RETAKE

RETAKE – CO_2 Removal through Alkalinity Enhancement: Potential, Benefits and Risks

New findings on capturing CO_2 by increasing the alkalinity of seawater: The seven most important outcomes of RETAKE research

CDRmare INSIGHTS

In the CDRmare research consortium RETAKE, experts investigate how enhanced weathering of minerals can increase the ocean's acid-binding capacity (alkalinity). They examine whether or not this process amplifies the seawater's natural carbon dioxide (CO_2) uptake and assess its potential risks and benefits. In the following, we summarise seven of their most relevant findings.

1. Today, a wide range of methods are under discussion that can increase the ocean's acid-binding capacity (alkalinity) to increase its carbon dioxide uptake. Each method must be investigated individually and assessed in connection with different deployment sites.

2. Research into methods of increasing the ocean's alkalinity is the subject of societal debate. According to critics, it raises hopes of supposed climate solutions that may lead to reduced efforts by humans to fully avoid CO_2 emissions.

3. The implementation of ocean alkalinity enhancement methods is subject to natural and technical limitations.

4. The effects of alkalinity-enhancing methods on marine life can be substantial. Accordingly, their use must always be carefully planned, and relevant environmental parameters must be jointly monitored in cooperation with independent experts and the responsible authorities.

5. The CO_2 removal potential and effectiveness of alkalinity-enhancing methods differ from region to region. Along the German coastline, certain methods are naturally better suited than others from a scientific perspective.

6. By applying two or three alkalinity enhancement methods in its waters, Germany could remove several million metric tons of CO_2 from the atmosphere per year – well before the year 2045, by which time the nation plans to be greenhouse-gas-neutral.

7. Quantifying and verifying the additional CO_2 removal achieved through alkalinity enhancement is problematic.

CDRmare
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Key message 1

Today, a wide range of methods are under discussion that can increase the ocean's acid-binding capacity (alkalinity) to increase its carbon dioxide uptake. Each method must be investigated individually and assessed in connection with different deployment sites.

The methods chiefly differ as follows: whether the seawater's alkalinity is to be increased using electrochemical approaches or through the accelerated dissolution and weathering of finely ground minerals like lime and silicates. The effect is the same: acidic protons in the seawater are bound, and the percentage of dissolved carbon dioxide (CO_2) declines. As a result, the ocean's surface can absorb new CO_2 from the atmosphere. (For more detailed information, please see our Fact Sheet: Minerals for enhanced carbon dioxide uptake by the ocean.)

Electrochemical approaches are highly energy-intensive and produce large amounts of acid. They are currently being developed by a handful of start-ups, primarily in the US. In contrast, the experts from the RETAKE consortium are focusing on the accelerated weathering of finely ground minerals, which can be achieved in several ways. Theoretically, the mineral powder could simply be distributed across the ocean's surface. Alternatively, it could be spread out on beaches or in the surf or directly pumped to the ocean floor using long hoses.

