there is still no scientific consensus on the length of time that must elapse for carbon dioxide removal and storage to be classed as genuinely permanent and therefore climate-relevant.

In politics and business, the hope appears to be slowly growing that through the use of carbon dioxide removal (CDR) methods or the capture and storage of carbon dioxide from fossil sources (CCS), it will be possible to claw back the time wasted by our decades of constant foot-dragging on effective climate action. With so much pressure to take action, the much-needed social debate on the use of ocean-based CDR is falling short. This much is already certain: this is not an easy debate, for there are numerous aspects to consider.

On the one hand, we face the increasingly urgent need for drastic emission reductions. On the other, there are justified concerns about marine and species conservation, and about potential utilization claims and conflicts. On top of that, there are issues of climate and distributive justice. And finally, a further task is to establish legal frameworks and develop institutions and mechanisms to steer and control the possible use of ocean-based CDR methods.

It is almost impossible for casual observers to keep pace with the scientific and political debate about CDR methods. Almost every week, new scientific findings or new policy strategies, recommendations and debates emerge at both the national and the international level. In most cases, it is not immediately foreseeable which role these findings and strategies will play further down the line. Seemingly innocuous technical details may acquire immense significance – for example, when it comes to the question of how much time must elapse for carbon dioxide storage to qualify as "permanent". Some experts are proposing a minimum period of 200 to 300 years. Others argue that removal with subsequent storage for 50, 60 or 100 years helps to offset emissions in the short term; in their view, this makes an important contribution and should be supported through the allocation of subsidies or the granting of time-limited removal certificates, for example.

This chapter can therefore do no more than provide a snapshot of the current state of knowledge and debate. We are guided by the following questions. Should ocean-based CDR methods be deployed if they prove to have a positive impact on the climate? And if the answer is yes, which legal and policy instruments may be suitable for steering and regulating their use – and who are the key stakeholders in this process?

The ocean is not an untouched void

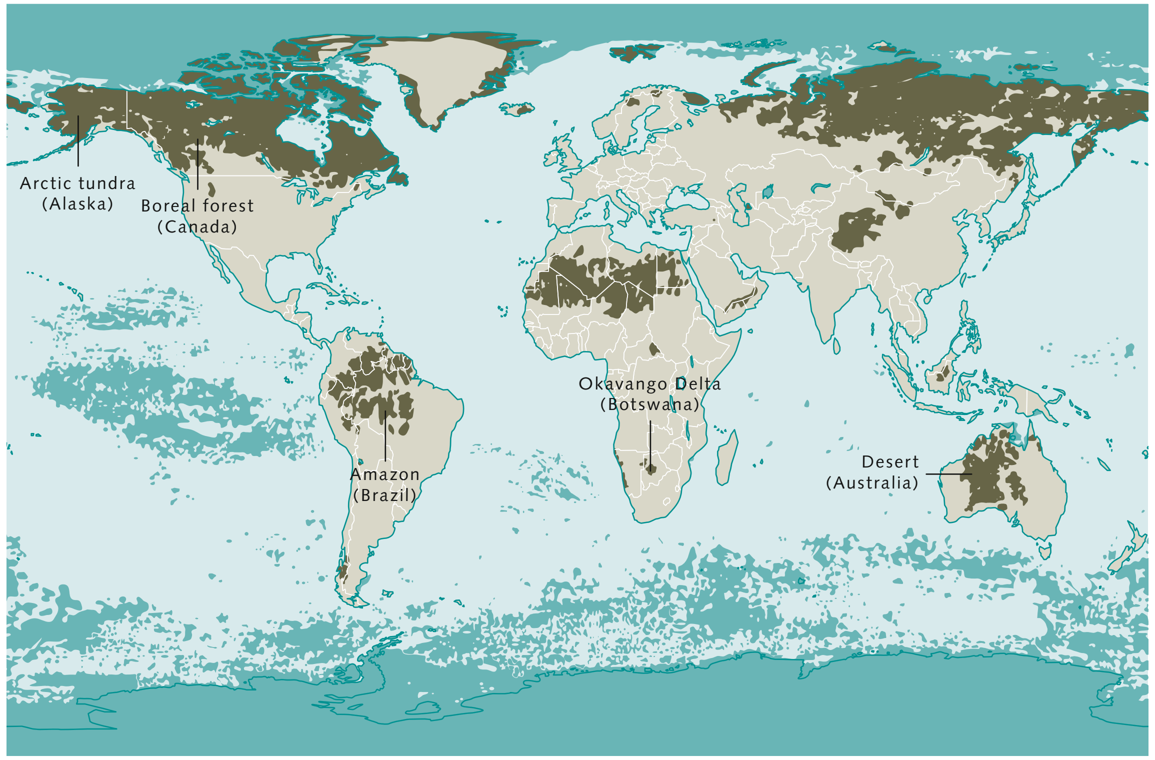
In early June 2023, a leading British daily newspaper published a passionate appeal against over-hasty use of marine CDR procedures. The main argument put forward was that the ocean is viewed by a growing number of politicians and corporate stakeholders as a vast empty space and hence as an untapped resource, ripe for human exploitation and, with a large measure of inventiveness, for transformation into something useful.

This is an extremely dangerous view, the article continued. Firstly, it ignores the ocean's central role in ensuring the continued existence of life on Earth. And secondly, it overlooks the close linkages between physical, chemical and biological processes in the sea, as well as the fact that marine organisms are already under pressure. Any use of CDR methods will therefore bring about changes in the marine environment on a scale that is almost impossible to predict precisely because we do not yet understand how all these processes work and interact.

As scientific observers of the political debate about marine CDR procedures will confirm, proponents of increased use of ocean-based CDR often argue that the ocean is a realm of unlimited possibilities and that its use to offset emissions creates fewer problems and conflicts compared with land-based measures. An aspect ignored by these supporters of ocean-based CDR, however, is that the world's oceans are already an intensively used space and that the human footprint is visible in almost every marine region. For example, a study published in 2018 revealed that by that point in time, 87 per cent of the ocean had already been modified by human activities. Only in the Arctic and Antarctic oceans were there a few remaining areas of marine wilderness which, by then, had seen little or no fishing and no shipping and where there was still no evidence of chemical or plastic pollution.

The prospect of industrial-scale use of ocean-based CDR methods also awakens fears that coastal waters could be privatized for commercial purposes, with displacement of local communities. These concerns have

The few spots of wilderness remaining worldwide



9.1 > The search for genuine wilderness on Earth will soon be futile: 77 per cent of land (excluding Antarctica) and 87 per cent of the ocean has already been modified by human interventions in the natural environment.

9.2 > Stilt fishing is a centuries-old tradition in Sri Lanka and a source of food and income for many artisanal fishing families. Their claims to the sea must be taken into account when the use of CDR methods is considered and discussed.

sparked an international debate about "ocean grabbing", demonstrating just how important issues of distributive and climate justice are in this context as well.

A possible framework for discussion – nine propositions on the ethics of CDR

The current scenario, then, is as follows: intensive use by humans has already modified large areas of the ocean and its biocoenoses. At the same time, the mounting impacts of climate change compel us to take effective mitigation measures at long last – with the aid of the ocean where possible. This dilemma, philosophers argue, raises two crucial moral questions for our society: if CDR methods can contribute to the mitigation of climate change, does this mean that we should actually deploy them? And which of the potentially feasible methods are permissible or, indeed, imperative? German climate and environmental ethicists have attempted to encapsulate this philosophical debate in the following nine propositions which serve as a framework for discourse in society:

1. **A generalized assessment of CDR methods is not possible – instead, a nuanced approach is required.**
   In the philosophers' view, there is neither a convincing argument justifying CDR methods in all cases and contexts, nor a convincing argument proving that the use of these methods should never be permitted. The potentially positive climate impact of these methods is of such moral significance that a considerable number of practical CDR projects are probably permissible or even imperative from a moral perspective.

2. **An overly cautious approach misjudges the threat posed by climate change.**
   Climate change has the potential to become one of the most cataclysmic disasters in human history. Furthermore, the ethicists say, the hazardous effects of climate change are no longer a future scenario; on the contrary, in many parts of the world, they are already harsh reality. Nevertheless, humankind can still take action to curb climate change. A non-interventionist position, by contrast, is less convincing: there is far too much at stake for that. If CDR methods should indeed prove suitable as a means of lessening the immense threat posed by climate change, this would weigh heavily in favour of their use. Negative spillover effects and other concerns should be measured against the potential benefits of using CDR methods. In the ethicists' view, understanding that in order to mitigate climate change, it may be morally imperative to deploy measures that are themselves morally problematical means having a clearer understanding of the tragic predicament into which humankind has manoeuvred itself by failing to take more timely and resolute action.

3. **An insufficiently cautious approach underrates the risks associated with CDR methods.**
   Nevertheless, from a moral perspective, humankind does not have carte blanche to undertake climate-regulating interventions in the ocean, for two reasons. Firstly, other options are available to us. There is scope to achieve larger emissions reductions and to invest more resources in adaptation. And even hard-to-avoid residual emissions could be avoided if, as a society, we were willing to pay the price for this, both economic and non-economic. And secondly, CDR measures could have knock-on effects that are highly problematical from a moral perspective. As CDR methods may differ considerably, the extent to which this applies to each method varies. A nuanced assessment of individual methods and specific usage scenarios is therefore required, the experts say. And as they point out, the moral situation is complicated by the fact that the people who may be impacted by the use of CDR methods are not necessarily those who are otherwise at risk from climate change itself. The message here, then, is that even the most serious condition (the impacts of climate change) does not justify administering every potentially beneficial remedy (use of CDR methods) if third parties are harmed as a result.

4. The use of CDR methods must not hinder decarbonization.

Highest on the list of priorities, from a moral perspective, is decarbonization, which ultimately means the avoidance of anthropogenic greenhouse gas emissions. In this context, one argument often put forward in the debate about CDR measures relates to "mitigation deterrence". This refers to the concern that the prospect of CDR methods becoming available, and their subsequent use, could result in humankind making less effort to avoid greenhouse gas emissions. While climate researchers present very clear arguments showing that avoiding emissions is a much more effective method to limit global warming than removing carbon dioxide from the atmosphere after it has been emitted, the ethicists draw attention to another important moral question which they see underlying this debate – namely the issue of which emissions may legitimately be offset by CDR measures and which may not. In the philosophers' view, certain forms of offsetting may well be morally acceptable as a transitional solution – notably for particularly hard-to-avoid residual emissions in food production and cement manufacturing.

9.3 > Toxic algal blooms caused by eutrophication of coastal waters are becoming increasingly common and can cause mass fish die-offs. Successful human intervention to minimize these additional stress factors would improve the health of the ocean and increase its natural carbon dioxide uptake.

5. Climate change is a major environmental disaster – and not the only one.

Climate change is an environmental disaster which gives rise to major global injustices and may provide moral justification for the use of CDR methods. Nevertheless, the goal of greenhouse gas neutrality is not the only imperative at present, the ethicists say. In view of the sixth mass extinction which is occurring at the same time (more on this topic in Chapter 1), ecological neutrality must be the goal, in their view. In other words, climate change mitigation and its technologies must notcome at the cost of environmental and species protection. These two dimensions require joined-up thinking in order to preserve our planet's natural resources and identify a solution to the environmental crises.

6. CDR measures that also support nature conservation deserve particular consideration.

Precisely because the climate and the biodiversity crises can only be solved in tandem, measures that are compatible with nature conservation goals and simultaneously achieve a positive climate impact deserve particular consideration, the experts say. Morally speaking, these are "low-hanging fruit"; in other words, there are strong arguments in favour of these measures from multiple perspectives. It is essential, therefore, to investigate and leverage their potential.

7. The burdens resulting from the use of CDR methods should be shared equitably.

The use of CDR methods will undoubtedly give rise to burdens, the experts note. Firstly, economic resources (money, energy, raw materials, etc.) will be consumed; and secondly, any use of CDR on a global scale will likely have substantial negative side-effects as well. Who will these burdens fall on? This is a key issue of distributive justice in the context of carbon dioxide removal measures. At this juncture, the ethicists point to the "polluter pays" principle and propose that the

9.4 > Long condensation trails (contrails) over the North Sea reveal the flight paths taken by passenger aircraft to and from Europe. International aviation is one of the fastest growing sources of greenhouse gases, accounting for around 2.5 per cent of global CO_2 emissions in 2018.

burdens should mainly fall on those stakeholders that have contributed most to the problem of climate change since it first came to light. This, they say, applies first and foremost to the prosperous strata of society, who often, although not invariably, live in affluent countries. It is unacceptable to expect demographic groups that would benefit most from the positive climate effects of the use of CDR to cover the costs – for in the main, these are poor and particularly vulnerable communities.

8. **Procedural equity is important – but challenging in practice.**
The issue of procedural equity plays an important role in the CDR debate. This includes the ambition that CDR methods will not only be transparently researched but will also be implemented fairly, should the situation arise. The requirement for transparent communication is uncontentious, in the ethicists' view. Unless there are compelling reasons against such an approach, the mechanisms and the anticipated and actual impacts of CDR use should be made public so that those affected are able to reach an informed position.
A second and much-discussed requirement is that all stakeholders who may be affected by the possible use of CDR should have the right to make their voices heard in the relevant decision-making processes. However, this raises a number of questions: who qualifies as "affected", and what kind of right to have a say is required – does this mean a right of veto or a weaker option? It can be plausibly argued that at the very least, people who will suffer the negative spillover effects of CDR use and those who will benefit from its positive climate impact count as stakeholders. However, the ethicists argue that the group of beneficiaries may be extremely large and widely distributed in time and space. Involving them in decision-making processes will therefore be very difficult. Yet excluding them is not a convincing approach either. There are therefore good grounds for at least allowing representatives or ombudspersons from communities benefiting from the positive climate impacts to participate in decision-making processes.

9. **The debate reveals our moral failure.**
In the ethicists' view, the climate crisis is not only the result of the emissions produced over the last 200 years; it also stems from the inadequate climate policies pursued in recent decades. There is thus a broad consensus in the field of climate ethics that the hitherto inadequate responses to climate change are morally reprehensible. Our situation, in other words, is characterized by moral failure. Nevertheless, there is still an opportunity to respond in a morally acceptable way to climate change, at least from this moment onwards.
The unwillingness to talk about responses to climate change that are themselves morally problematical is understandable, the ethicists say, but it fails to do justice to the situation. A key challenge for a moral debate about the use of CDR methods is therefore to acknowledge the severity of the situation without falling into fatalism, the sense that "we can do whatever we like today because it will all be too late tomorrow".

Key principles for the governance and regulation of CDR methods

Based on this philosophical line of argument and a wealth of information from the environmental and social sciences, researchers have developed four key principles to guide the governance and regulation of land- and ocean-based CDR. According to these principles,

- the reduction and avoidance of greenhouse gas emissions should be prioritized in all decision-making,
- the climate effectiveness and permanence of carbon dioxide removal should always be ensured,
- the environmental integrity of the corresponding measures should be considered, and
- potential goal conflicts should be managed.

Prioritize emissions reduction

Given that removing carbon dioxide from the atmosphere does not address the real cause of climate change (high greenhouse gas emissions), the goal of emissions avoidance must be prioritized in all climate policy decisions, for three reasons. Firstly, preventing the emission of one tonne of carbon dioxide limits global warming far more effectively than removing the same amount of carbon dioxide from the atmosphere. This is due to the multiple interactions in the Earth's climate system. Secondly, merely removing carbon dioxide certainly does not mean that the gas will not escape back into the atmosphere and affect the climate at some future time. And thirdly, the removal of carbon dioxide from the atmosphere or the ocean by technological means necessarily involves the use of energy and resources and may undermine environmental goals. It also releases additional amounts of greenhouse gases, limits opportunities for emissions avoidance or takes up areas (of the sea) that could be used for other purposes.

For this reason, climate policy-makers must ensure that emissions avoidance and reduction are prioritized at all levels. A key step would be to require governments to list their carbon dioxide removal targets separately from their emissions reduction targets, so that it can be determined at any time whether sufficient efforts have been invested in avoiding emissions.

A clear differentiation must be made in the corporate sector as well: firms should not be permitted to use CDR measures as they see fit in order to offset avoidable emissions. Otherwise, emission reductions could all too easily be neglected in favour of offsetting measures – a strategy known as "mitigation deterrence" in the debate about CDR. This can be prevented by stringent

9.5 > The Earth's coastal zones are some of the most intensively used landscapes on our planet. Measures to increase carbon dioxide uptake by the ocean would constitute a further intervention which, depending on the method, may benefit, limit or even preclude other forms of use.

rules in European emissions trading, among other things. Without a more rigorous focus on prioritizing emission reduction measures, the experts conclude, there is a fear that efforts to tackle the causes of the climate crisis will decrease.

Effective and permanent carbon dioxide removal

As carbon dioxide can linger in the atmosphere for very long periods of time while continuing to affect the climate, it is essential to ensure, when CDR methods are applied, that the removal of carbon dioxide from the atmosphere is permanent wherever possible. If this cannot be guaranteed, potential leakage pathways along which the removed carbon dioxide can escape back into the atmosphere must be considered in decision-making – for example, by accounting for these deductions when inventorizing carbon dioxide removals. In the experts' view, carbon dioxide storage sites must be continuously monitored, and funding for this monitoring must be secured for the long term. In order to assess the specific contribution of a given method to carbon dioxide removal, all greenhouse gas emissions that are caused indirectly must also be accounted for. This includes emissions from transport and the manufacturing of precursor products, but also from the generation of the energy that is used.

Comprehensively assess CDR methods – from a climate, environmental and social perspective

The use of marine CDR methods consumes energy, resources and space. In some cases, it may adversely affect coastal areas and their ecosystems or, indeed, the ocean as a whole, particularly if the methods are to be applied on a global scale. It may also have potentially negative social impacts which can arise if human communities that are heavily dependent on marine resources are suddenly no longer able, or are no longer permitted, to access them to the full extent. The impacts of a technology may often also vary according to local conditions.

For these reasons, CDR methods should not only be assessed in terms of their potentially positive climate impact. Their effects on people and the environment must also be comprehensively reviewed – the experts are almost unanimous in voicing this demand. What is lacking at present, however, are adequate strategies for achieving this goal. One proposal is to set minimum criteria for specific technologies or groups of technologies to ensure the intervention's climate effectiveness and minimize possible environmental impacts and resource consumption. Experts from a German research mission are currently developing review guidelines which are intended to aid decision-makers in conducting this type of assessment of CDR methods and specific projects.

Successfully resolve or avoid goal conflicts

On their own, however, minimum criteria will not be sufficient as a steering mechanism to resolve or avoid the goal conflicts that will arise from the use of interventionist, resource-intensive CDR methods. The problems associated with the climate and biodiversity crises and, simultaneously, the ongoing overexploitation of our natural resources are far too complex for that, the experts say. It is crucial, therefore, to conserve the spaces and resources that we have left, or at least to use them as efficiently as possible. Should there be a case, nonetheless, for resorting to minimum criteria for the governance and regulation of CDR measures, these criteria must be regularly reviewed and amended to bring them into line with the best available science and technology. And on a cautious note, the experts point out that it is also important to consider, from the outset, the option of exiting from less sustainable methods and consistently implement this approach if a method proves to have adverse effects.

It may be expedient to hold a competition in order to identify the most sustainable solutions, which should then be integrated into the criteria-led selection or funding of the methods concerned. Here, it is essential to consider not only the climate-specific advantages and disadvantages of all the natural and technological CDR options but also the positive impacts on biodiversity and ecosystems. As a desired outcome of this approach, the measures selected should mainly be those which strengthen natural carbon sinks, thus generating additional benefits for ecosystems.