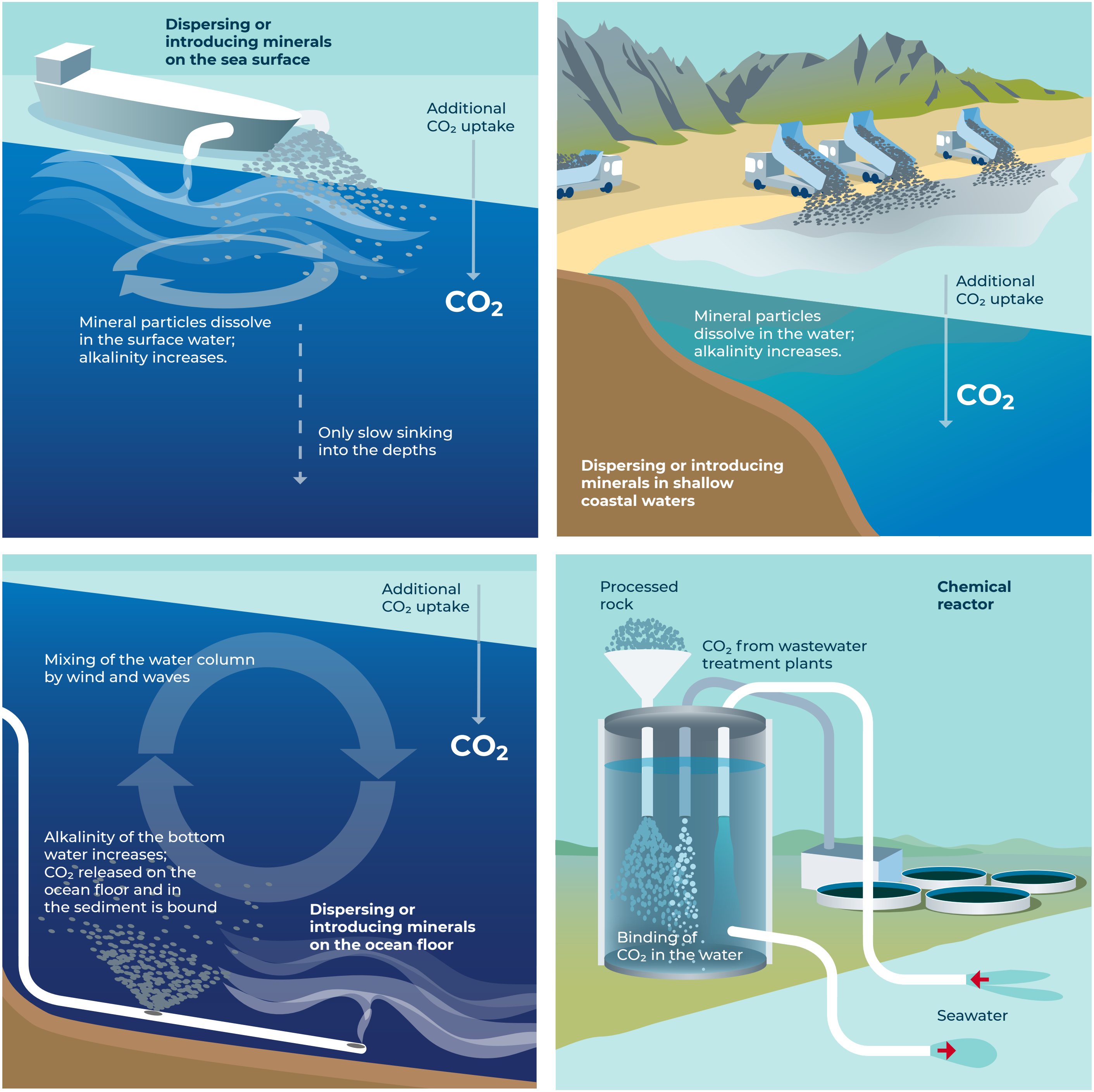
If the goal is to increase the ocean's carbon dioxide uptake by spreading rock dust on the water's surface, the mineral particles have to remain in the surface water until they dissolve – since the alkalinity of the surface water has to be increased before the ocean can absorb more CO_2 from the atmosphere. If the particles sink to the bottom too quickly, the alkalinity of the deep water rises, but the acid-binding capacity of the surface water, which exchanges gases with the atmosphere, remains virtually unchanged – meaning almost no additional CO_2 can be absorbed from the atmosphere.

In shallow coastal waters, it's a different story: here, the wind and waves mix the water column so thoroughly that the acid-binding, soluble products of rock weathering on the seafloor make their way to the surface water, altering its chemical composition and enabling it to absorb additional CO_2 from the atmosphere.

If the rock dust were directly distributed on the seafloor, its weathering would fix CO_2 from the bottom water, which is released when ocean floor-dwelling microbes break down the animal and plant matter stored in the sediment. To use this method to remove additional CO_2 from the atmosphere, the alkalinised bottom water has to reach the ocean's surface. In the shallow Baltic, this takes a few months up to a year, as the wind and waves mix the water masses to a sufficient depth. But in deeper waters, the bottom water can only upwell if there are favourable local currents.

Over the past three years, experts from the CDRmare research consortium RETAKE have also investigated a method in which finely ground lime is weathered in a reactor. The resulting solution can then be subsequently pumped out to sea. In this type of weathering, the rock dust is mixed with water in a reactor that has previously been enriched with captured CO_2. During the weathering process, the CO_2 is chemically fixed and, after being pumped out to sea, is distributed by currents and eventually stored in the ocean depths.

The first practical tests of these reactors in Germany are currently being planned and carried out. The reactors are installed at wastewater treatment plants, whose residual sewage sludge or generated foul gas is incinerated so that CO_2 can be captured. The alkalinised reactor water is then either released into rivers or directly into the North Sea or Baltic Sea together with the treated wastewater.



Graphics: Rita Erven, CDRmare

There are now many different methods for increasing the alkalinity of the ocean. The CDRmare research network RETAKE is investigating the following four methods: the dispersion or introduction of minerals or alkaline solutions 1) on the sea surface (top left), 2) in shallow water or coastal areas (top right) and 3) directly on the ocean floor (bottom left). As a fourth method, the experts are testing the accelerated weathering of minerals in chemical reactors (bottom right). In this process, however, CO_2 is primarily bound in the water, which was previously captured during combustion processes. This process is only a genuine CO_2 removal from the atmosphere if the captured CO_2 originates from the combustion of biomass, for the creation of which plants once absorbed CO_2 from the atmosphere.

The Hamburg-based company Planeteers develops processes for the accelerated dissolution of minerals to capture CO_2 in chemical reactors. Prototypes of such reactors are currently being built and tested at selected wastewater treatment plants in northern Germany. The CO_2 bound in the reactor water originates from the exhaust gases of the local power plants, which either burn residual sewage sludge or foul gas produced by bacteria in the treatment plants' digesters.

Photo: Planeteers

An important aspect to bear in mind: if the CO_2 used to enrich the reactor water stems from the exhaust gases of treatment plants or the burning of plant biomass, then chemically fixing it by means of alkalinity enhancement actually constitutes removing CO_2 from the atmosphere. In contrast, if the CO_2 is from fossil sources, chemically fixing it in water is a form of emission avoidance.

It remains unclear how effective and productive it would be to distribute mineral powder on the open ocean; aside from a trial run conducted by a North American start-up, no corresponding field research has been pursued. In Germany, the type of field experiments called for are prohibited. In order for researchers to investigate under realistic environmental conditions the circumstances under which carbon dioxide removal could be achieved, and what changes the added mineral powder triggers in the ocean, this ban would need to be lifted.

Key message 2

Research into methods of increasing the ocean's alkalinity is the subject of societal debate. According to critics, it raises hopes of supposed climate solutions that may lead to reduced efforts by humans to fully avoid CO_2 emissions.

There is no factual basis for such hopes: the ocean cannot possibly solve humanity's massive emissions problem in time – and couldn't do so even if alkalinity enhancement methods were applied around the globe. The methods currently available are simply too complex in terms of their large-scale implementation, and their CO_2 removal rates are much too low. In 2024, humanity released a record-breaking 37.4 billion metric tons of fossil CO_2 from the burning of coal, oil, and natural gas alone. If we add the CO_2 emissions produced by land-use changes, the number climbs to a staggering 41.6 billion metric tons of CO_2.

Applying ocean-based methods for targeted CO_2 removal could only compensate for a fraction of that amount. Accordingly, we have to do everything within our power to avoid CO_2 emissions –

in energy production and transport alike, in industry, food production, construction, and heating. CO_2 removal methods can only help compensate for residual emissions that are difficult or impossible to avoid, e.g., CO_2 emissions in agriculture or heavy goods vehicle traffic.

The idea that the ocean can serve as unlimited carbon dioxide storage is unfounded. As the judges of the International Tribunal for the Law of the Sea (ITLOS) explained in their groundbreaking statement on 21 May 2024, the release of fossil CO_2 emissions by humans into the atmosphere can be considered a form of marine pollution — among other reasons because the ocean takes up some of that CO_2, which then leads to acidification. The obligation to reduce pollution of the marine environment derives directly from the United Nations Convention on the Law of the Sea (UNCLOS). Consequently, the parties to this multilateral treaty are also under an indirect obligation to reduce the release of fossil CO_2 emissions.

As the ITLOS judges have determined, states must also fulfil their duty not to transfer damage or hazards in keeping with Article 195 of the UNCLOS, according to which it is fundamentally impermissible to transform one form of pollution into another. Accordingly, measures that intentionally pollute the ocean to compensate for other forms of pollution are prohibited. To what extent the enhanced weathering of finely ground lime and silicates to compensate for hard-to-avoid residual emissions constitutes the type of pollution forbidden in the UNCLOS is the subject of ongoing scientific and legal debates.