What is needed is a clear strategy for managing residual emissions. The fact is that the use of CDR methods on the required scale cannot be organized as an afterthought: it will take time and will require targeted incentives, international cooperation and clear rules for all stakeholders. Consistent implementation of the key principles outlined above may help to ensure that carbon dioxide removals from the atmosphere make an additional contribution to combating the climate crisis without worsening the existing environmental crises. Under these circumstances, any delay in reducing avoidable emissions must be ruled out; the same applies to any further weakening of terrestrial and marine ecosystems through the use of CDR.

Existing regulations on marine CDR procedures

Procedures for the removal of carbon dioxide from the atmosphere have featured as a topic in various international bodies and negotiations at least since the signing of the Paris Agreement in 2015, although the Agreement itself does not refer specifically to carbon dioxide removal and its possible regulation. The main focus of the Agreement is the mitigation of greenhouse gas emissions and the goal of global greenhouse gas neutrality in the second half of this century. The text of the Agreement leaves unanswered the question of how the desired "balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases" is to be achieved. Nor does it differentiate explicitly between natural sinks (terrestrial vegetation and ocean) and technological sinks. According to expert opinion, therefore, the Paris Agreement does not give rise to a legal obligation to perform technical procedures for carbon dioxide removal.

If the Paris Agreement is in future to serve as a global regulatory framework for carbon dioxide removal methods – which is entirely conceivable – the Parties would have to adopt a corresponding amendment to the existing Agreement or agree its revision by passing resolutions at the annual Conference of the Parties. To date, only the Article 6.4 mechanism has been negotiated in earnest. Its purpose is to establish a regulatory framework specifying the conditions for the issuing of emission reduction and carbon removal certificates to countries, companies and individuals, as well as for the trading of these certificates within and between states.

At the present time (autumn 2023), the development of a global regulatory framework for CDR methods under the Paris Agreement seems a fairly unlikely prospect, largely because the individual land- and ocean-based CDR technologies differ from each other in fundamental ways. Developing a common regulatory framework that would be appropriate for all the various CDR methods would be an extremely challenging task. A further factor to consider is that not all countries are in a position to implement ocean-based procedures. Landlocked countries such as Switzerland and Austria have no coastal waters of their own where they would be able to sequester captured carbon dioxide in subsea formations or massively expand the coastal ecosystems. Does this mean that land-locked countries should be excluded from possible negotiations on a global regulatory framework for marine CDR?

International environmental law, too, does not currently include any binding CDR-specific norms which would regulate the exploration and use of these technologies on a comprehensive and overarching basis. Experts doubt that the international community will ever agree on a universally applicable regime for climate engineering in international law that would then also regulate the use of marine CDR procedures. At present, there are two factors mitigating against such an approach. Firstly, the provisions of international environmental law are already highly fragmented. Interventions which, in essence, involve the discharge of substances into the sea are regulated by the Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol). Other techniques, such as the creation of artificial clouds or solar radiation management in the stratosphere, are covered by the Vienna Convention for the Protection of the Ozone Layer and the accompanying Montreal Protocol, or by the Geneva Convention on Long-range Transboundary Air

Climate engineering
The term "climate engineering" describes various human interventions whose purpose is to counteract global warming. They typically include carbon dioxide removal methods (CDR) and solar radiation management measures (SRM). The term "geoengineering" is sometimes used as a synonym for climate engineering.

Pollution. Secondly, most efforts made in recent years to reduce this fragmentation through the development of new overarching treaties have failed. A positive exception is the new global Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Treaty), adopted in June 2023.

Legally binding norms and principles of international environmental law

The thematic area of "marine CDR procedures" is not entirely unregulated at present, however, as various general norms and principles pertaining to the management of the environment – most of which are recognized in customary international law – apply, which would regulate the use of marine CDR procedures both for research purposes and for large-scale deployment to offset residual emissions. They include:

- the prevention principle,
- the notification and consultation requirement,
- the duty to conduct an environmental impact assessment before initiating a planned intervention,
- the precautionary principle,
- the principle of cooperation, and
- the guiding principle of sustainable development.

The prevention principle

The prevention principle is based on the prohibition of significant transboundary environmental harm and imposes a duty on states to take all possible and reasonable measures, prior to a planned activity, to prevent probable transboundary environment harm, and to do so by exercising due diligence. This means that technical standards, such as "best available techniques" and "best environmental practices" must be adhered to.

The notification and consultation requirement

In order to safeguard compliance with the prevention principle, information-sharing and communication are essential. Countries that are planning an intervention which involves a risk of significant transboundary environmental harm therefore have a duty to provide prior and timely notification about these activities to potentially affected countries. They must then engage in consultations.

The requirement to conduct an environmental impact assessment before initiating a planned intervention

Environmental Impact Assessment (EIA) is a statutory multi-staged process involving the timely identification, characterization and evaluation of all the direct and indirect effects of a given project on specific environmental factors, including its cumulative ecological impacts. For projects with transboundary environmental impacts, the environmental impact assessment must be conducted in a cross-border context. It is thus a key element of the prevention principle. However, general international law does not specify precisely which criteria should apply to environmental impact assessments in individual cases. This may, however, be determined from specialized international treaty law, European Union law and/or the national law of the states concerned. The gaps existing at the global level will in future be closed by the provisions of the Agreement on the Conservation and Sustainable Use of Marine Biological Diversity of Areas Beyond National Jurisdiction (BBNJ Treaty), provided that it enters into force. It defines minimum standards for environmental impact assessments which all Parties must comply with in future.

The precautionary principle

The precautionary principle states that the environment is protected most effectively when conceivable harms are avoided from the start. It thus supports risk assessment and takes effect at an earlier stage than the prevention principle, namely as soon as an environmental hazard potentially exists but there is scientific uncertainty about its occurrence. The precautionary principle is enshrined in international treaties in a variety of ways, which hinders its operationalization. A key question, for example, is this: how should states proceed if there is a lack of conclusive scientific certainty about possible risks? Some countries, including Germany, apply a highly restrictive approach in such cases. They tend to start by prohibiting anything that may pose a risk, and then examine, on a case-by-case basis, where there is scope for allowing exceptions. In the US, by contrast, risks are accepted more readily. This involves a trade-off, however: all stakeholders are aware that in the event of any harm being done, they face paying substantial sums in compensation.

Despite these differences, many experts in international law view the precautionary principle as a vital risk management tool. Against the backdrop of climate change in particular, one idea being proposed is to operationalize the precautionary principle as an evaluation mechanism that can be used to manage goal conflicts between various assets that are protected under international environmental law, e.g. between biodiversity conservation on the one hand, and mitigation of climate change on the other. This view is not yet widely accepted, however.

The cooperation principle

According to this principle, environmental protection is a task for all the forces within society; in other words, all governmental and social stakeholders should collaborate in environmentally relevant opinion-forming and decision-making processes.

The guiding principle of sustainable development

The concept of sustainable development was recognized as a guiding principle by the international community at the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil, in 1992. Since then, it has informed environmental law at national, transregional and international level. Sustainable, environmentally compatible development is human-centred in principle. It aims to satisfy everyone's socioeconomic needs and guarantee decent living conditions for all the world's people. However, these goals should not be achieved at the expense of future generations.

A further key element is that due to the close linkages and interactions between them, all the various environmental, economic and social objectives can only be achieved on a sustainable basis through a holistic approach. Economic development and poverty reduction have thus become key topics in international efforts to protect the environment.

9.6 > A parrot and a flower feature on one of several commemorative stamps issued by Brazil's national postal service to mark the United Nations Conference on Environment and Development (Rio Summit) in Rio de Janeiro in 1992.

Individually assessing and regulating ocean-based CDR methods

Based on these six principles of international environmental law and the provisions of the United Nations Convention on the Law of the Sea (UNCLOS), experts identify a need for very detailed regulation of ocean-based methods of carbon dioxide removal. But which specific form should a regulatory mechanism take? That must be assessed and determined for each CDR method on an individual basis. Method-specific answers must therefore be found to a multitude of questions. The most important include the following: where can the method be applied with the least possible risk? What should a prior risk assessment look like? Would it be feasible to suspend a method once it has begun? Are there any best practice examples that would serve as a basis for identifying regulatory approaches? And how can predictable harms be minimized?

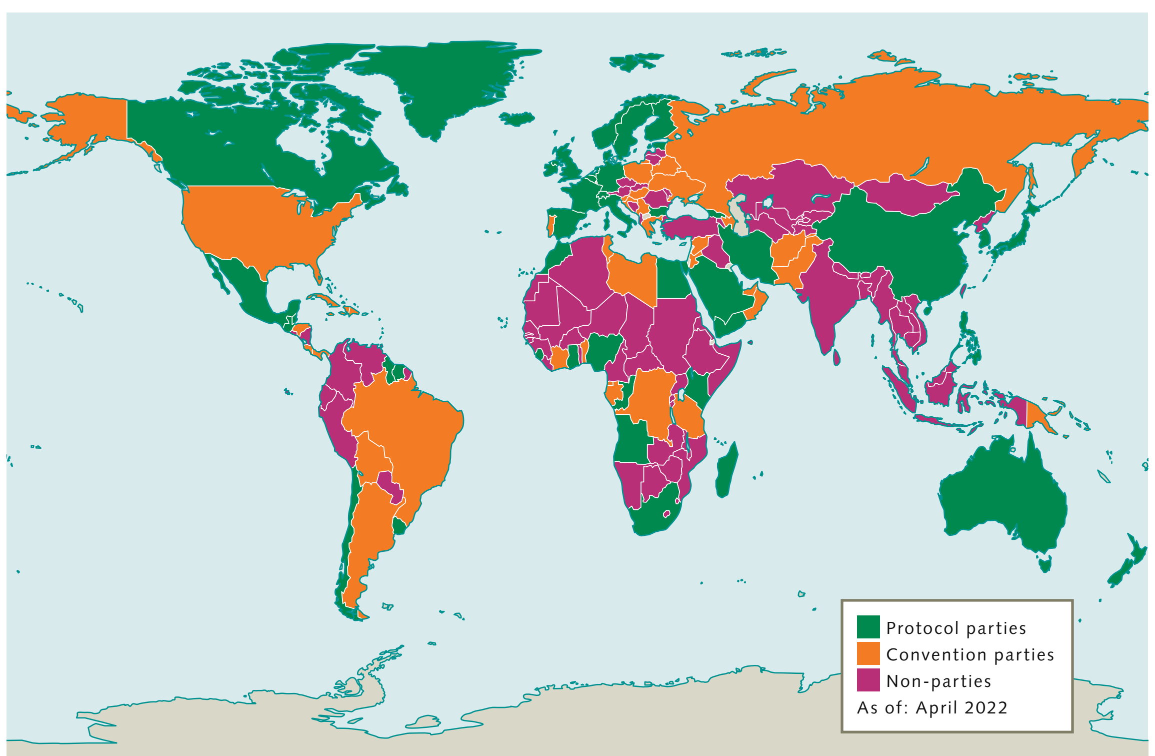
As the answers to these questions will vary considerably depending on the CDR method concerned, legal experts recommend regulating marine CDR procedures separately by integrating them into their respective specific regulatory contexts. This is a feasible approach, as the example of the London Protocol shows. This international agreement, which originally solely covered waste disposal and incineration at sea, is in essence applicable to all activities involving the discharge of substances into the marine environment. This includes technologies to boost the alkalinity of the ocean, as well as artificial upwelling techniques, methods to expand carbon-rich coastal ecosystems, and concepts for carbon dioxide storage in deep sub-seabed formations.

The London Protocol model

The United Nations Convention on the Law of the Sea (UNCLOS) requires States Parties to adopt globally applicable laws, regulations and standards to prevent, reduce and control pollution of the marine environment from the introduction of substances and materials. The international community complied with this requirement with the adoption of the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) in 1972. In 1996, the Convention was amended and modernized by the London Protocol – at least for all 53 States Parties that have so far ratified the Protocol, enabling it to enter into force in 2006. The provisions of the London Protocol follow a clear logic: in essence, any discharge of materials and substances is prohibited. However, there is scope for exemptions from this provision where convincing grounds exist.

The London Protocol has its own scientific working groups whose members monitor international developments in marine and environmental policy and make recommendations to Parties on the extent to which the Protocol would need to be amended in order to guarantee

Scheme of parties to the London Convention/Protocol



9.7 > The London Convention and its additional London Protocol have not yet been ratified by all countries. The scheme shows which countries had acceded to the Convention/Protocol by April 2022 and which had not.

that a scientifically informed regulatory framework is in place. In this way, legal principles and procedural rules on carbon dioxide storage in sub-seabed formations were introduced in 2006. This was followed three years later by further provisions specifying the conditions under which countries with no sub-seabed carbon dioxide storage sites of their own may export the captured greenhouse gas for the purpose of sub-seabed storage in other countries. Due to an insufficient number of ratifications, these latter provisions have not yet entered into force; however, Contracting Parties have agreed to allow provisional application of these provisions. To that end, they must deposit a formal declaration with the International Maritime Organization (IMO), which is the Secretariat for the London Protocol.

Legal developments which came about between 2008 and 2013 are of key importance for any future regulation of marine CDR procedures under the London Protocol, however. Initially, they related solely to ocean fertilization activities. At the time, there were serious concerns that companies might apply this technique on a large scale in pursuit of their commercial interests, without sufficient knowledge being available on how the methods might work and what kind of risks they posed to the environment. In 2013, a formal amendment to the London Protocol was then adopted which, provided that it enters into force, will potentially be applicable to all marine geoengineering methods. It brings together the following key amendments in particular.

Firstly, marine geoengineering interventions were included in the Protocol's scope of application. A new article now defines "marine geoengineering" as "a deliberate intervention in the marine environment to manipulate natural processes, including to counteract anthropogenic climate change and/or its impacts, and that has the potential to result in deleterious effects, especially where those effects may be widespread, long lasting or severe". Nowadays, the term "marine geoengineering" is considered obsolete, but in essence, it refers to marine CDR procedures.

Secondly, the Contracting Parties agreed to establish an approval process, initially for scientific research only. At the present time (autumn 2023), commercial uses of ocean-based CDR methods aimed at offsetting greenhouse gas emissions from fossil sources are still prohibited. And even the fundamental willingness to assess research projects is strictly limited: it merely encompasses those ocean-based CDR methods which are listed in a new annex to the Protocol, namely Annex 4. Ocean fertilization is, however, the only activity included in the listing at present.

For research projects on ocean fertilization, the London Protocol's Contracting Parties agreed a clearly defined assessment process back in 2010, which was formally integrated into the London Protocol with its amendment in 2013. The assessment process must be integrated by the Contracting Parties into the approval procedures conducted under their respective national laws and entails the following:

1. an assessment of the proposed project in order to determine whether a proposed activity is covered by the listing in Annex 4 and is thus eligible to be considered for evaluation as a research project;
2. a detailed environmental impact assessment of the planned research project;
3. a decision on whether the given experiment may be conducted or not;
4. subsequent review of the project; the findings should inform future decision-making and improve future assessments.

This assessment process relies heavily on elements of risk characterization and risk management; in essence, the London Protocol states that marine researchers may conduct experiments on ocean fertilization if they are able to clearly estimate the potential harm and apply appropriate precautionary measures for its prevention. In all cases, however, they require a government permit for their research projects. The assessment process thus embodies and implements the precautionary principle and forms an indirect link between the international law of the sea and international environmental law. The key principle which applies here is: "If the risks and/or uncertainties are so great that they are deemed to be unacceptable in terms of protecting the marine environment with due regard for the precautionary principle, a decision should be taken to review or reject the proposal."

But which risks or uncertainties may be deemed unacceptable? The provisions of the London Protocol do not provide clarification here. According to experts in international law, this circumstance and the explicit reference to the precautionary approach show that the assessment process may be informed by recourse to the stipulations of international environment law, as well as by social policy discourses that extend beyond the purely legal aspects.

It is also important to note that planned research projects are not assessed by the London Protocol's own international experts. This task and the final decision on whether a permit will be issued are a matter for the authority responsible for implementing the London Protocol on behalf of the Contracting Party under whose jurisdiction the experiment would be conducted. In the case of a project by German marine researchers, for example, this would be the German Environment Agency (UBA, *Umweltbundesamt*).

The competent authority at the national level, in turn, must respect the stipulations of the London Protocol. One such stipulation is that permission may only be granted to research projects which comply with all the provisions of the Protocol. Legal scholars term this a decision "ad referendum". In accordance with Article 210, paragraph 6 of the United Nations Convention on the Law of the Sea, the provisions of the London Protocol apply to all States Parties to UNCLOS, not only those which have acceded to the Protocol.

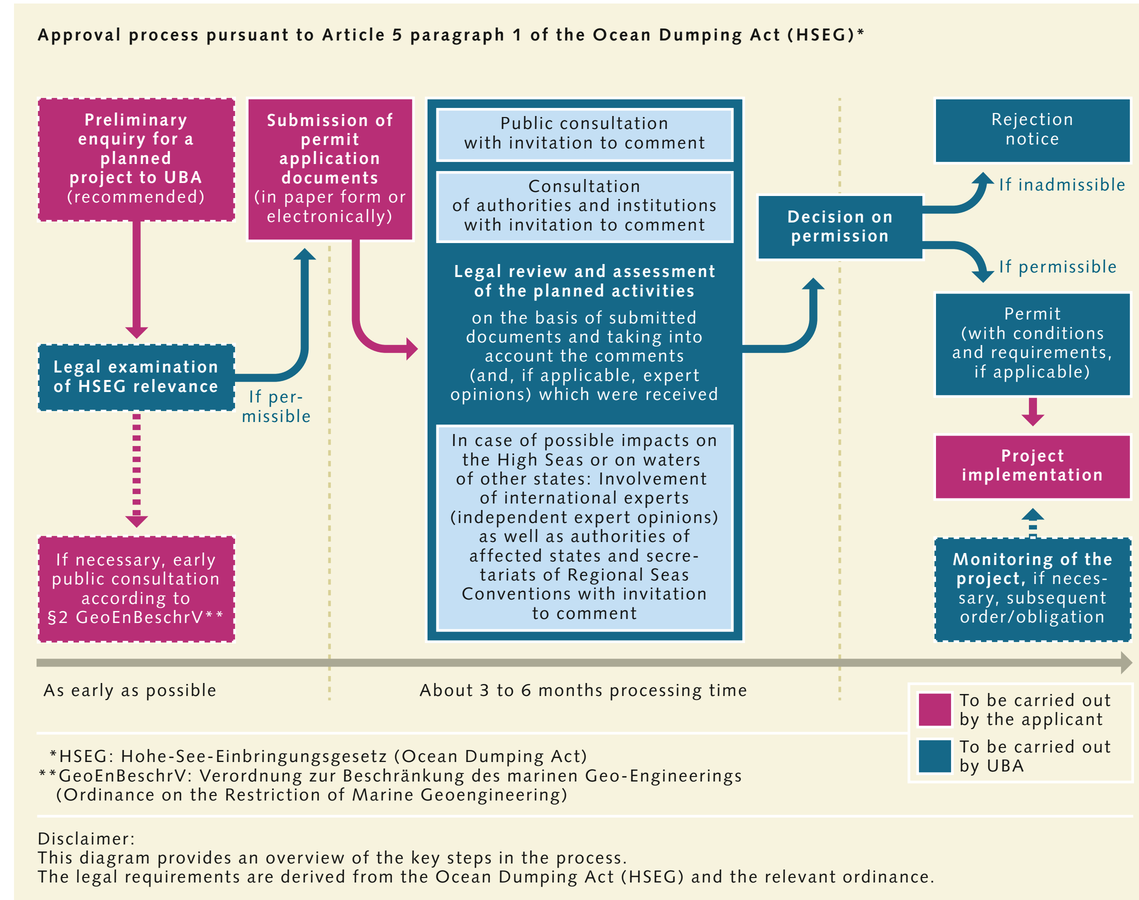
To recapitulate: the regulatory mechanism for marine geoengineering under the London Protocol currently applies solely to research projects on ocean fertilization. In the experts' opinion, however, it would be relatively straightforward to extend this mechanism to other ocean-based CDR methods – firstly, because the regulations on ocean fertilization have already proved their worth; and secondly, because it is quicker to elaborate rules dealing with this type of specific issue than to develop an overarching treaty, thereby enabling all the competent bodies to agree on specific provisions fairly swiftly.