However, one thing is clear: targeted alkalinity enhancement can mitigate the climate-related acidification of seawater, at least in the short term. This would, above all, benefit bivalves, foraminifera, and other calcifying marine fauna, as it is easier for them to form their shells and skeletons in less acidified water. One drawback: when calcium carbonate is formed in seawater, CO_2 is always released – regardless of whether it is produced by the organisms themselves or by chemical changes.

Key message 3

The implementation of ocean alkalinity enhancement methods is subject to natural and technical limitations.

The ocean's alkalinity can't simply be increased indefinitely. As the laws of chemistry dictate, when too much of a mineral powder or alkaline substance is added to the seawater, new solids can be formed through precipitation – in many cases, calcium carbonate. When this happens, the alkalinity is exhausted, and CO_2 is released.

Precipitation must be avoided in alkalinity enhancement projects. Experimental studies conducted by the RETAKE consortium show that precipitation processes can take on a life of their own: once set in motion, initial precipitation can trigger other chemical reactions in the ocean. Potentially, so much carbonate could be precipitated that the alkalinity of the seawater would ultimately be lower than it was before the minerals were added. Since the precipitation of carbonate releases previously sequestered CO_2, improperly "dosed" alkalinity enhancements can have the opposite effect, reducing the ocean's uptake of CO_2 instead of increasing it.

Moreover, RETAKE research has confirmed that silicate olivine is not suitable for broad-scale deployment on the ocean's surface for two main reasons. First, it dissolves in seawater much too slowly. While grinding the material to a finer size could reduce the weathering time, even a grain size of 10 micrometers (0.01 millimeters) would not be sufficient to fully dissolve olivine added to the North Sea over the course of 100 years. Secondly, silicates like olivine can contain heavy metals like nickel. If large quantities of these heavy metals were released during the weathering process, it would harm marine life (see also Key Message 4).

Based on RETAKE findings, quicklime (calcium hydroxide) would be a suitable material. It dissolves quickly in water and contains no toxic impurities. However, its manufacture involves unavoidable CO_2 emissions, which would need to be captured and stored underground (Carbon Capture and Storage (CCS)). This, in turn, means that sufficiently large CO_2 storage facilities, as well as the infrastructure for transporting the carbon dioxide, would also be needed. Nevertheless, compared to other CO_2 removal methods, the projected costs of alkalinity enhancement with quicklime are quite competitive, even when the additional costs for CCS are included.

The planned weathering reactors could also reach their technical limits: only a certain amount of water can be alkalinised in each reactor at a time. Given the current state of research, it remains unclear whether or not sufficiently large reactors, or a sufficient number of such reactors, could be installed and operated to produce climate-relevant effects in time.

The researchers also gained new insights regarding the duration of chemical CO_2 storage in the ocean. Model-based studies indicate that CO_2 absorbed by the ocean through alkalinity enhancement remains there for several thousand years. In order to more precisely gauge the storage duration, they would still need to determine whether and if so, how calcifying organisms and processes in the top layer of the seafloor respond to the increased alkalinity and whether these organisms and processes affect the acid-binding capacity of the water masses.