Initial discussions on extending the Annex 4 listing are already under way. Experts from the GESAMP Working Group 41 on Ocean Interventions for Climate Change Mitigation have proposed the inclusion of other procedures to the London Protocol's scientific bodies and developed criteria for method-specific risk assessments. In October 2022, the London Protocol's Contracting Parties identified four of these proposed techniques for priority evaluation. However, only two of them involve carbon dioxide removal. The other two focus on management of solar radiation on the surface of the sea. The proposals involve:

- the application of substances to enhance ocean alkalinity (goal: to increase carbon dioxide uptake by the ocean – CDR),
- macroalgae cultivation combined with artificial upwelling (goal: to increase carbon dioxide uptake by the ocean – CDR),
- spraying tiny seawater droplets on the surface of the sea; this is known as marine cloud brightening (goal: to increase the ability of the sea's surface to reflect incoming sunlight back into space – SRM),
- production of microbubbles in surface water, or introduction of reflective particles/material (goal: to increase the ability of the sea's surface to reflect incoming sunlight back into space – SRM).

If these methods are adopted at any point in future, the corresponding research projects would be assessed in the same way as scientific projects on ocean fertilization.

However, to enable commercial/large-scale CDR interventions to be regulated under the London Protocol, its scope would have to be expanded accordingly. Will the Contracting Parties agree this move? That remains to be seen. So far, not even the 2013 amendment to the Protocol has entered into force. For that, it would have to be ratified by at least two-thirds of the London Protocol's Contracting Parties. Unofficially, however, most Parties operate as if the new provisions were already in force.



9.8 > In Germany, the German Environment Agency (UBA) is the competent authority for permitting and monitoring scientific projects attributed to marine geoengineering and involving intended substance discharges into the oceans. Each of these projects must pass through the application and approval process shown here.

Which stakeholders now come into play?

Regardless of whether or not marine CDR procedures are to be deployed on a large scale at some future time, the international community should do its utmost to establish a common regulatory framework in good time. The world's ocean, with its international waters as the "common heritage of mankind", concerns us all and, like the climate, it can only be protected effectively and managed sustainably on a collective basis. Key steps in establishing a common regulatory framework are accession by as many countries as possible to the London Protocol, and ratification of the agreement and all the amendments already adopted on marine geoengineering. Their respective provisions must then be transposed into national law; this is the responsibility of national governments and parliaments.

According to some experts, market-based incentives are also required. Often, what such statements imply is a call for a market for the trading of carbon removal credits or certificates. Stakeholders would be issued with certificates for their carbon dioxide removals and would be able to sell them on to producers of hard-to-avoid emissions. If this type of market were initiated or carbon removal certificates integrated into the existing emissions trading systems, this might spur countries and companies to boost their investment in the research and application of CDR methods, supporters argue.

The German Environment Agency (UBA) and other experts, for their part, criticize proposals that would enable emitters to offset their emissions, whether hard-to-avoid or not, by purchasing CDR certificates. These mechanisms, they argue, could deter companies from reducing their avoidable emissions – particularly if that required high-cost interventions. Instead, carbon dioxide removal interventions should be accounted for separately from emissions trading, and the use of removal certificates for the purpose of fulfilling emission reduction commitments should not be permitted. Stakeholders that voluntarily engage or invest in carbon dioxide removal could be given support in the form of government subsidies, for example. However, these funds should only be disbursed if the CO_2 removals are properly certified.

Notwithstanding the above, anyone intending to issue emissions certificates for a specific carbon dioxide removal will require a harmonized procedure to measure, document and verify the actual carbon dioxide fluxes in a removal project. Successfully establishing a harmonized system worldwide would make it possible to reduce legal uncertainties, prevent abuse and introduce appropriate environmental standards for CDR methods.

There are high expectations of the scientific community as well. Scientists should provide core data as the basis for the proper conduct of the environmental impact assessments stipulated by the London Protocol. They are also tasked with developing concepts and technologies for a reliable monitoring, documentation and verification system, which is fundamental for the issuing of emissions certificates. In addition, all the findings must be shared in a transparent and timely manner with decision-makers and the general public alike.

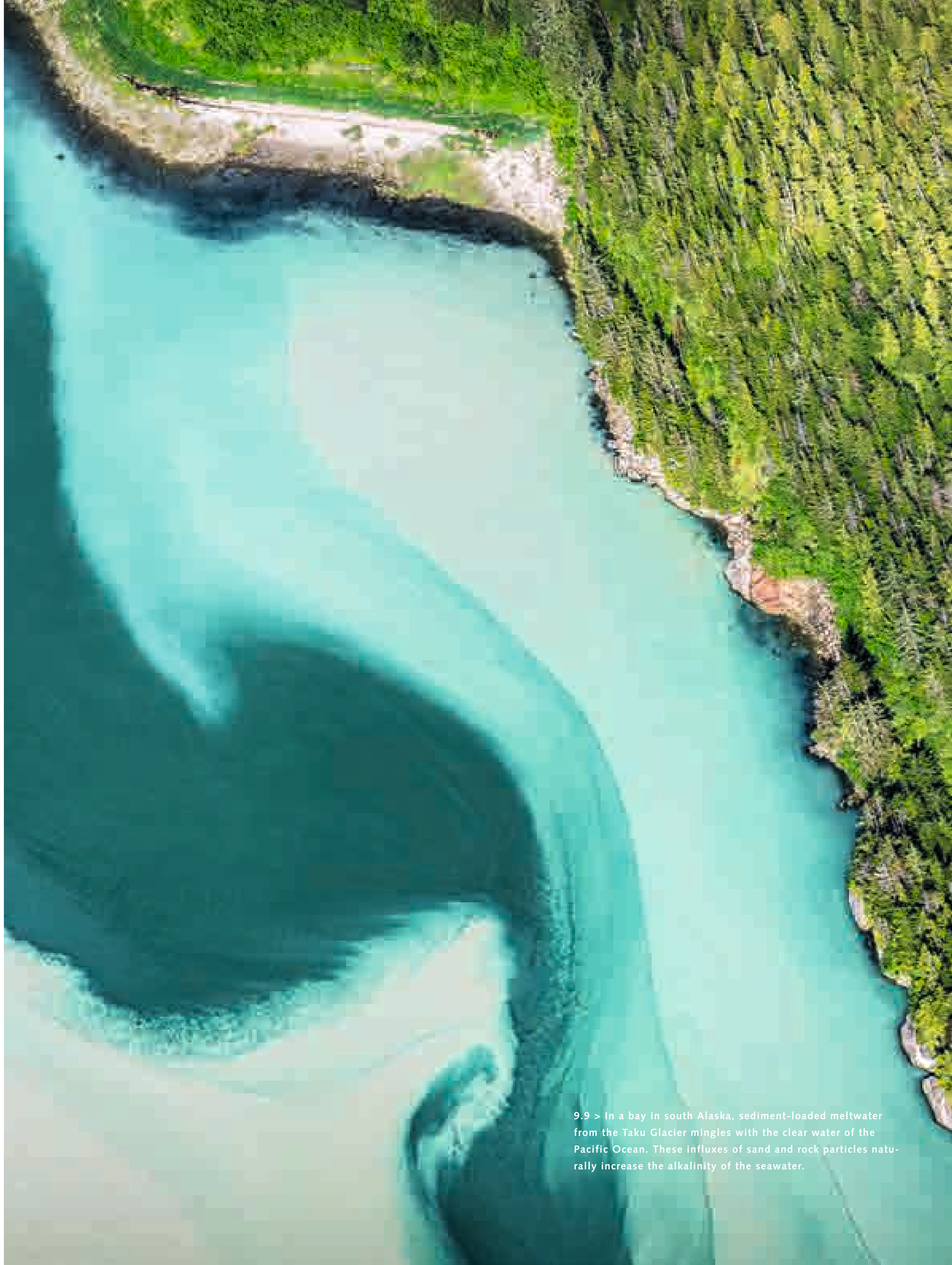
A long overdue public debate

A far more intensive public debate is also required, however, focusing on whether humankind should intervene in the ocean system for the purpose of mitigating climate change, and if so, which risks and harms we are willing to accept to achieve this objective and how we intend to compensate those affected. This highly significant social debate is not yet taking place. It is unclear, therefore, how the public would react to various CDR methods or to specific plans for their deployment.

Researchers note that when forming an opinion, people are often led by their emotional responses to interventions in nature rather than by rational arguments. In many cases, opinion-forming is also coloured by a close attachment to social norms. People's positions on CDR will depend, among other things, on whether they perceive a technique to be "natural" or "unnatural". For example, if the capture of carbon dioxide from the ambient air and its subsequent storage are described as "removal by artificial trees", the method will encounter far more support than if it is depicted as a chemical process in a technical installation. When it comes to ocean-based CDR techniques, experience shows that methods involving the restoration and expansion of mangrove forests, seagrass beds and salt marshes or intensive macroalgae cultivation are perceived to be "natural", whereas ocean alkalinity enhancement is more likely to be viewed as unnatural and risky even though this technique is also based on natural processes.

The general level of public awareness of individual CDR methods and the opinions that people form on this basis will be crucial in determining how we move forward with methods to remove carbon dioxide from the atmosphere. It is already clear that the political and social debate about marine CDR procedures will not be easy; firstly, because there are not always clear and straightforward answers that would provide clarity on questions about possible risks; this applies even if these methods are tested in large-scale field trials at some point in the future. And secondly, in view of ongoing global warming and the associated harms, it is surely quite apparent that we have delayed taking effective climate action for far too long and that under the present circumstances, we can no longer preserve the full array of environmental assets. Our overarching goal can only be to reduce greenhouse gas emissions as swiftly as possible and do the best we can to adapt to the new climate in order to minimize the risks it poses to ourselves and the natural world.

To succeed, we must engage in new discussions about the trade-offs arising from the entirely new challenges we face. To take one example: if our society considers it necessary to use marine CDR procedures, we will probably have to accept that this will involve some residual risk.



9.9 > In a bay in south Alaska, sediment-loaded meltwater from the Taku Glacier mingles with the clear water of the Pacific Ocean. These influxes of sand and rock particles naturally increase the alkalinity of the seawater.

The EU Emissions Trading System (EU ETS) – Europe's most effective climate change mitigation mechanism

The European Union is the third largest producer of carbon dioxide emissions worldwide and is simultaneously pursuing an ambitious climate goal: it aims to significantly reduce its greenhouse gas emissions by 2030 and achieve net zero emissions by 2050. A key mechanism on the pathway towards greenhouse gas neutrality is the EU Emissions Trading System (EU ETS), established in 2005. It covers not only the 27 EU Member States but also Norway, Iceland and Liechtenstein, as well as electricity generators in Northern Ireland. The EU ETS has also been linked to the Swiss emissions trading system since 1 January 2020.

The EU ETS enshrines the "polluter pays" principle and currently requires operators of around 9000 European power plants and energy-intensive industrial installations, as well as intra-European aircraft operators (since 2012), to submit an emission allowance for each tonne of greenhouse gas that they emit. One allowance gives the right to emit one tonne of carbon dioxide equivalent.

The EU ETS reporting period is a calendar year. By the end of March each year, operators calculate the greenhouse gas emissions from their plants for the preceding year. These data are checked first by nationally accredited verifiers and are then forwarded to the national authority responsible for the implementation of the EU ETS; in Germany, this is the German Emissions Trading Authority (DEHSt, *Deutsche Emissionshandelsstelle*). The data are also entered into the Union registry for emissions trading. The operator must surrender sufficient allowances by the end of April to cover its reported emissions for the preceding year.

Companies may obtain emission allowances at primary market auctions run at the European Energy Exchange (EEX) in Leipzig. Emission allowances are auctioned here on a more or less daily basis by individual Member States and by the European Commission. Since the start of the third trading period (2013 to 2020), auctioning has been the basic principle for allocating allowances Europe-wide in the EU ETS. Emissions-intensive industries and heat producers continue to receive a free allocation of allowances for a transitional period, based on a "benchmarking" approach. Product benchmarks are based on the average greenhouse gas emissions of the best performing installations manufacturing that product. Free allocation is intended to reduce the risk of "carbon leakage", i.e. the shifting of emissions to other countries. However, there are plans to phase out free allocation in the coming years.

Emission allowances can also be traded by market participants on the secondary market, e.g. on the exchange or through bilateral transactions. This has given rise to the term "emissions trading", but strictly speaking, it is the allowances – i.e. the right to emit the corresponding quantity of greenhouse gases – rather than the emissions themselves which are traded. Trading is the price-forming mechanism for greenhouse gas emissions, and it is the price which is intended to motivate participating companies to reduce their emissions.

So that it becomes increasingly costly to emit greenhouse gases, the total number of available emission allowances decreases year on year. This reduction is determined at the political level. Germany has a share of around 22 per cent of this Europe-wide auction volume. In 2021, approximately 101 million emission allowances with an average price of 52.59 Euros were auctioned for Germany. The following year, 85 million allowances were auctioned; the average price was 80.32 Euros. In the first half of 2023, Germany auctioned around 45 million emission allowances at an average price of 87.11 Euros per allowance.

The financial pressure generated by the EU ETS is now having the desired effect; by 2021, emissions from installations covered by the EU ETS fell by 38 per cent compared to 2005.

From 2027, emissions from buildings and the transport sector will also be covered

Up to 2023, the installations covered by the EU ETS produced an estimated 40 per cent of the EU's greenhouse gas emissions. In order to increase the share of emissions covered by the trading system, the European Parliament and the governments of the Member States agreed in spring 2023 to extend mandatory emissions trading to small industry and maritime transport (incrementally from 2024). In addition, a second emissions trading system (EU ETS 2) will be introduced in 2027. EU ETS 2 will cover carbon dioxide emissions from fuel combustion in buildings and road transport. It will have its own quantitative limits and probably also different price levels and will operate independently of the existing EU ETS. Participants in EU ETS 2 will also be able to acquire emission allowances and trade them with each other. Unlike the existing EU ETS, which covers companies that produce emissions themselves (so-called downstream emissions trading), the new system will involve businesses that place fuels on the market, such as gas suppliers and petroleum industry companies (so-called upstream emissions trading).

The two emissions trading systems will in future cover 85 per cent of all the EU's greenhouse gas emissions. It has also been agreed that the total number of emission allowances available will be reduced by 62 per cent by 2030 compared to 2005.

Concepts for the inclusion of carbon dioxide removal credits in the EU ETS

In view of this reduction in the number of emission allowances, businesses and experts are asking whether and how it might be possible to utilize carbon dioxide removals in the EU ETS system in order to offset greenhouse gas emissions and prevent an excessively rapid rise in the price of emission allowances over the long term. The assumption is that overly high emission prices might disadvantage Europe's economy and reduce public acceptance of emissions trading as a climate policy instrument.

Currently, carbon dioxide removals achieved by CDR methods are not covered by the EU ETS. Experts are now considering how carbon dioxide removals could be integrated into emissions trading. One proposal is to establish a central carbon agency which would, in the near future, start acquiring and accumulating carbon dioxide removal credits on Europe's behalf. A corresponding certification process is currently being developed at EU level. The agency would then release the removal credits to the EU ETS if the price of emission allowances rose above a specific level.

Currently, however, only Direct Air Carbon Capture and Storage (DACCS) and Bioenergy with Carbon Capture and Storage (BECCS) are being discussed as reliable methods for the generation of these removal credits; both involve the subsequent storage of carbon dioxide in deep geological formations. There are two reasons for focusing on these methods. Firstly, DACCS and BECCS are technically advanced and ready for use. Secondly, these two methods are most likely to allow controlled removal and permanent storage of carbon dioxide in the amounts needed to have a tangible impact on prices in the EU ETS. For that to be achieved, both methods would have to be deployed on a much larger scale than at present.

The proposal to use BECCS on a larger scale has met with criticism, however. The German Environment Agency (UBA, *Umweltbundesamt*), for example, in its Evaluation of the *Commission Proposal on Certification of Carbon Dioxide Removals*, voices clear opposition to certification of bioenergy with carbon capture and storage removals, given the limited availability of sustainable biomass.

Development of the price of emission allowances (EUA)

9.10 > In Europe's emissions trading system, the price of an emission allowance was far lower than expected for some considerable time. In recent years, however, the participating companies have had to pay much higher prices, creating more incentive to invest in emission reduction measures.

Ten key terms in the CDR debate	
Anyone wishing to have a voice in the debate about emission reductions and carbon dioxide removal needs to understand the concepts behind the following ten technical terms:	
Term	**Brief definition**
Carbon neutrality or **net zero CO_2 emissions**	Arithmetically, net zero anthropogenic carbon dioxide emissions are achieved when residual CO_2 emissions are balanced by CO_2 removals from the atmosphere.
Greenhouse gas neutrality or **net zero greenhouse gas emissions** (commonly known as climate neutrality)	Arithmetically, net zero anthropogenic greenhouse gas emissions are achieved when residual emissions of all relevant greenhouse gases are balanced by removals of equivalent climate-relevant greenhouse gas emissions.
Fossil carbon dioxide sources	Burning of fossil fuels, such as coal, oil and natural gas, and industrial processes in which carbon-based components (e.g. limestone) are used and carbon dioxide is released during the processing of these materials (e.g. cement manufacturing).
Biogenic carbon dioxide sources (known as land-use emissions)	Microorganisms, flora and fauna which naturally emit carbon dioxide, e.g. when they break down biomass and oxidize carbon. These natural processes have always formed part of the Earth's carbon cycle. However, many of them are additionally initiated or amplified by human activity, e.g. in land-use changes, intensive soil use in agriculture, drainage of wetlands, or overexploitation and degradation of carbon-storing forests and coastal ecosystems such as mangroves and seagrass beds.
Carbon Dioxide Removal (CDR)	The IPCC defines CDR as anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial (e.g. soil/vegetation) or ocean reservoirs, or in products. CDR experts additionally identify three fundamental principles with which CDR interventions must comply: 1. The carbon dioxide that is removed must come from the atmosphere. 2. The subsequent storage of the removed carbon dioxide must be permanent; the CO_2 must not escape back into the atmosphere later. 3. The carbon dioxide removal must result from human efforts and be additional to the Earth's natural CO_2 uptake processes.
Net (carbon dioxide) removal	Difference between the amount of removed carbon dioxide and all new greenhouse gas emissions (calculated in carbon dioxide equivalent) resulting from the removal process.
Net negative (greenhouse gas) emissions	Net negative (greenhouse gas) emissions are achieved when, as a result of human activities, more greenhouse gases (particularly CO_2) are removed from the atmosphere than are emitted into it.
Conventional CDR methods (known in Germany as **natural climate protection**; known at EU level as **carbon farming**)	All the sustainable agricultural and forestry methods that have been used for centuries and enhance carbon storage in soil and terrestrial vegetation. Examples are afforestation/reforestation, restoration of degraded ecosystems, sustainable forest management and soil-conserving farming practices. Many of these methods are already deployed on a large scale and are listed in national climate action plans. They account for more than 99 per cent of current removals globally.
Novel CDR methods	Methods that involve the storage of captured carbon dioxide in geological formations, in the ocean or in products. At present, these techniques are only deployed on a small scale and some have not yet been tested. Examples of novel CDR methods are Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture and Storage (DACCS), production and use of plant-based biochar, and ocean alkalinity enhancement. Novel CDR methods currently account for a 0.1 per cent share of total global carbon dioxide removals.
Carbon management	Carbon management typically refers to the following three process chains: • Carbon Capture and Storage (CCS), • Carbon Capture and Utilization (CCU) and • Carbon Dioxide Removal (CDR).

However, if new scientific findings then show that this may have entirely unexpected negative consequences, the competent authorities must intervene immediately. For this reason too, intensive scientific control and monitoring of individual CDR projects are so crucial.

An informed and transparent social debate also requires clarity on what terminology and definitions are used. The plethora of specialist terms, often with highly diverse definitions and usages, makes it much more difficult for casual observers to follow the scientific and political debate at present. This lack of terminological clarity simultaneously impedes rapid progress on the development of effective interventions, legal provisions, funding guidelines and regulations. This is exemplified by the discussion about when the term "residual emissions" should be used, and when we should be talking about "hard-to-avoid" emissions.

Experts from a German research mission, for example, define "residual emissions" as merely denoting anthropogenic greenhouse gas emissions that will enter the atmosphere during and after the target year for net zero. They differentiate between residual emissions and hard-to-avoid emissions. Which emissions are classed as "hard-to-avoid"? Definitions vary across stakeholder groups and depend on the individual motives, the experts say; the reasoning underlying categorization often differs as well. Other stakeholders, by contrast, still use the terms "residual emissions" and "hard-to-avoid emissions" as synonyms.

A matter of human survival

Following the political, technological and social debates and developments around land- and ocean-based CDR methods is and will remain a challenge. However, this should not act as a deterrent, given that ultimately, nothing less than our survival is at stake. If we wish to prevent even more serious climate-related loss and damage to people and nature, we must succeed in our efforts to keep global warming below two degrees Celsius – and ideally limit it to 1.5 degrees Celsius. We will only achieve this target if we emit less carbon dioxide from 2050 onwards than we remove from the atmosphere by various methods. From a scientific perspective, this is now beyond reasonable doubt.

Ocean-based removal methods may help us to offset residual emissions. However, it is already clear that we cannot rely on one single method to remove the very large quantities of carbon dioxide from the atmosphere in an environmentally friendly and equitable manner that would enable us to limit global warming to well below two degrees Celsius Instead, we will have to use a broad mix of land- and ocean-based CDR methods – deploying each one wherever its use, including all its positive and negative spillover effects, is most compatible with the goal of sustainable development. Methods which rely on the restoration and expansion of carbon-rich coastal ecosystems could even be implemented relatively soon. Technological processes such as alkalinity enhancement, by

9.11 > In November 2018, climate activists at the Aletsch Glacier in Switzerland used a postcard covering 2500 square metres and made up of 125,000 regularly-sized postcards from children and young people from more than 35 countries to demonstrate for effective climate action and compliance with the 1.5-degree target.

contrast, are still largely untested. It is likely to take some years, if not decades, for the majority of these processes to reach a level of technological advancement that would allow their large-scale and controlled deployment.

The common feature of all CDR methods – those with which we are already familiar, and those which are still being developed – is that in each case, their feasibility and carbon dioxide removal potential will depend on local, context-specific conditions. This includes the locality's climate and environmental characteristics, the availability of infrastructures and resources, and the level of much-needed public support. Clear rules governing their use are also required, along with political incentives, in order to prevent harm to people and the environment, make optimum use of the theoretical removal potential and leverage possible additional benefits.

CDR approaches that look promising must be integrated into national and international strategies on the management of residual emissions. The required transport networks and infrastructures will also need to be established – a step which must be taken in parallel to the further expansion of renewable energies and more broad-scale use of technologies and behaviours that boost energy efficiency and conserve resources. In the experts' view, carbon dioxide removal methods can only help us reach our 2050 goal of global greenhouse gas neutrality if they are combined with the maximum feasible greenhouse gas emissions reductions and improved energy and resource efficiency. And the principle which applies at all times is that the lower our residual emissions, the less carbon dioxide removal will be required to offset them. Now for the good news: the international community already has a mechanism available that would facilitate the governance and regulation of, first, research projects and then large-scale deployments of marine CDR procedures. Yet these deployments will not be entirely without risks or consequences. For that reason, careful consideration of trade-offs is required in all decision-making. This is an immensely challenging task. However, the time for simple solutions is long gone, due to our inaction on climate change.

Conclusion

Regulating potential uses of CDR – clear strategies and rules are vital

In view of the increasingly dramatic impacts of climate change, humankind must do its utmost to keep global warming to a minimum. This will need to include the employment of promising ocean-based CDR methods. They are not the only solution to the climate crisis, however. They must rather form part of a broader programme of action designed to manage residual emissions. Above all, it is essential to drastically reduce and avoid anthropogenic emissions; this approach facilitates faster, more effective, more affordable and less risky mitigation of climate change compared to any CDR method.

If ocean-based CDR methods are used, they will put further pressure upon an ocean that is already subjected to diverse forms of human use and exploitation. In order to conserve ocean ecosystems and guarantee fair burden-sharing, carefully considered CDR strategies are required at national and international level alike, with clear targets and rules for all stakeholders. Experts have already developed initial principles for the governance and regulation of land-based and ocean-based CDR. In their view, in addition to prioritizing emissions avoidance, it will be important to ensure in advance that the carbon dioxide removal is permanent and that the interventions will not themselves emit more greenhouse gases than the quantity of carbon dioxide removed from the atmosphere. The methods must also be assessed comprehensively in advance from a climate, environmental and social perspective and possible goal conflicts avoided or resolved; this will need to be achieved in an eco-friendly and equitable manner.

In the experts' opinion, there are few indications at present that the international community will agree on a common regulatory framework for all forms of carbon dioxide removal. The numerous land-based and ocean-based CDR methods vary too much for there to be a one-size-fits-all solution. Proposals on separate regulation of ocean-based CDR methods in their specific regulatory context 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 also been included. Such a regulatory approach offers scope for similar integration of provisions on other CDR methods involving the introduction of substances or technologies in the sea.

Harmonized procedures for monitoring, documenting and verifying the carbon dioxide fluxes that arise in removal projects are also urgently required. Monitoring is essential because it can reduce legal uncertainties and prevent abuse while offering scope for certification of permanent CO_2 removals. A robust system of this sort would encourage companies to invest in ocean-based CDR projects if certified CO_2 removals were to attract public funding or came with other benefits.

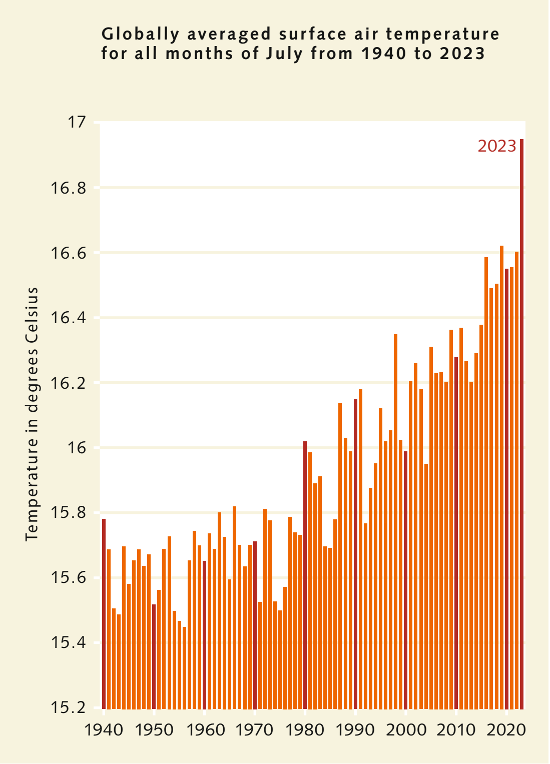
At the same time, we need a broad debate involving all sections of society about the possible use of carbon dioxide reduction methods. So far, this debate has merely involved scientists, businesses and a small number of political institutions. Yet strong public engagement is essential for successful climate change mitigation for many reasons. This applies particularly to social groups living in areas where CDR interventions may be implemented. The struggle against climate change is now a struggle for human survival. We must all play a part in mastering this challenge.

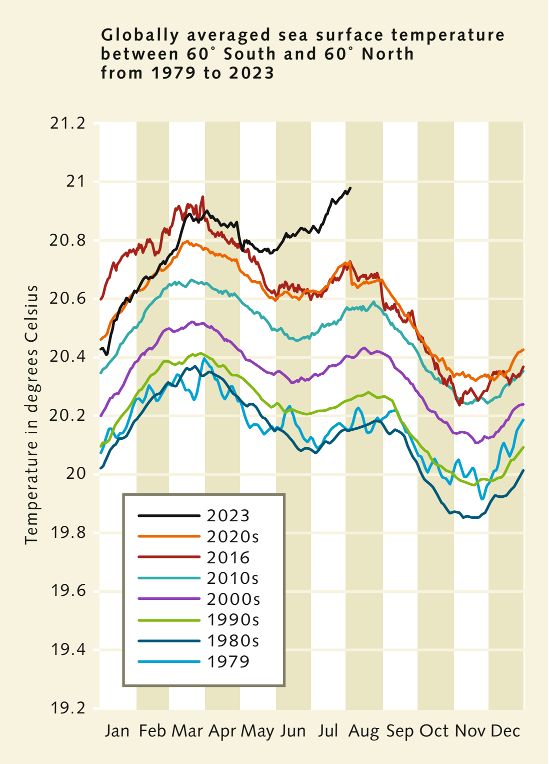
world ocean review
Living with the oceans. 2024

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 northwestern 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.

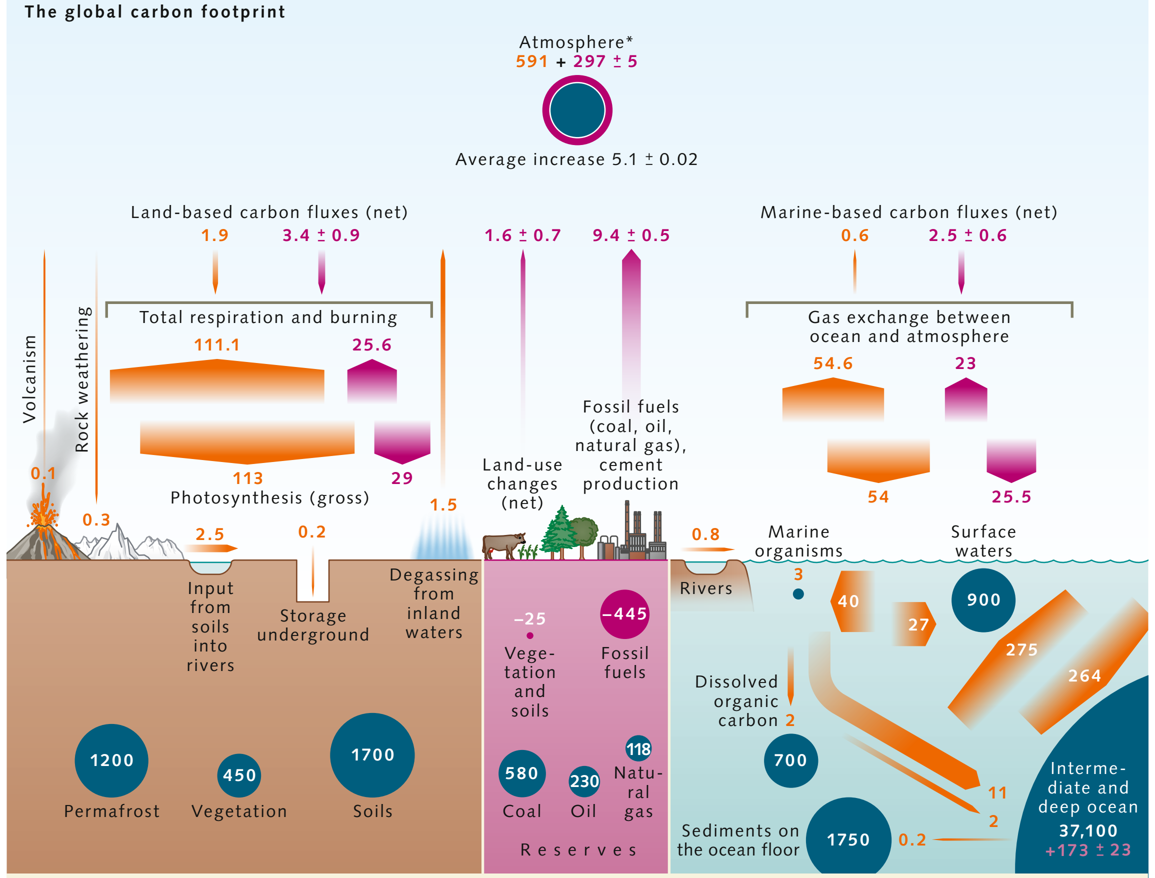
Overall-Conclusion

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

The global carbon footprint



Carbon fluxes (Amounts shown in billions of tonnes of carbon per year)
Natural carbon fluxes (Amounts for the year 1750)
Anthropogenic carbon fluxes (Numbers are annual average values for the period from 2010 to 2019)

Carbon storage (Amounts shown in billions of tonnes of carbon)
Carbon storage (Amounts shown in white are the storage size in the year 1750, numbers in pink express the changes caused by humans since then)
Changes in carbon storage caused by humans (The white numbers in or beside the circle stand for anthropogenic changes)

* Carbon accumulation in the atmosphere is calculated as net emissions from land-use changes plus emissions from the burning of fossil fuels, minus additional carbon taken up by the land and ocean.

> 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.

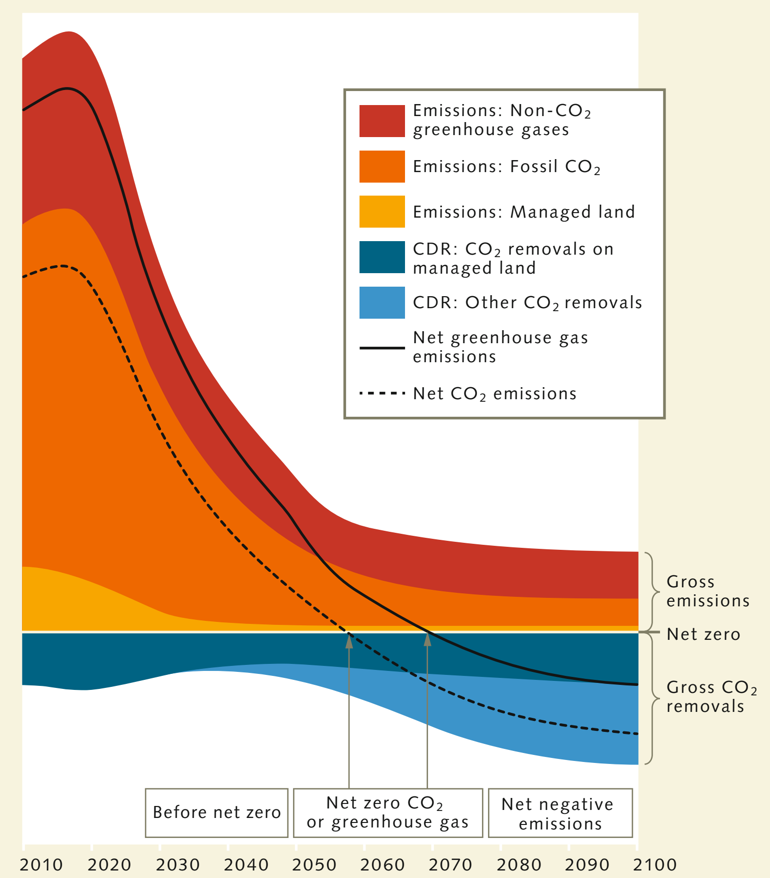
political support that would enable them to take the necessary precautionary measures. Simultaneously, already ravaged ecosystems are increasingly failing to deliver their services. This much is clear: the climate and nature make no compromises. For humankind, combating climate change is thus a matter 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.

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 gas emissions (stylised pathway)



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

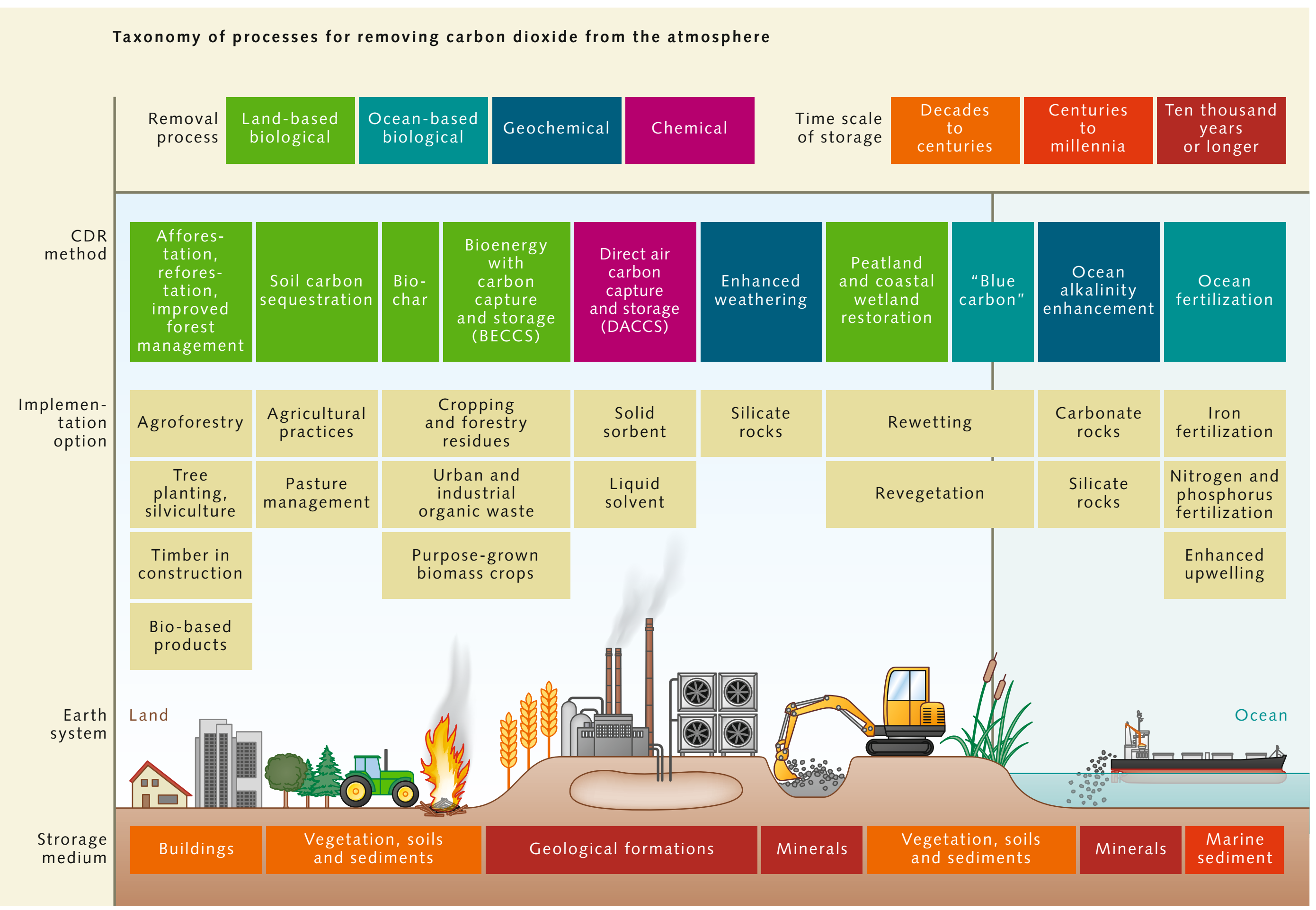
atmosphere and its subsequent permanent storage; such removal must also result from human efforts and be additional to natural CO_2 uptake processes.