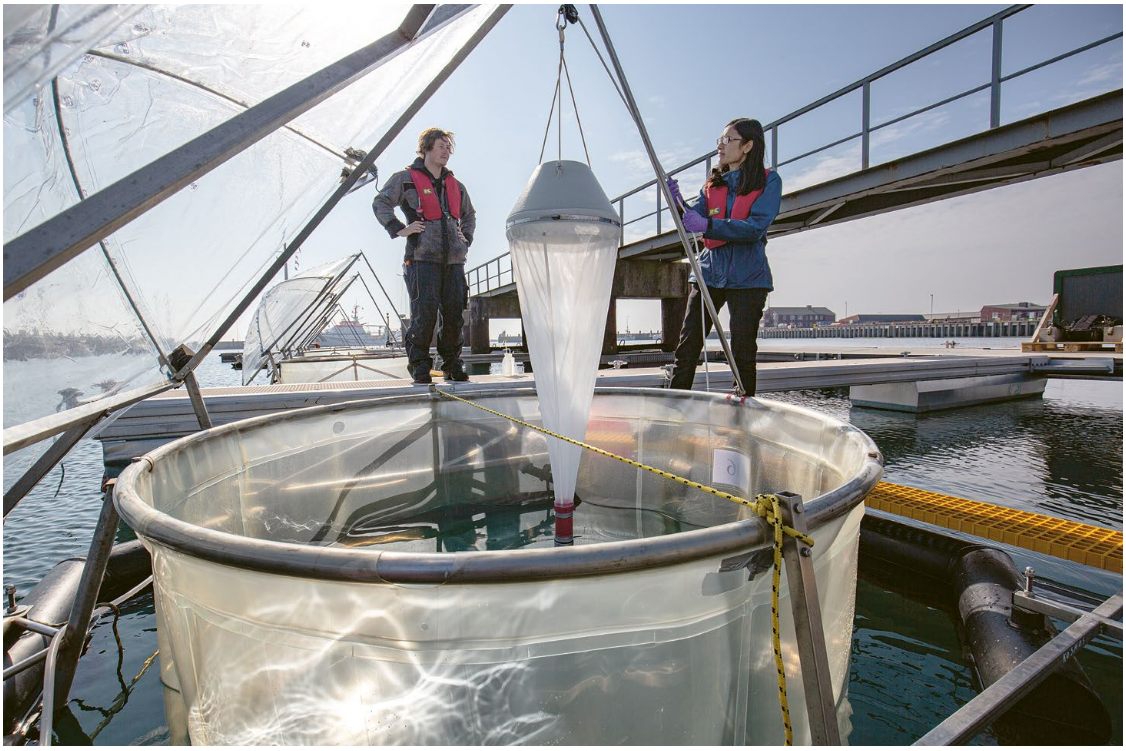
Key message 4

The effects of alkalinity-enhancing methods on marine life can be substantial. Accordingly, their use must always be carefully planned, and relevant environmental parameters must be jointly monitored in cooperation with independent experts and the responsible authorities.

In a range of laboratory and mesocosm-based experiments, experts from the RETAKE consortium have investigated the potential effects of alkalinity-enhancing mineral powders and solutions on the growth of single-celled marine algae and zooplankton species, organisms that form the basis of marine food webs. The experiments showed that when high doses of alkalinity-enhancing substances were introduced, the plankton community was very sensitive to sudden increases in the acid-binding capacity in the water column. This was especially the case in experiments conducted in spring, the time of year when microalgae produce blooms and the zooplankton species are still in the growth phase.

The researchers attribute their observations to the fact that, in water with high alkalinity (i. e., water in which a great deal of CO_2 is chemically fixed), less CO_2 is available for photosynthesis. As a result, growth slows down. For example, the coccolithophore and keystone species *Emiliania huxleyi* stops growing when the seawater's CO_2 content drops below 100 micromoles per kilogramme. In addition, microalgae demonstrate varying degrees of sensitivity to toxic heavy metals like nickel, which silicates can contain. In corresponding experiments, in particular, the diatom *Thalassiosira weissflogii* experienced growth problems in response to even moderate nickel concentrations.

Further, it makes a difference whether the minerals are added to the mesocosms in powder form or as a solution in which the minerals are already pre-weathered (also referred to by experts as pre-dissolved alkalinity). In mesocosm experiments using a solution, interactions between different phytoplankton and zooplankton species changed from a certain dosage level: when the seawater's alkalinity increased by 250 micromoles per kilogramme. Put in perspective, this represents a 10 to 15 percent increase in ocean alkalinity. However, depending on the wind, currents and



Photos: Michael Sswat, GEOMAR

To study the effects of increasing alkalinity on marine life, RETAKE experts on Helgoland filled large plastic tubes (mesocosms) with seawater and all the organisms that live in it. They then increased the alkalinity of the water in the tubes and documented how the algae and zooplankton community responded.

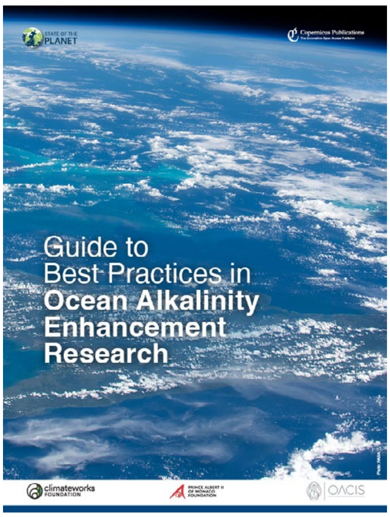
mixing conditions, the alkalinity of the surface water would locally rise by the same amount if alkalinity enhancement methods were applied in the field – though most likely only for a short time.