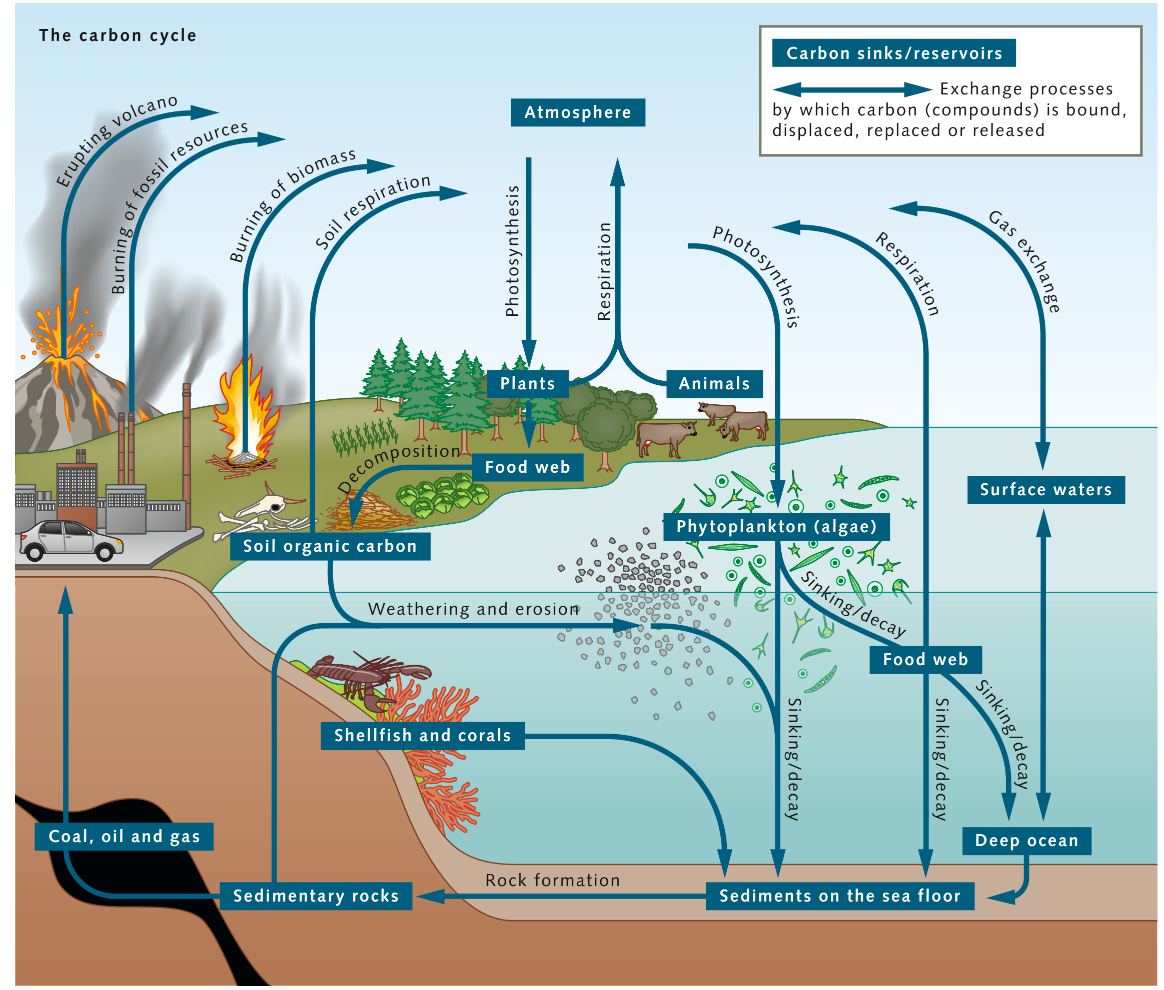
The ocean – a carbon dioxide uptake champion

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.





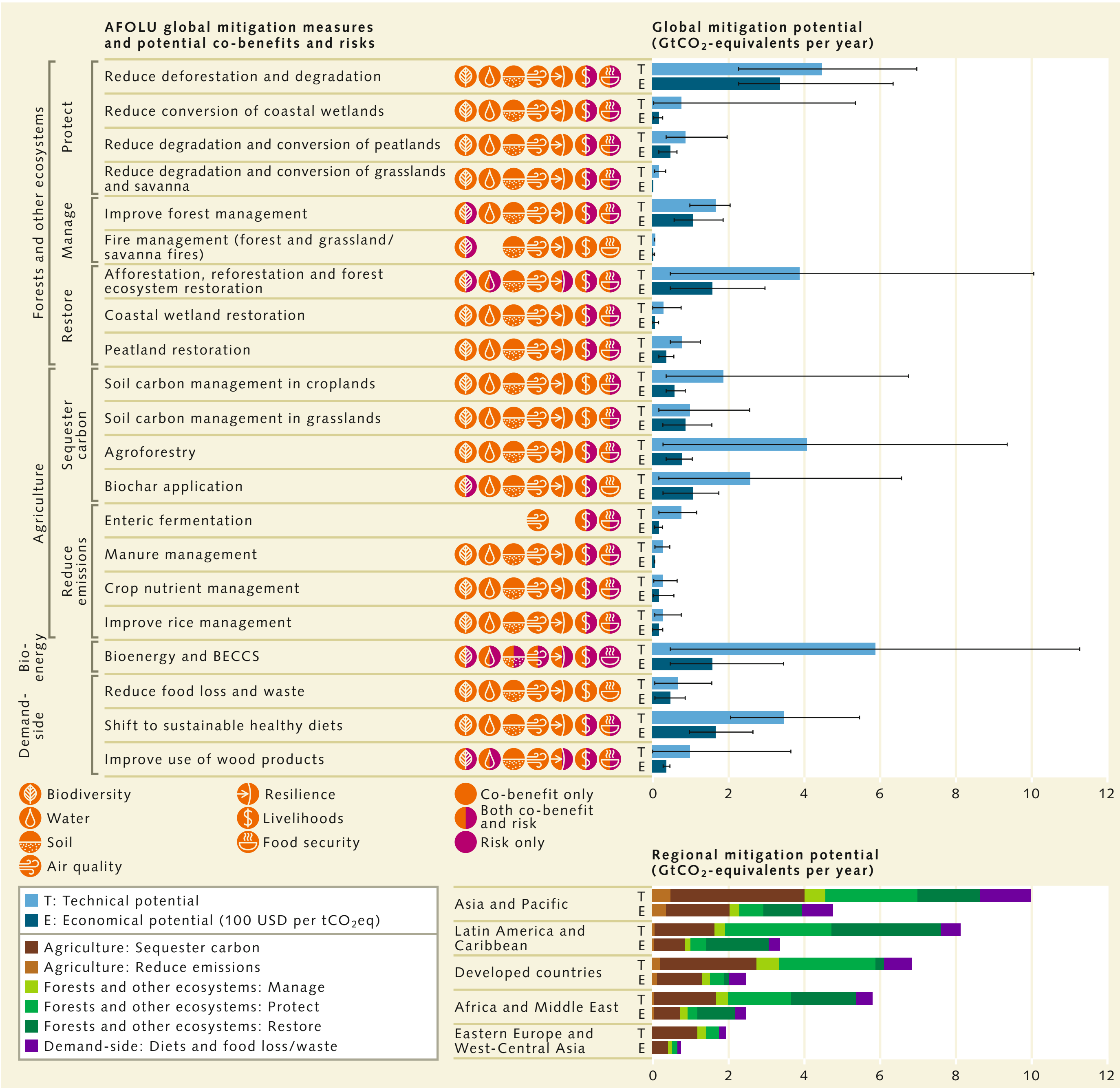
> The Earth's natural carbon cycle: Carbon sinks, or reservoirs, in which carbon or one of its many compounds are stored, are shaded in blue. The arrows represent exchange processes through which carbon or one of its many compounds are bound, stored, exchanged or released.

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

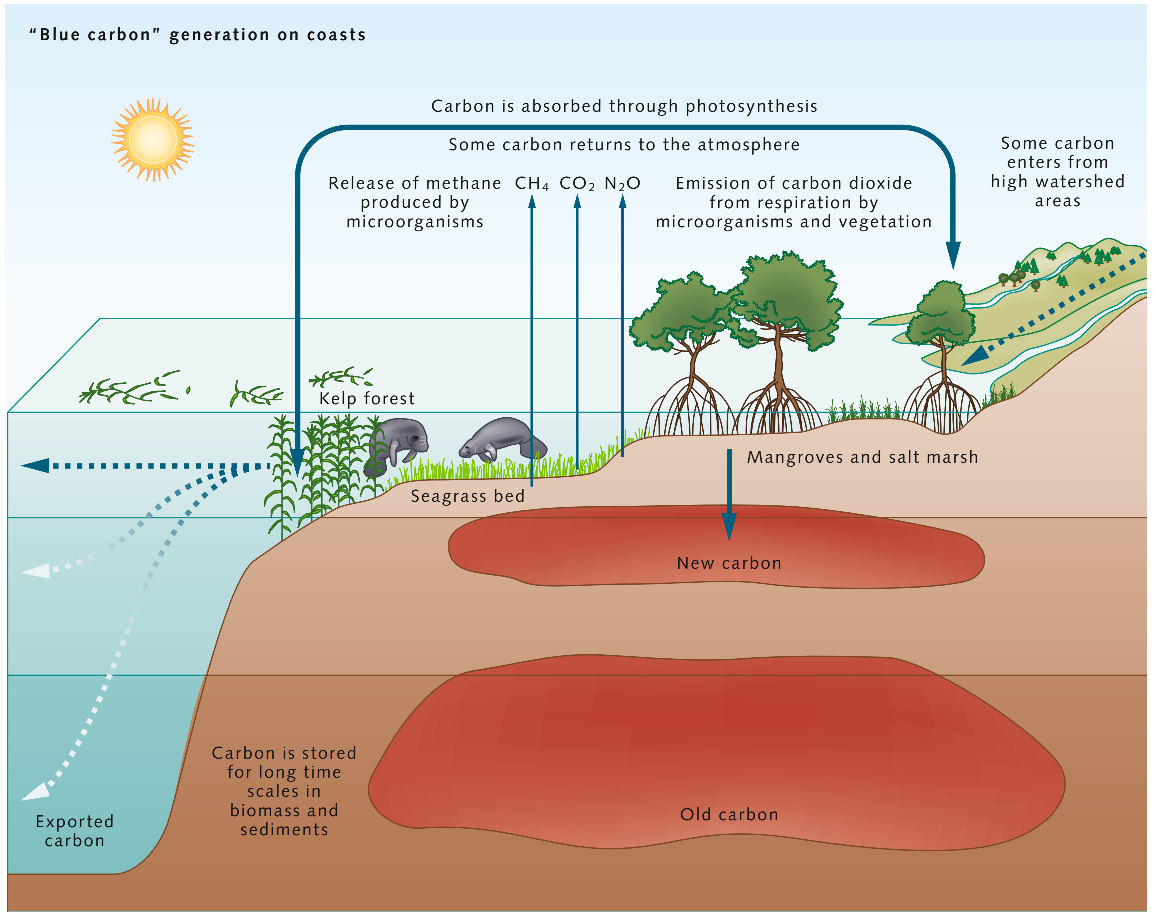
There is scope to enhance carbon dioxide uptake by the ocean using a variety of CDR methods. Biological methods are based on photosynthesis: here, algae and marine or coastal plants break down carbon dioxide, convert the carbon that it contains into organic compounds and store it in the form of biomass. 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



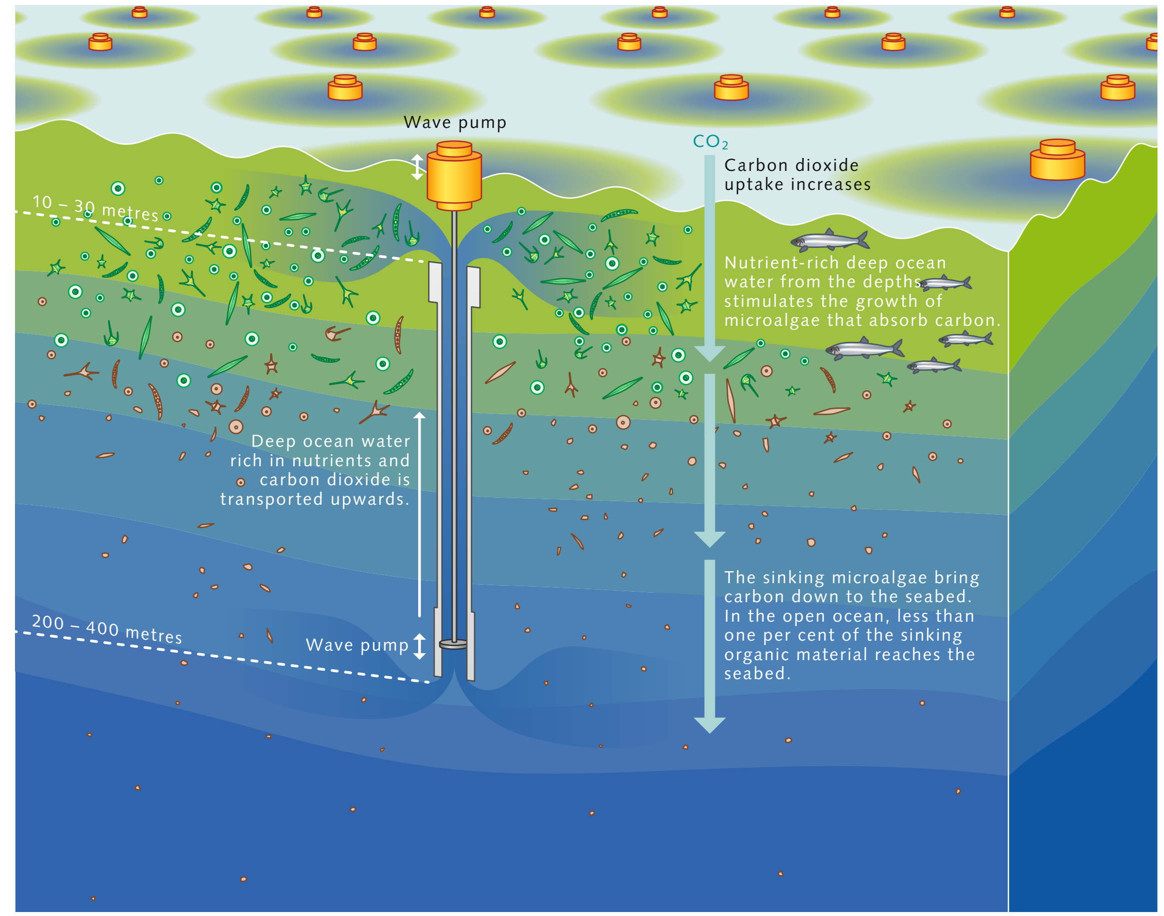
> The amount of carbon that coastal ecosystems store underground in the long term depends on a number of factors. These include inputs of material from terrestrial sources or from other marine regions as well as the amount of biomass consumed by animals or decomposed by microorganisms.

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

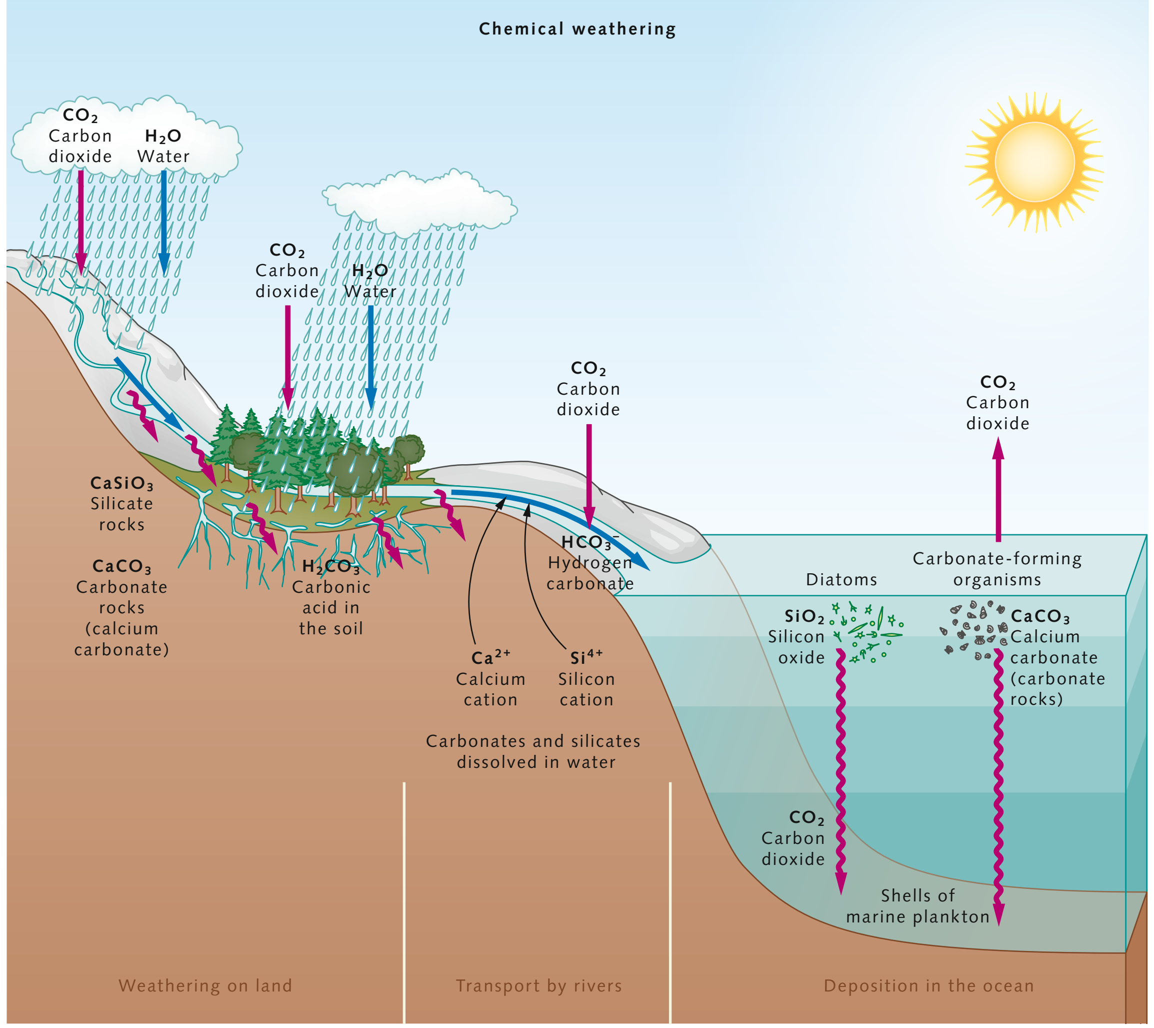
Dissolution products from the natural weathering of rocks increase the ocean's acid-binding capacity (alkalinity). They thus enable chemical bonding of dissolved carbon dioxide in the ocean and the subsequent absorption of new carbon dioxide from the atmosphere. This natural process of climate regulation 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