When researchers added minerals to the mesocosms in powder form as part of an international partner project, the threshold value was even lower: from an alkalinity enhancement of 150 micromoles per kilogramme of water, microplankton quantity and biomass began to decline. This was especially the case with diatoms. The even smaller nanoplankton and picophytoplankton benefited from the decline in diatoms, most likely thanks to the unused nutrients now available. However, there were also confirmed effects on the zooplankton; as a result, the threshold value for alkalinity enhancement of 150 micromoles per kilogramme of water applies to the algae and the algae-eating zooplankton alike.

As such, the RETAKE experts recommend exercising caution: too high a dose of alkaline substances can alter the composition of the plankton community and, with it, the basis of food webs. Consequently, in order to assess the feasibility of applying alkalinity enhancement methods in the ocean on a large scale, the potential effects of increased alkalinity must be extensively investigated – both with regard to entire marine communities and to relevant keystone species.

The interactions within marine biotic communities in response to alkalinity enhancement are complex and not yet fully understood. Even minor effects on individual species can alter the composition of the microalgae community. This change can, in turn, have substantial effects on the community's population size and, therefore, its ecological and biogeochemical relevance. Consequently, projects focusing on ocean alkalinity enhancement should only be pursued if they are accompanied by an environmental monitoring programme.

The design of such an accompanying programme is currently being explored in the RETAKE project. Here, the experts also discuss whether the alkalinity values used in the experiments to date could actually be achieved in the field. For example, the effects of wind, waves and currents could rapidly mix the highly alkalinised water with the surrounding water. The high alkalinity values would then rapidly decline and the effects on the plankton community, observed in laboratory experiments, might not come to pass. In the project's first phase, the question of which lab scenario most closely matches reality was not definitively answered.