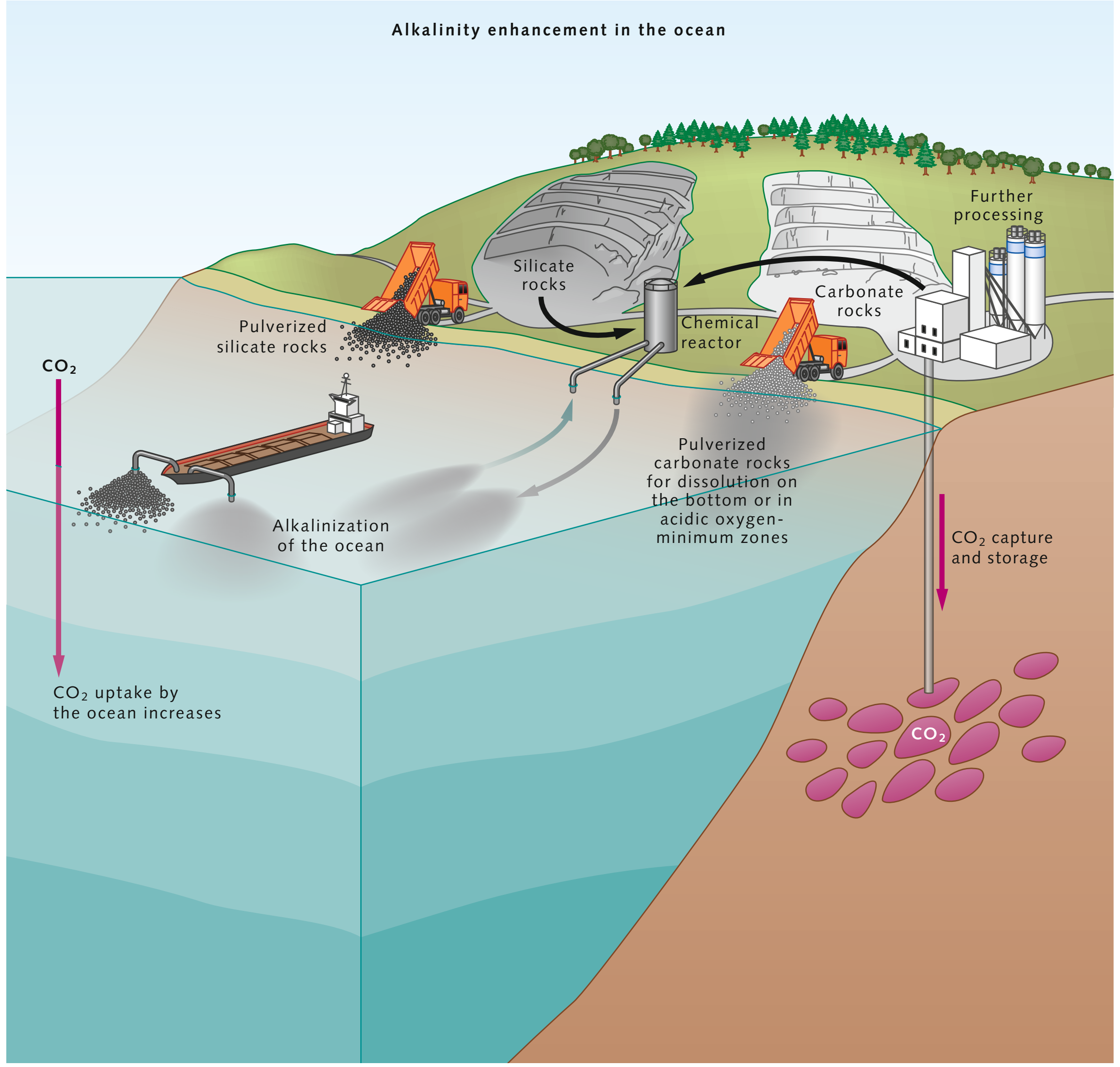
processes would also have the benefit of reducing acidification in the treated water masses and improving the living conditions for many marine organisms.

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.

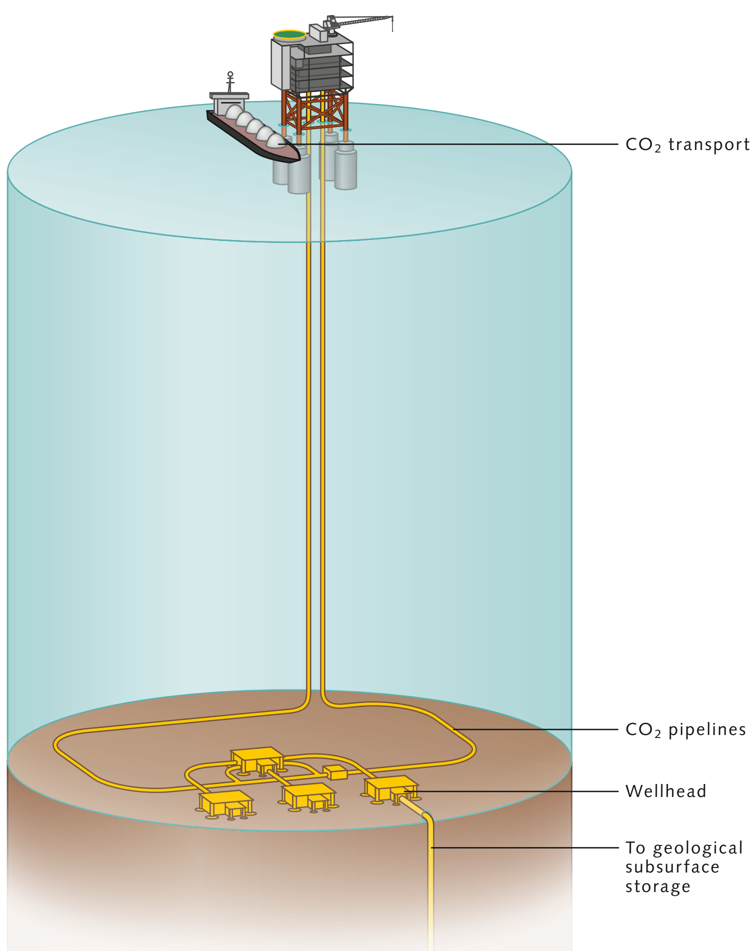
Overall-Conclusion

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.

Abbreviations

ABNJ Areas Beyond National Jurisdiction

AGGI Annual Greenhouse Gas Index

AUD Currency code of Australian dollar

BBNJ Biodiversity Beyond National Jurisdiction

BECCS Bioenergy with Carbon Capture and Storage

Ca Symbol of calcium

$CaCO_3$ Chemical formula for calcium carbonate (lime)

$CaSiO_3$ Chemical formula for silicate rocks

CBD Convention on Biological Diversity

CCS Carbon Capture and Storage

CCU Carbon Capture and Utilization

CDR Carbon Dioxide Removal

CFCs Chlorofluorocarbons

CH_4 Chemical formula for methane

CO_2 Chemical formula for carbon dioxide

DAC Direct Air Capture

DACCS Direct Air Carbon Capture and Storage

DACCU Direct Air Carbon Capture and Utilization

EU European Union

EU ETS European Union Emissions Trading System

EEX European Energy Exchange

EEZ Exclusive economic zone

GESAMP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection

Gt Gigatonne

H^+ Hydrogen cation (also termed proton)

H_2CO_3 Chemical formula for carbonic acid

H_2O Chemical formula for water

HCO_3^- Chemical formula for hydrogen carbonate ion

IAM Integrated Assessment Model

IEA International Energy Agency

IMO International Maritime Organization

IPCC Intergovernmental Panel on Climate Change

ISA International Seabed Authority

KSpG Kohendioxid-Speicherungsgesetz; German Carbon Capture and Storage Act

MIT Massachusetts Institute of Technology

N_2O Chemical formula for nitrous oxide, also termed laughing gas

NOAA National Oceanic and Atmospheric Administration

ppm parts per million

RCP Representative Concentration Pathways

SDGs Sustainable Development Goals

Si^{4+} Chemical formula for silicon cation

SiO_2 Chemical formula for silicon oxide

SSP Shared Socioeconomic Pathway(s)

UN United Nations

UNCLOS United Nations Convention on the Law of the Sea

UNFCCC United Nations Framework Convention on Climate Change

USD Currency code of US american dollar

WMO World Meteorological Organization

Bibliography

Chapter 1
Urgently sought – ways out of the climate crisis

Barnosky, A., et al., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471, pp. 51–57, doi:10.1038/nature09678

Begum, T., 2021. What is mass extinction and are we facing a sixth one? Natural History Museum, https://www.nhm.ac.uk/discover/what-is-mass-extinction-and-are-we-facing-a-sixth-one.html

Borunda, A., 2021: Los Angeles confronts its shady divide. National Geographic, https://www.nationalgeographic.com/magazine/article/los-angeles-confronts-its-shady-divide-feature

Carbon Brief – clear on climate, britisches Nachrichtenportal zur Klimaforschung, zu Klimapolitik und Energiethemen, www.carbonbrief.org

Climate Action Tracker, 2022. Warming Projections Global Update, November 2022. https://climateactiontracker.org/

FAO, 2020: Global Forest Resource Assessment 2020. Main report. Rome, doi:10.4060/ca9825en, https://www.fao.org/forest-resources-assessment/en/

Foster, P. M., et al., 2023. Indicators of Global Climate Change 2022: Annual update of large-scale indicators of the state of the climate system and the human influence. Earth System Science Data, doi:10.5194/essd-2023-166

Friedlingstein, P., et al., 2022. Global Carbon Budget 2022. Earth System Science Data, doi:10.5194/essd-14-4811-2022

IEA, 2022. Global Energy Review: CO_2 Emissions in 2021 – Global emissions rebound sharply to highest ever level. IEA Publications, www.iea.org

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA, in press, doi:10.1017/9781009157896

IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926

IPCC, 2023: Climate Change 2023: Synthesis Report. A Report of the Intergovernmental Panel on Climate Change. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Core Writing Team, H. Lee and J. Romero (Ed.). IPCC, Geneva, Switzerland, in press

Liu, X., et al., 2022. Global agricultural water scarcity assessment incorporating blue and green water availability under future climate change. Earth's Future, 10, e2021EF002567, doi:10.1029/2021EF002567

Marotzke, J., S. Milinski & C. D. Jones, 2021. How close are we to 1.5 degC or 2 degC of global warming? Royal Meteorological Society, Weather – April 2022, Vol. 77, No. 4, doi:10.1002/wea.4174

NOAA, 2023. The NOAA Annual Greenhousegas Index (AGGI). https://gml.noaa.gov/aggi/aggi.html

Ocko, I. B., et al., 2021. Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming. Environmental Research Letters, Vol. 16, No. 5, doi:10.1088/1748-9326/abf9c8

Paustian K., et al., 2019. Soil C Sequestration as a Biological Negative Emission Strategy. Frontiers in Climate, 1:8. doi:10.3389/fclim.2019.00008

Penn, J. L. & C. Deutsch, 2022. Avoiding ocean mass extinction from climate warming. Science 28 April 2022, Vol. 376, Issue 6592, pp. 524–526, doi:10.1126/science.abe9039

Piatt, J. F., et al., 2020. Extreme mortality and reproductive failure of common murres resulting from the northeast Pacific marine heatwave of 2014–2016. PLoS ONE 15(1): e0226087, doi:10.1371/journal.pone.0226087

Smith, S. M., et al., 2023. The State of Carbon Dioxide Removal – 1st Edition. https://www.stateofcdr.org

Trewin, B., et al., 2021. Headline Indicators for Global Climate Monitoring. Bulletin of the American Meteorological Society, doi:10.1175/BAMS-D-19-0196.1

Vecellio, D. J., et al., 2022. Evaluating the 35°C wet-bulb temperature adaptability threshold for young, healthy subjects (PSU HEAT Project). Journal of Applied Physiology 2022 132:2, pp. 340–345, doi:10.1152/japplphysiol.00738.2021

Verein Deutscher Zementwerke e.V., https://www.vdz-online.de/

Weller, E., et al., 2015. Human contribution to the 2014 record high sea surface temperatures over the western tropical and northeast Pacific Ocean. Bulletin of the American Meteorological Society 96(12): pp. 100–104, doi:10.1175/BAMS-D-15-00055.1

Williams, A. P., B. I. Cook & J. E. Smerdon, 2022. Rapid intensification of the emerging southwestern North American megadrought in 2020–2021. Nature Climate Change, 12, pp. 232–234 (2022), doi:10.1038/s41558-022-01290-z

World Meteorological Organization, 2022. State of the Global Climate 2021, Genf, Schweiz

World Meteorological Organization, 2023. State of the Global Climate 2022, Genf, Schweiz

World Weather Attribution Initiative, wissenschaftliche Expertengruppe für die Zuschreibung von Wetter- und Klimaextremen, www.worldweatherattribution.org

United Nations Environment Programme & Climate and Clean Air Coalition, 2021. Global Methane Assessment: Benefits and Costs of Mitigating Methane Emissions. Nairobi: United Nations Environment Programme

Chapter 2
The role of the ocean in the global carbon cycle

Armstrong McKay, D., S. E. Cornell, K. Richardson & J. Rockström, 2021. Resolving ecological feedbacks on the ocean carbon sink in Earth system models. Earth System Dynamics, 12, pp. 797–818, doi.org:10.5194/esd-12-797-2021

Bopp, L., C. Bowler & L. Guidi, 2019. The Ocean, a Carbon Pump. www.ocean-climate.org

Bruhwiler, L., et al., 2018. Chapter 1: Overview of the global carbon cycle. In: Second State of the Carbon Cycle Report (SOCCR2): A Sustained Assessment Report. Cavallaro, N., G. Shrestha, R. Birdsey, M. A. Mayes, R. G. Najjar, S. C. Reed, P. Romero-Lankao, & Z. Zhu (Ed.). U. S. Global Change Research Program, Washington, DC, USA, pp. 42–70, https://doi.org/10.7930/SOCCR2.2018.Ch1

CDRmare, 2023. The Earth's natural carbon cycle. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

Cole, J. J., 2012. The carbon cycle: With a brief introduction to global biogeochemistry. Fundamentals of Ecosystem Science. pp. 109–135

Gruber, N., P. Landschützer & N. S. Lovenduski, 2018. The Variable Southern Ocean Carbon Sink. Annual Review of Marine Science, doi:10.1146/annurev-marine-121916-063407

Hauck, J., et al., 2020. Consistency and Challenges in the Ocean Carbon Sink Estimate for the Global Carbon Budget. Frontiers in Marine Science. 7:571720. doi:10.3389/fmars.2020.571720

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA, in press, doi:10.1017/9781009157896

IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

Johnson, D. W., 2022. Selection on offspring size and contemporary evolution under ocean acidification. Nature Climate Change 12, pp. 757–760, doi:10.1038/s41558-022-01425-2

Kwiatkowski, L., et al., 2020. Twenty-first century ocean warming, acidification, deoxygenation, and upper-ocean nutrient and primary production decline from CMIP6 model projections. Biogeosciences, doi:10.5194/bg-17-3439-2020

Long, M. C. et al., 2021. Strong Southern Ocean carbon uptake evident in airborne observations. Science 374, pp. 1275–1280 (2021), doi:10.1126/science.abi4355

Nayak, A. R. & M. S. Twardowski, 2020. "Breaking" news for the ocean's carbon budget. Science 367, pp. 738–739 (2020), doi:10.1126/science.aba7109

Pörtner, H.-O., 2022: Versauerung der Ozeane und Meeresökosysteme. In: Thunberg, G., 2022. Das Klima-Buch von Greta Thunberg, S. Fischer Verlage

Stockholm Resilience Centre, 2021. In a warming world the ocean will struggle as a carbon sink, https://www.stockholmresilience.org/research/research-news/2021-12-13-in-a-warming-world-the-ocean-will-struggle-as-a-carbon-sink.html

WBGU, 2006. Die Zukunft der Meere – zu warm, zu hoch, zu sauer, Sondergutachten. Berlin

Chapter 3
Harnessing the untapped potential of terrestrial ecosystems

Carbon Brief – clear on climate, British news portal on climate research, climate policy and energy issues, www.carbonbrief.org

Degener, J. F., 2015. Atmospheric CO_2 fertilization effects on biomass yields of 10 crops in northern Germany. Frontiers in Environmental Science, 3:48, doi:10.3389/fenvs.2015.00048

Doelman, J. C. & E. Stehfest, 2022. The risks of overstating the climate benefits of ecosystem restoration. Nature 609, E1–E3, doi:10.1038/s41586-022-04881-0

Edenhofer, O., et al., 2021. Wissensstand zu CO_2-Entnahmen. Bedarf & Potenziale, Technologien & Politikinstrumente, weltweit & in Deutschland. Mercator Research Institute on Global Commons and Climate Change (MCC) gGmbH, Berlin

Edwards, T. 2022. What is soil organic carbon? Government of Western Australia, Department of Primary Industrie and Regional Development, https://www.agric.wa.gov.au/measuring-and-assessing-soils/what-soil-organic-carbon

Erlach, B., et al., 2022: „Was sind negative Emissionen, und warum brauchen wir sie? (Kurz erklärt!)", Akademienprojekt „Energiesysteme der Zukunft" (ESYS), doi:10.48669/ESYS_2022-2

FAO, 2022. The State of the World's Forests 2022. Forest pathways for green recovery and building inclusive, resilient and sustainable economies. Rome, FAO. doi:10.4060/cb9360en

Friedlingstein, P., et al., 2022. Global Carbon Budget 2022. Earth System Science Data, doi:10.5194/essd-14-4811-2022

Green, J. K. & T. F. Keenan, 2022. The limits of forest carbon sequestration, Science 376, pp. 692–693 (2022), doi:10.1126/science.abo6547

Gurevitch, J., 2022. Managing forests for competing goals. Science, 376 (6595), doi:10.1126/science.abp8463

IEA, 2022. Direct Air Capture, IEA, Paris, https://www.iea.org/reports/direct-air-capture

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi:10.1017/9781009157926

Lorenz, K. & L. Rattan, 2016. Soil Organic Carbon – An Appropriate Indicator to Monitor Trends of Land and Soil Degradation within the SDG Framework?, Texte 77/2016, Umweltbundesamt, Dessau-Roßlau

Pongratz, J., et al., 2021. Land Use Effects on Climate: Current State, Recent Progress, and Emerging Topics. Current Climate Change Reports 7, pp. 99–120 (2021), doi:10.1007/s40641-021-00178-y

Poore, J. & T. Nemecek, 2018. Reducing food's environmental impacts through producers and consumers. Science, 1 June 2018, Vol. 360, Issue 6392, pp. 987–992, doi:10.1126/science.aaq0216

Xu, S., et al., 2022. Delayed use of bioenergy crops might threaten climate and food security. Nature 609, pp. 299–306 (2022). doi:10.1038/s41586-022-05055-8

Chapter 4
Ocean-based CDR – research under massive expectations

Boettcher, M., et al., 2021. Navigating Potential Hype and Opportunity in Governing Marine Carbon Removal. Frontiers in Climate, 3:664456; doi:10.3389/fclim.2021.664456

Castanon, L., 2021. An Ocean of Opportunity. Oceanus Fall 2021, Woods Hole Oceanographic Institution, https://www.whoi.edu/oceanus/feature/an-ocean-of-opportunity/

Cooley, S. R., et al., 2023. Sociotechnical Considerations About Ocean Carbon Dioxide Removal. Annual Review of Marine Science 2023 15:1, pp. 41–66, doi:10.1146/annurev-marine-032122-113850

Keller, D. P., K. Brent, L. T. Bach & W. Rickels, 2021. Editorial: The Role of Ocean-Based Negative Emission Technologies for Climate Mitigation. Frontiers in Climate Science, 3:743816. doi:10.3389/fclim.2021.743816

Lebling, K., et al., 2022. Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. Report. Washington, DC: World Resources Institute. doi:10.46830/wrirpt.21.00090

Loomis, R., et al., 2022. A Code of Conduct Is Imperative for Ocean Carbon Dioxide Removal Research. Frontiers in Marine Sciense, 9:872800. doi:10.3389/fmars.2022.872800

OceanNETs, EU-Forschungsprojekt, https://www.oceannets.eu

Yoon, J.-E., et al., 2018. Reviews and syntheses: Ocean iron fertilization experiments – past, present, and future looking to a future Korean Iron Fertilization Experiment in the Southern Ocean (KIFES) project. Biogeosciences, 15, pp. 5847–5889, doi:10.5194/bg-15-5847-2018, 2018

Chapter 5
More carbon sequestration in marine meadows and forests?

Apple Media, 2021. Apple and partners launch first-ever $200 million Restore Fund to accelerate natural solutions to climate change. Press release, https://www.apple.com/newsroom/2021/04/apple-and-partners-launch-first-ever-200-million-restore-fund/

Bertram, C., et al., 2021. The blue carbon wealth of nations. Nature Climate Change 11, pp. 704–709 (2021), doi:10.1038/s41558-021-01089-4

Blaufelder, C., et al., 2023. A blueprint for scaling voluntary carbon markets to meet the climate challenge. McKinsey & Company, https://www.mckinsey.com/capabilities/sustainability/our-insights/a-blueprint-for-scaling-voluntary-carbon-markets-to-meet-the-climate-challenge

Carbon Brief – clear on climate, britisches Nachrichtenportal zur Klimaforschung, zu Klimapolitik und Energiethemen, www.carbonbrief.org

Cai, J., et al., 2021. Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development. FAO Fisheries and Aquaculture Circular. No. 1229. Rome, FAO. doi:10.4060/cb5670en

CDRmare, 2023. Increased carbon storage through the expansion of marine meadows and forests. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

Deutsche Emissionshandelsstelle, https://https://www.dehst.de/EN/home/home_node.html

FAO, 2022. The State of World Fisheries and Aquaculture 2022. Towards Blue Transformation. Rome, FAO, doi:10.4060/cc0461en

Gallagher, A. J., et al., 2022. Tiger sharks support the characterization of the world's largest seagrass ecosystem. Nature Communications 13, 6328 (2022), doi:10.1038/s41467-022-33926-1

Gallagher, J. B., 2022. Kelp won't help: why seaweed may not be a silver bullet for carbon storage after all. The Conversation, https://theconversation.com/kelp-wont-help-why-seaweed-may-not-be-a-silver-bullet-for-carbon-storage-after-all-178018

IPCC, 2022. Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., doi:10.1017/9781009325844

Kiwelu, L., E. de Wit & E. Gasparotto, 2022. Draft Core Carbon Principles for the Voluntary Carbon Market released, Norton Rose Fulbright, https://www.nortonrosefulbright.com/

Krause-Jensen, D., et al., 2018. Sequestration of macroalgal carbon: the elephant in the Blue Carbon room. Biological Letters, 14: 20180236, doi:10.1098/rsbl.2018.0236

Leal, M. & M. Spalding, 2022. The State of the World's Mangroves 2022. Global Mangrove Alliance, www.mangrove alliance.org

Lebling, K., et al., 2022. Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. Report. Washington, DC: World Resources Institute. doi:10.46830/wrirpt.21.00090

Macreadie, P. I., et al., 2021. Blue carbon as a natural climate solution. Nature Reviews Earth & Environment 2, pp. 826–839 (2021), doi:10.1038/s43017-021-00224-1

Macreadie, P. I., et al., 2022. Operationalizing marketable blue carbon. One Earth, Vol. 5, Issue 5, pp. 485–492, doi:10.1016/j.oneear.2022.04.005

Murray, N. J., et al., 2022. High-resolution mapping of losses and gains of Earth's tidal wetlands. Science, 13 May 2022, 376(6594), pp. 744–749. doi:10.1126/science.abm9583

Needelman, B. A, et al., 2018. The Science and Policy of the Verified Carbon Standard Methodology for Tidal Wetland and Seagrass Restoration. Estuaries and Coasts 41, pp. 2159–2171 (2018), doi:10.1007/s12237-018-0429-0

Saderne, V., et al., 2019. Role of carbonate burial in Blue Carbon budgets. Nature Communications 10, 1106 (2019), doi:10.1038/s41467-019-08842-6

The Taskforce on Scaling Voluntary Carbon Markets, https://www.iif.com/tsvcm

Unsworth, R. K. F., et al., 2022. The planetary role of seagrass conservation. Science 377, pp. 609–613 (2022), doi:10.1126/science.abq6923

Wang, F., et al., 2020. Global blue carbon accumulation in tidal wetlands increases with climate change. National Science Review, doi:10.1093/nsr/nwaa296

Williamson, P. & J.-P. Gattuso, 2022. Carbon Removal Using Coastal Blue Carbon Ecosystems Is Uncertain and Unreliable, With Questionable Climatic Cost-Effectiveness. Frontiers in Climate 4:853666, doi:10.3389/fclim.2022.853666

Worthington, T. & M. Spalding, 2018. Mangrove Restoration Potential: A Global Map Highlighting A Critical Opportunity. Cambridge, MA: Apollo – University of Cambridge Repository, doi:10.17863/CAM.39153

Wu, J., et al., 2022. Carbon Dioxide Removal via Macroalgae Open-ocean Mariculture and Sinking: An Earth System Modeling Study. Earth System Dynamics, doi:10.5194/esd-2021-104

Chapter 6
Artificial upwelling – the idea of greening the ocean

Bristow, L., et al., 2017. Nutrients that limit growth in the ocean. Current Biology, Vol. 27, Issue 11, pp. R474–R478, doi:10.1016/j.cub.2017.03.030

CDRmare, 2023. Artificial upwelling: More power for the ocean's biological carbon pump Fact Sheet. Updated version june 2023, https://cdrmare.de/en/fact-sheets/

CDRmare, 2023. Alle Hoffnung auf die grüne Wolke. Science Stories, https://cdrmare.de/science-stories/

Fan, W., et al., 2019. Nutrient Removal from Chinese Coastal Waters by Large-Scale Seaweed Aquaculture Using Artificial Upwelling. Water 11 (9):1754; doi:10.3390/w11091754

Goldenberg, S. U., et al., 2022. Nutrient composition (Si:N) as driver of plankton communities during artificial upwelling. Frontiers in Marine Science 9:1015188, doi:10.3389/fmars.2022.1015188

Koweek, D. A., 2022. Expected Limits on the Potential for Carbon Dioxide Removal From Artificial Upwelling. Frontiers in Marine Science 9:841894, doi:10.3389/fmars.2022.841894

Lebling, K., et al., 2022. Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. Report. Washington, DC: World Resources Institute. doi:10.46830/wrirpt.21.00090

Nötig, E. & K. Metfies, 2017. Das Phytoplankton im Überblick. In: Hempel, G., K. Bischof & W. Hagen. Faszination Meeresforschung – Ein ökologisches Lesebuch. 2. Auflage, Springer-Verlag, doi:10.1007/978-3-662-49714-2

Tagliabue, A., et al., 2017. The integral role of iron in ocean biogeochemistry. Nature 543, pp. 51–59 (2017), doi:10.1038/nature21058

Chapter 7
Targeted interventions in marine chemistry

Albright, R., et al., 2016. Reversal of ocean acidification enhances net coral reef calcification. Nature 531, pp. 362–365 (2016), doi:10.1038/nature17155

Callagon La Plante, E., et al., 2021. Saline Water-Based Mineralization Pathway for Gigatonne-Scale CO_2 Management. ACS Sustainable Chemistry & Engineering, 9, 3, pp. 1073–1089, doi:10.1021/acssuschemeng.0c08561

CDRmare, 2023. Minerals for enhanced carbon dioxide uptake by the ocean. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

CDRmare, 2023. Experimente zur Alkalinitätserhöhung: Wie reagiert das Leben im Meer. Science Stories, https://cdrmare.de/science-stories/

Clam Garden Network, https://www.clamgarden.com

Hartmann, J., et al., 2023. Stability of alkalinity in ocean alkalinity enhancement (OAE) approaches – consequences for durability of CO_2 storage. Biogeosciences, doi:10.5194/bg-20-781-2023

Kim, S., et al., 2023. Asymmetric chloride-mediated electrochemical process for CO_2 removal from oceanwater. Energy & Environmental Science, Issue 5 2023, pp. 2030–2044, doi:10.1039/D2EE03804H

Lebling, K., et al., 2022. Towards Responsible and Informed Ocean-Based Carbon Dioxide Removal: Research and Governance Priorities. Report. Washington, DC. World Resources Institute. doi:10.46830/wrirpt.21.00090

Lenton, A., et al., 2018. Assessing carbon dioxide removal through global and regional ocean alkalinization under high and low emission pathways. Earth System Dynamics, Vol. 9, Issue 2, pp. 339–357, doi:10.5194/esd-9-339-2018

Lozán, J. L., et al., 2023. Warnsignal Klima: Hilft Technik gegen die Erderwärmung – Climate Engineering in der Diskussion. Hamburg. https://www.warnsignal-klima.de

Renforth, P., et al., 2022. Using ikaite and other hydrated carbonate minerals to increase ocean alkalinity for carbon dioxide removal and environmental remediation. Joule, Vol. 6, Issue 12, pp. 2674–2679, doi:10.1016/j.joule.2022.11.001

Schmidt., J., 2022. Clamshells Face the Acid Test. Hakai Magazine, https://hakaimagazine.com/news/clamshells-face-the-acid-test/

Voosen, P., 2022. Ocean geoengineering scheme aces its first field test. Science, doi:10.1126/science.adg3427

Chapter 8
Injecting carbon dioxide deep beneath the sea

CDRmare, 2023. Carbon dioxide storage in geological formations below the German North Sea. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

CDRmare, 2023. A deep-sea experiment on carbon dioxide storage in oceanic crust. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

CDRmare, 2023. Kohlendioxid-Speicherung in der Tiefsee: Ein Forschungsduo trotzt dem Druck, Science Stories, https://cdrmare.de/science-stories/

Deutsche Energie-Agentur, 2022. Vergleich der „Big 5" Klimaneutralitätsszenarien. https://www.dena.de/newsroom/publikationsdetailansicht/pub/vergleich-der-big-5-klima neutralitaetsszenarien/

Deutscher Bundestag, 2018. Unterrichtung durch die Bundesregierung: Evaluierungsbericht der Bundesregierung über die Anwendung des Kohlendioxid-Speicherungsgesetzes sowie die Erfahrungen zur CCS-Technologie, Drucksache 19/6891

Deutscher Bundestag, 2022. Unterrichtung durch die Bundesregierung: Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetz, Drucksache 20/5145

Europäische Kommission, 2023. Proposal for a Regulation of the European Parliament and of the Council on establishing a framework of measures for strengthening Europe's net-zero technology products manufacturing ecosystem (Net Zero Industry Act). Brüssel, 16 March 2023 COM(2023) 161 final 2023/0081 (COD)

Europäisches Parlament & EU-Rat, 2009. Richtlinie 2009/31/EG über die geologische Speicherung von Kohlendioxid und zur Änderung der Richtlinie 85/337/EWG des Rates sowie der Richtlinien 2000/60/EG, 2001/80/EG, 2004/35/EG, 2006/12/EG und 2008/1/EG des Europäischen Parlaments und des Rates sowie der Verordnung (EG) Nr. 1013/2006, Amtsblatt der Europäischen Union, 5.6.2009

Global CCS Institute, 2022. Global Status of CCS 2022. https://status22.globalccsinstitute.com/

IEA, 2021. CCUS around the world, IEA, Paris, https://www.iea.org/reports/ccus-around-the-world

IEA, 2023. Carbon Capture, Utilisation and Storage. IEA, Paris, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage

IEA, 2023. CO_2 Transport and Storage. IEA, Paris, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/co2-transport-and-storage

Kelemen, P., et al., 2019. An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations. Frontiers in Climate, 15 November 2019, doi:10.3389/fclim.2019.00009

Lozán, J. L., et al., 2023. Warnsignal Klima: Hilft Technik gegen die Erderwärmung – Climate Engineering in der Diskussion. Hamburg. https://www.warnsignal-klima.de

Proelß, A. & L. Westmark, 2022: Seevölkerrechtliche Anforderungen der unterseeischen Speicherung von CO_2. Klima und Recht, 8/2022, pp. 234–240

Proelß, A. & L. Westmark, 2023. Unterseeische Speicherung und Export von CO_2 in Deutschland: Rechtliche Hürden und Reformbedarfe – Teil I. Klima und Recht, 5/2023, pp. 145–150

Ringrose, P. S., et al., 2013. The In Salah CO_2 storage project: lessons learned and knowledge transfer, Energy Procedia, Vol. 37, 2013, pp. 6226–6236, doi:10.1016/j.egypro.2013.06.551

Robertson, B. & M. Mousavian, 2022. The Carbon Capture Crux – Lessons Learned. Institute for Energy Economics and Financial Affairs, https://ieefa.org

Chapter 9
Key principles and rules for the use of marine CDR procedures

Boettcher, M., et al., 2021. Navigating Potential Hype and Opportunity in Governing Marine Carbon Removal. Frontiers in Climate, 3:664456, doi:10.3389/fclim.2021.664456

CDRmare, 2023. An assessment framework for marine carbon dioxide removal methods. Fact Sheet, Updated version june 2023, https://cdrmare.de/en/fact-sheets/

Czerski, H., 2023. Why we need to respect Earth's last great wilderness. The Guardian, 4 June 2023

Deutsche Emissionshandelsstelle, https://www.dehst.de

Erbguth, W. & S. Schlacke, 2012. Umweltrecht, 4. Auflage, Nomos Verlag, Baden-Baden

Europäische Kommission, 2022. Bericht der Europäischen Kommission an das Europäische Parlament und den Rat über das Funktionieren des CO_2-Marktes im Jahr 2021 der EU gemäß Artikel 10 Absatz 5 und Artikel 21 Absatz 2 der Richtlinie 2003/87/EG (geändert durch Richtlinie 2009/29/EG und Richtlinie (EU) 2018/410). Brüssel, 14.12.2022, COM(2022) 516 final

Europäische Kommission, 2023. Carbon Removal Certification. https://climate.ec.europa.eu/eu-action/sustainable-carbon-cycles/carbon-removal-certification_en

Europäisches Parlament, 2023. Reform des Emissionshandelssystems der EU. https://www.europarl.europa.eu/news/de/headlines/society/20170213STO62208/reform-des-emissionshandelssystems-der-eu

Lewandrowski, D. & N. Pauly, 2023. Auktionierung (EU-ETS) Deutsche Versteigerungen von Emissionsberechtigungen. Deutsche Emissionshandelsstelle (DEHSt) im Umweltbundesamt, Berlin – Zweites Quartal 2023

Lozán, J. L., et al., 2023. Warnsignal Klima: Hilft Technik gegen die Erderwärmung – Climate Engineering in der Diskussion. Hamburg

International Maritime Organization, 2023. Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter. London, https://www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

Meyer-Ohlendorf, N. & D. Spasova, 2022. Carbon Dioxide Removals in EU Member States. Ecologic Institute, Berlin

Meyer-Ohlendorf, N., et al., 2023. Interim Report Certification of Carbon Dioxide Removals Evaluation of the Commission Proposal, Umweltbundesamt, Climate Change 13/2023

Proelß, A., 2020. Völkerrecht. Fünfter Abschnitt. Raum und Umwelt im Völkerrecht. De Gruyter, doi:10.1515/9783110633269-005

Proelß, A. & R. Steenkamp, 2021. Report on attribution of private conduct to States in relation to oceanbased NETS under the international law of the sea. OceanNets Deliverable, D2.7, Ocean NETs, Kiel, Germany, 25 pp. doi:10.3289/oceannets_d2.7

Proelß, A. & R. Steenkamp, 2022. Report on the Future Regulation of Ocean-based NETs. OceanNets Deliverable, D2.8, OceanNETs, Kiel, Germany, 22 pp. doi:10.3289/oceannets_d2.8

Rickels, W., et al., 2022. Procure, Bank, Release: Carbon Removal Certificate Reserves to Manage Carbon Prices on the Path to Net-Zero. Energy Research & Social Science, Vol. 94, 2022, 102858, doi:10.1016/j.erss.2022.102858

Schenuit, F., M. Boettcher & O. Geden, 2022. CO_2-Entnahme als integraler Baustein des Europäischen „Green Deal“. SWP-Aktuell, Nr. 37, Juni 2022, Stiftung Wissenschaft und Politik, Berlin

Schenuit, F., M. Boettcher & O. Geden, 2023. „Carbon Management“: Chancen und Risiken für ambitionierte Klimapolitik. SWP-Aktuell, Nr. 30, Mai 2023, Stiftung Wissenschaft und Politik, Berlin

Smith, S. M., et al., 2023. The State of Carbon Dioxide Removal – 1st Edition. https://www.stateofcdr.org

Umweltbundesamt, 2022. Genehmigung von Forschungsprojekten zu marinem Geo-Engineering. https://www.umweltbundesamt.de/themen/wasser/meere/genehmigung-von-forschungsprojekten-zu-marinem-geo

UNFCCC, 2023. Information note: Summary of the views submitted by Parties and observers on activities involving removals, Version 01.0. https://unfccc.int/sites/default/files/resource/a64-sb005-aa-a10v1.pdf

Watson, J. E. M., et al., 2018. Protect the last of the wild. Nature 563, pp. 27–30 (2018). doi:10.1038/d41586-018-07183-6

Overall-Conclusion

Carbon Brief – clear on climate, britisches Nachrichtenportal zur Klimaforschung, zu Klimapolitik und Energiethemen, www.carbonbrief.org

Copernicus Climate Change Service, 2023. July 2023, the warmest month in Earth's recent history. Monthly Climate Bulletin, Copernicus Climate Change Service/ECMWF, https://climate.copernicus.eu/july-2023-warmest-month-earths-recent-history

IPCC, 2022. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. P. R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley (Ed.). Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926

World Weather Attribution Initiative, 2023. Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change. 25 July 2023, https://www.worldweatherattribution.org/extreme-heat-in-north-america-europe-and-china-in-july-2023-made-much-more-likely-by-climate-change/

WMO, 2023. July 2023 is set to be the hottest month on record. Press release published 31 July 2023, https://public.wmo.int/en/media/press-release/july-2023-set-be-hottest-month-record

WMO, 2023. Exceptional heat and rain, wildfires and floods mark summer of extremes. Press release published 3 August 2023, https://public.wmo.int/en/media/news/exceptional-heat-and-rain-wildfires-and-floods-mark-summer-of-extremes

Zachariah, M., et al., 2023. Extreme heat in North America, Europe and China in July 2023 made much more likely by climate change. Grantham Institute for Climate Change, World Weather Attribution Initiative, doi:10.25561/105549

Contributors

Many experts contributed their specialist knowledge during the compilation of the World Ocean Review 2024. They included, in particular, scientists working at the member institutions of the German Marine Research Consortium (KDM).

Dr. Thorben Amann is a geologist and postdoctoral researcher at the Institute for Geology, University of Hamburg. One of his main topics of research is accelerated rock weathering. He investigates its potential, technical feasibility and possible risks for deployment on land (*CDRterra* research mission) and at sea (*CDRmare* research mission), with a particular focus on various ocean alkalinity enhancement methods.

Prof. Dr. Christian Baatz is engaged in research and teaching on climate ethics, sustainability and global justice in the Department of Philosophy at Kiel University, where he is a Junior Professor. In this capacity, the environmental ethicist leads the research group "Financing Adaptation to Climate Change in the Global South: Investigating a Fair and Practical Distribution of Scarce Resources", which is funded by the German Federal Ministry of Education and Research (BMBF). His studies on political and ethical principles for targeted carbon dioxide removal provide input for three research projects: one of which is developing review guidelines for ocean-based CDR methods as part of the German *CDRmare* research mission, and two projects on the ethics of land-based CDR.

Dr. Miranda Böttcher is a political scientist and research associate in the Climate Policy and Politics Research Cluster at the German Institute for International and Security Affairs (SWP) in Berlin. She monitors environmental and climate policy processes at national and international level and looks at which strategies and rules would facilitate environmentally sound and socially equitable use of ocean-based CDR methods in future. She is one of the world's leading experts on the political and institutional feasibility of carbon dioxide removal and is a member of the GESAMP Working Group on Ocean Interventions for Climate Change Mitigation, which among other things provides advice to the London Protocol's bodies. Together with colleagues in the German *CDRmare* research mission, she is currently developing review guidelines for ocean-based CDR methods, which are intended to aid policy-makers, business and civil society stakeholders in conducting transparent and accessible assessments of proposed CDR projects and facilitate fact-based decision-making thereafter.

Dr. Oliver Geden is a social scientist and Head of the Climate Policy and Politics Research Cluster at the German Institute for International and Security Affairs (SWP) in Berlin. His main areas of research are European and international policy on energy, climate and environmental topics, with a current focus on social and political developments in relation to atmospheric carbon dioxide removal (CDR). His expertise and research findings provide input for the German research missions on land-based CDR *(CDRterra)* and ocean-based CDR *(CDRmare)*. As a Lead Author for the IPCC's Working Group III, Oliver Geden and fellow authors summarized the international body of knowledge on carbon dioxide removal for the IPCC's *Sixth Assessment Report (AR6)*. He also made a significant contribution to the *AR6 Synthesis Report* as a Chapter Coordinator. In July 2023, Oliver Geden was elected Vice-Chair of Working Group III (Mitigation of Climate Change) and became a member of the IPCC Bureau. In this role, he will facilitate and support the compilation of the report in the seventh assessment cycle.

Dr. David P. Keller is a senior scientist in the Marine Biogeochemical Modelling Department at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. His main areas of research include assessments of carbon dioxide removal (CDR) approaches for climate change mitigation; and feedbacks between biogeochemical cycles and the climate. He also studies the interactions between marine ecosystems and biogeochemistry. David Keller uses Earth System modelling for many of his scientific studies. On complex research topics, he appreciates the benefits of close cooperation with academics from many other disciplines. David Keller currently leads the *OceanNETs* project (Ocean-based Negative Emission Technologies), which is funded by the European Union's *Horizon 2020* Programme and investigates ocean-based CDR approaches. As one of four lead scientists, he currently coordinates the international Carbon Dioxide Removal Model Intercomparison Project and has a lead role in five other research projects on carbon dioxide removal (CDR). He provided expert input on CDR for the IPCC's *Sixth Assessment Report* and was a Contributing Author for the Working Group I and Working Group III reports.

Prof. Dr. Achim Kopf heads the Marine Geotechnics group at the Center for Marine Environmental Sciences (MARUM), University of Bremen. As a geologist, he mainly researches the structure and physical properties of the sub-seafloor. Within the framework of the *CDRmare* research mission, he currently leads the research activities on storage of carbon dioxide in the upper oceanic crust. The purpose of these studies is to conduct ocean research drilling in the upper basalt crust in preparation for injecting carbon dioxide, or water containing CO_2, into the reactive rock on an experimental scale. With the aid of a close-meshed network of sensors on the seafloor and in boreholes, the aim is then to observe how carbon dioxide is distributed in the basalt crust and how quickly it mineralizes.

Dr. Christine Merk is the Deputy Director of the Global Commons and Climate Policy Research Center at Kiel Institute for the World Economy. Her main research interests include individual trade-offs between mitigation, carbon dioxide removal (CDR) and stratospheric aerosol injection. She conducts behavioural economics experiments and surveys to explore lay and expert perceptions and reactions. She is currently involved in two research projects that look at acceptance of ocean-based carbon dioxide removal: she leads the work package on public perceptions of marine CDR in the *Horizon2020* consortium *OceanNETs* and contributes to a German research project on seagrass restoration. In parallel, she provides expert input for the GESAMP Working Group on Ocean Interventions for Climate Change Mitigation and is involved in developing review guidelines for ocean-based CDR projects and methods as part of the *CDRmare* research mission. In addition, together with partners at the Norwegian Research Centre (NORCE), she explores perceptions of the cross-border transportation of CO_2 for storage in Germany and Norway.

Dr. Sebastian Milinski holds a PhD in Earth System Sciences from the University of Hamburg and is now a scientist at the European Centre for Medium-Range Weather Forecasts (ECMWF) in Bonn. As a Chapter Scientist, he supported the team of authors producing the Working Group I contribution (The Physical Science Basis) for the IPCC's *Sixth Assessment Report* and assisted in gathering and evaluating the current body of knowledge on climate projections (Chapter 4). Forecasting when global warming will exceed 1.5 degrees Celsius and which development pathways will drive climate change and to what extent were key topics in this context.

Dr. Katja Mintenbeck is a marine biologist. Until summer 2023, she was Director of Science at the IPCC Working Group II Technical Support Unit. In this function, among other duties, she was responsible for the IPCC *Special Report on the Ocean and Cryosphere in a Changing Climate*, which was published in September 2019, and Volume II (Impacts, Adaptation and Vulnerability) of the IPCC *Sixth Assessment Report*, published in February 2022. She also supported work on the IPCC *Synthesis Report* in the sixth assessment cycle. Prior to working for the IPCC, Katja Mintenbeck was a marine biologist in the Integrative Ecophysiology Division at the Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research (AWI) in Bremerhaven. Her work focused on the ecology of Antarctic marine biocoenoses and, specifically, the sensitivity of Antarctic fish to disturbances and environmental change, particularly increasing ocean acidification.

Prof. Dr. Andreas Oschlies is an oceanographer and Head of the Biogeochemical Modelling Research Unit at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. His research interests include the physical, biogeochemical and ecological processes of oceanic carbon uptake and possible changes in these processes as a result of climate change. For example, he and his team develop biogeochemical models to investigate changes in the oxygen content of the oceans and their ecological impacts. Since the early 2000s, Andreas Oschlies has been involved in researching and assessing climate engineering techniques and led a German Research Foundation (DFG) interdisciplinary priority programme on this topic from 2013 to 2020. Since 2021, he has served as Co-Chair of the "Marine Carbon Sinks in Decarbonization Pathways" German research mission *(CDRmare)* in which around 200 scientists from 22 partner institutions conduct cross-disciplinary research on various marine carbon dioxide removal and storage methods.

Prof. Dr. Julia Pongratz holds the Chair of Physical Geography and Land Use Systems at the University of Munich (LMU) and is the Director of the Department of Geography. Her research explores the interactions between humans, vegetation and climate. An expert in vegetation modelling, she is particularly concerned with land use change and its impact on energy, water and carbon cycles in the Earth's climate system. For example, she studies how, through afforestation/reforestation, humans can potentially increase carbon dioxide uptake in terrestrial vegetation; she also investigates what effects large-scale tree planting would have on the local and supra-regional climate. An expert in land use change and its emissions, she contributed to the IPCC's *Sixth Assessment Report* at the invitation of Working Groups I and III. She is also involved with the prestigious Global Carbon Project and is the Speaker and Project Lead for the BMBF-funded *CDRterra* research programme in which experts from various German research institutions investigate the carbon dioxide removal potential of various land-based CDR methods. One question to which they are seeking answers is to what extent there is potential to apply these methods in Germany to achieve the goal of greenhouse gas neutrality without jeopardizing other sustainable development objectives.

Prof. Dr. Alexander Proelß is a legal scholar and lecturer on international maritime and environmental law, international law and public law in the Law Faculty of the University of Hamburg. In addition to aspects of general international and European law, his areas of research primarily include international environmental law and the law of the sea, foreign constitutional law and selected areas of national environmental law. He is involved in numerous national and international research projects and currently contributes his expertise to the German *CDRmare* research mission, among others. Here, he and his team investigate which legal frameworks are required to enable the use of ocean-based carbon dioxide removal methods and how the corresponding projects can be regulated at national and international level so as to ensure their compatibility with environmental and marine conservation objectives.

Prof. Dr. Gregor Rehder is a marine biogeochemist. He is Vice Head of the Department of Marine Chemistry at Leibniz Institute for Baltic Sea Research in Warnemünde (IOW) and teaches at the University of Rostock. At IOW, he is also the Work Group Leader of the Trace Gas Biogeochemistry Group in which he and his team study important key processes in the sea and in coastal areas regulating production of trace gases and greenhouse gases that affect climatic processes and biogeochemical cycles. The scientists are developing new techniques for efficient environmental monitoring. Gregor Rehder has been a Co-Chair of the *CDRmare* research mission since 2021 and coordinates the research activities of the six participating consortia together with Prof. Dr. Andreas Oschlies.

Prof. Dr. Wilfried Rickels is an economist and Director of the Global Commons and Climate Policy Research Center at Kiel Institute for the World Economy. He and his team study the measurement of sustainable marine and maritime development, particularly in the context of the global Sustainable Development Goals, and look at the role and significance of carbon dioxide removal for climate change mitigation. The development of composite indicators and the application of integrated assessment models are particularly important in addressing these research questions. Wilfried Rickels aims to progress both these areas in various research projects. Since January 2023, he has held an endowed professorship to research economic aspects of atmospheric carbon dioxide removal at the University of Kiel.

Prof. Dr. Ulf Riebesell is a marine biologist and expert in biological oceanography at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. A plankton specialist, he was one of the first scientists in the world to study the effects of rising carbon dioxide concentrations on marine organisms. He is familiar to the public primarily for his major mesocosm experiments on ocean acidification in various areas of the sea. Since 2015, Ulf Riebesell has been conducting research studies on artificial upwelling, initially with funding from the European Research Council *(Ocean artUp)* and, since 2021, as part of the German *CDRmare* research mission *(Test ArtUp)*. He is also involved in studies on the impacts of targeted ocean alkalinity enhancement (*Retake* and *Ocean Alk-Align*) and supervises research within the framework of the EU-funded *OceanNETs* project.

Dr. Michael Sswat is a postdoctoral scientist in the Biological Oceanography Division at the GEOMAR Helmholtz Centre for Ocean Research in Kiel. In his capacity as project manager, he coordinates research activities in the Test-ArtUp consortium of the German *CDRmare* research mission and the Helmholtz European Partnering project *Ocean-CDR*. In both projects, specialists from various research institutes investigate whether artificial upwelling technologies can usefully be deployed for carbon dioxide removal, to what extent they require technical optimization, which environmental risks and ecological impacts are associated with their use, and how possible deployments can be funded and regulated. In parallel, Michael Sswat is a research diver, photographer and freelance marine biologist.

Dr. Lukas Tank holds a PhD on the ethics of carbon pricing from Humboldt-Universität zu Berlin and has been a postdoctoral researcher in the Climate Ethics, Sustainability and Global Justice research group in the University of Kiel's Department of Philosophy since 2021. As well as sharing his expertise as an ethicist with the German *CDRmare* research mission, Lukas Tank gives public lectures on aspects of climate ethics and contributes to exhibitions and discussion forums. Together with Christian Baatz and his colleague Frederike Neuber, Lukas Tank compiled the positions on the ethics of CDR presented in Chapter 9.

Prof. Dr. Klaus Wallmann is a geoscientist. He leads the Marine Geosystems Research Unit at the GEOMAR Helmholtz Centre for Ocean Research in Kiel and teaches the foundations of marine biogeochemistry at Kiel University (CAU). His research interests include material turnover at cold seeps and mud volcanoes on the sea floor, the formation of gas hydrates, microbial degradation of organic matter in surface sediments, and the recycling of nutrients from the sediments into the ocean. He is regarded as Germany's foremost expert in carbon dioxide storage in subsea sandstone formations. From 2011 to 2015, he led an EU research project on the consequences of carbon dioxide storage below the sea floor. As part of the *CDRmare* research mission, he currently coordinates the GEOSTOR consortium in which researchers aim to identify methods that would allow carbon dioxide storage in geological formations below the seabed in the German sector of the North Sea in compliance with the precautionary principle.

Lennart Westmark studied law in Hamburg and is now a research associate in the working group led by Prof. Dr. Alexander Proelß at the University of Hamburg. His research currently focuses on the legal frameworks for carbon dioxide storage in sandstone formations below the seabed in the German sector of the North Sea. In the *CDRmare* research mission, Lennart Westmark analyses the international, European and German legislation on subsea carbon dioxide storage and, on this basis, develops recommendations for its practical implementation. For his PhD project, he is investigating the role of climate research in the legislative context.

Mirco Wölfelschneider studied biology and aquatic ecology and, as a scientific staff member, now conducts research in the Mangrove Ecology Working Group at the Leibniz Centre for Tropical Marine Research in Bremen. For his PhD project, he spent several months in Brazil, studying the exchange of organic matter between mangroves and coastal waters. In parallel, as project manager for the *CDRmare* research consortium on vegetated coastal ecosystems *(sea4soCiety)*, Mirco Wölfelschneider coordinates the many natural and social science studies on seagrass meadows, tidal marshes, kelp forests and mangroves and provides support for the consortium's Coordinator, Prof. Dr. Martin Zimmer.

Prof. Dr. Martin Zimmer is a biologist. He leads the Mangrove Ecology Working Group at the Leibniz Centre for Tropical Marine Research in Bremen, teaches at the University of Bremen and is a member of the IUCN SSC Mangrove Specialist Group. Every year, he spends several weeks conducting fieldwork in tropical coastal regions populated by mangroves, where he and his team study topics such as the exchange of matter and organisms between neighbouring coastal ecosystems. They analyse sub-surface carbon content and decomposition processes in organic matter and investigate the interactions between organisms in the species-rich mangroves and how these interactions affect ecosystem processes and services. Human-induced environmental changes and their ecological impacts in mangrove forests are a further area of research. Martin Zimmer has coordinated the consortium on vegetated coastal ecosystems *(sea4soCiety)*, part of the German *CDRmare* research mission, since 2021. In this interdisciplinary consortium, researchers from various institutions investigate the role of seagrass meadows, tidal marshes, mangroves and kelp forests in the ocean's carbon cycle and look at ways to increase their carbon dioxide uptake in an environmentally sound and socially equitable manner.

We also wish to thank the team at the German Emissions Trading Authority (DEHSt), who shared their advice and expertise during the preparation of the detailed overview of the EU Emissions Trading System and its forthcoming reform.

Index

Page numbers printed in **bold** draw attention to passages within the text which are especially important for an understanding of the concept in question.

Partners

Future Ocean: The research network harnesses the collective knowledge of marine scientists, economists, medical scientists, mathematicians, IT experts, legal scholars and social scientists in pursuit of the study of oceanic and climate change. A total of more than 250 scientists working at Kiel University (CAU), GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design join forces to develop options for sustainable marine conservation and use.

IOI: The International Ocean Institute is a non-profit organization founded by Professor Elisabeth Mann Borgese in 1972. It consists of a network of operational centres located all over the world. Its headquarters are in Malta. The IOI advocates the peaceful and sustainable use of the oceans.

KDM: The German Marine Research Consortium combines the broad expertise of German marine research. Its membership comprises all of the research institutes that are active in marine, polar and coastal research. A primary objective of the KDM is to collectively represent the interests of marine researchers to national and international policy-makers and the EU as well as to the general public.

mare: The bimonthly German-language magazine *mare*, which focuses on the topic of the sea, was founded by Nikolaus Gelpke in Hamburg in 1997. *mare's* mission is to raise the public's awareness of the importance of the sea as a living, economic and cultural space. Besides the magazine, which has received numerous awards for its high-quality reporting and photographs, its publisher mareverlag also produces a number of fiction and non-fiction titles twice a year.

Acknowledgement

Producing a publication like the *World Ocean Review* is an undertaking requiring major commitment and effort. I would therefore like to first express my thanks to all the participating scientists for their contributions to this review. I am also most grateful to the organizational team of the German Marine Research Consortium and the Future Ocean Network in Kiel for ensuring a smooth and uninterrupted communication process and for working so hard behind the scenes.

I further wish to express my particular appreciation to scientific journalist Sina Löschke, who gave structure to the individual texts and ensured that they could be read and enjoyed by scientists and the general public alike. My sincere thanks also go to designers and layouters Anna Boucsein and Andrea Best, photo editors Petra Koßmann and Anastasia Hermann, text editor Dimitri Ladischensky, copyreader Susanne Feyke, and last but not least Jan Lehmköster, the project manager at maribus, who nurtured the *World Ocean Review* from the beginning.

Nikolaus Gelpke
Managing Director of maribus gGmbH

This publication is endorsed by the United Nations Decade of Ocean Science for Sustainable Development as a Decade Activity. Use of the United Nations Decade of Ocean Science for Sustainable Development logo by a non-UN entity does not imply the endorsement of the United Nations of such entity, its products or services, or of its planned activities. For more information please access: https://forum.oceandecade.org/page/disclaimer.

Table of figures

Publication details

Project manager: Jan Lehmköster, maribus
Editing and text: Sina Löschke
Copy editing: Dimitri Ladischensky, mare
Design and typesetting: Anna Boucsein and Andrea Best, mare
Proofreading: Susanne Feyke
Photo editing: Anastasia Hermann, mare; Petra Koßmann, mare
Graphics: Walther-Maria Scheid
Production: HS Printproduktion, Holger Schmirgalski
Printing: Druckhaus Sportflieger
Paper: PrimaSet, FSC®-certified

ISBN 978-3-86648-734-5
Published by: maribus gGmbH, Pickhuben 2, 20457 Hamburg

www.maribus.com

Reproduction, translation, microfilming, electronic processing and transmission in any form or by any means are prohibited without the prior permission in writing of maribus gGmbH.
All the graphics in the *World Ocean Review* were produced exclusively by Walther-Maria Scheid, Berlin. The figure and photo credits state the original sources which were used as a basis for the preparation of the illustrations in some cases.

MIX
Papier aus verantwortungsvollen Quellen
FSC® C104247

klimaneutral gedruckt
www.klima-druck.de
ID-Nr. 1982652

Here you can download all WORs directly.
Link: https://worldoceanreview.com/en/download/

Here you can order all WORs directly.
Link: https://worldoceanreview.com/en/order/

Following *World Ocean Reviews* have already been published and can be ordered free of charge at: www.worldoceanreview.com

WOR 1, 2010
Living with the oceans – a report on the state of the world's oceans

WOR 2, 2013
The Future of Fish – The Fisheries of the Future

WOR 3, 2014
Marine Ressources – Opportunities and Risks

WOR 4, 2015
Sustainable Use of Our Oceans – Making Ideas Work

WOR 5, 2017
Coasts – A Vital Habitat Under Pressure

WOR 6, 2019
The Arktic and Antarctic – Extreme, Climatically Crucial and In Crisis

WOR 7, 2021
The Ocean, Guarantor of Life – Sustainable Use, Effective Protection