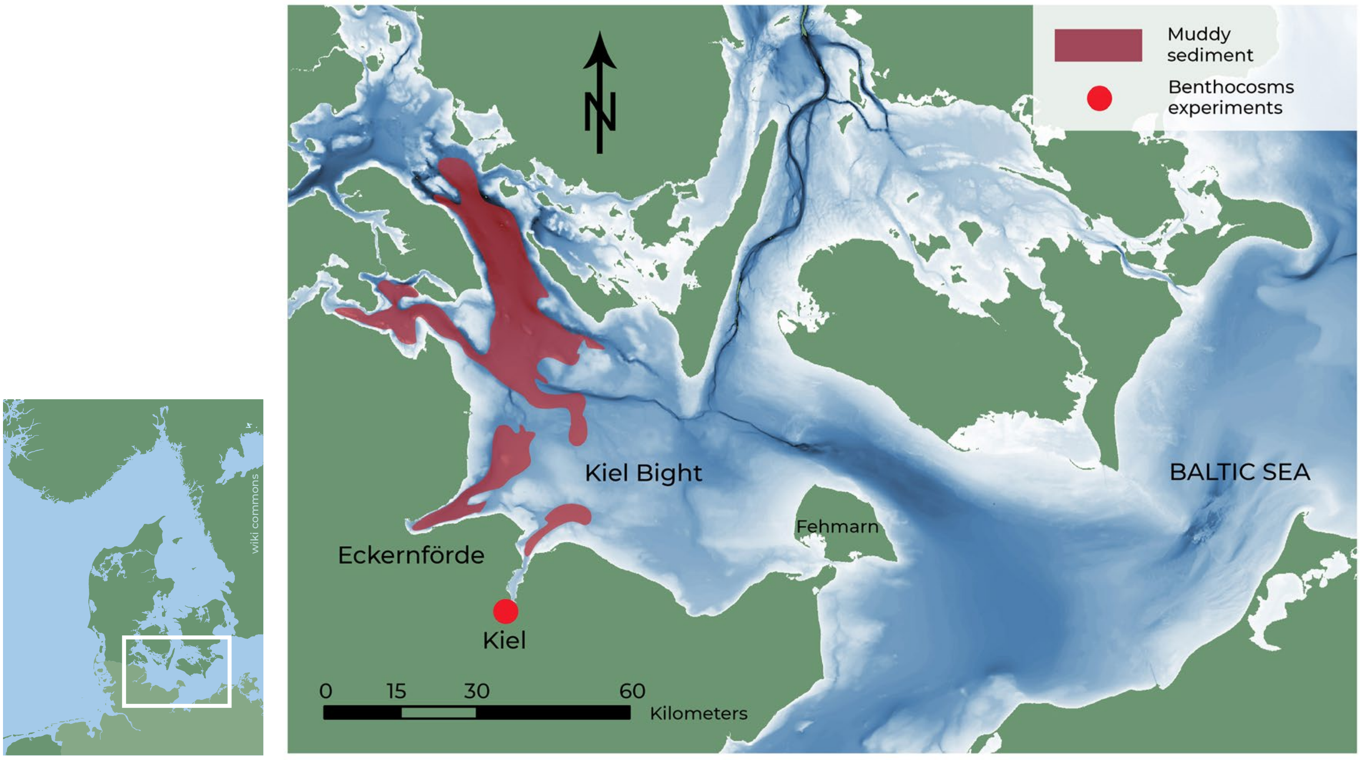


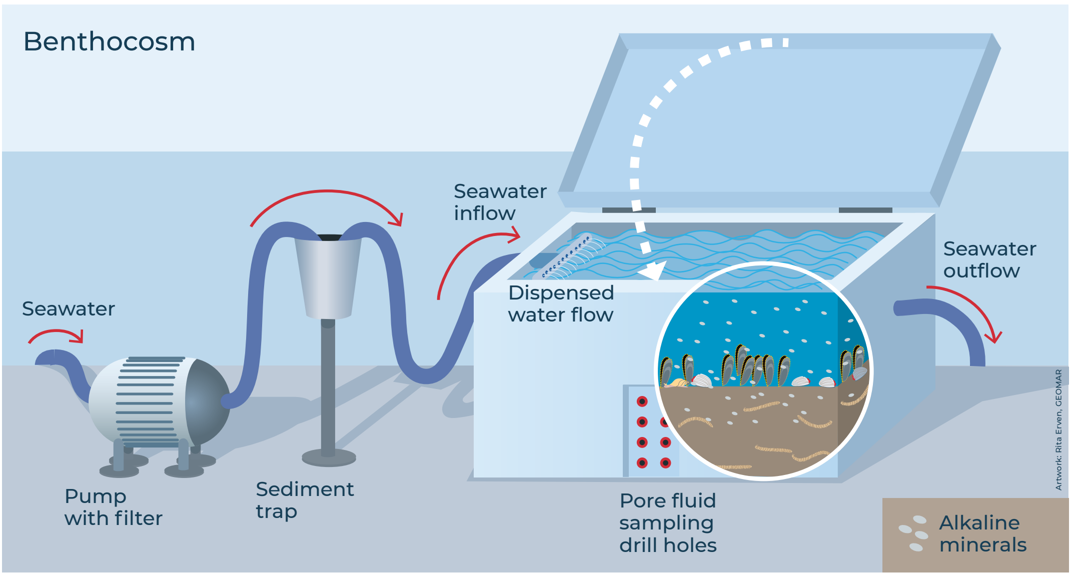
Further, eight leading RETAKE experts have taken part in the creation of international guidelines for responsible research into alkalinity enhancement methods. The publication, titled "Best Practices Guide to Ocean Alkalinity Enhancement Research", sheds light on the current state of knowledge regarding the strengths and weaknesses of various approaches and provides additional information on key research methods like mesocosm-based experiments. The goal is to encourage scientists around the world to pursue ocean alkalinity enhancement research that is comparable, integrative, and transparent for the public.

Key message 5

The CO_2 removal potential and effectiveness of alkalinity-enhancing methods differ from region to region. Along the German coastline, certain methods are naturally better suited than others from a scientific perspective.

All findings from the RETAKE project to date indicate that the suitability of the respective alkalinity enhancement methods depends on local environmental conditions. In this regard, relevant factors include the temperature and salinity of the local seawater, local currents, the degree of water mixing and, in areas with shallow waters, the characteristics of the seafloor.





Map: Michael Fuhr, Rita Erven, GEOMAR, Graphic: Rita Erven, CDRmare

In the western Baltic Sea, there are some areas where the seabed is muddy and rich in organic material. There, targeted weathering of minerals on the seabed could increase the CO_2 uptake of the Baltic Sea. RETAKE scientists have found evidence of this in laboratory experiments in which they tested the weathering of calcite on a small scale.

For example, spreading mineral powder is a method better suited to shallow coastal seas, as the wind and waves mix the water column down to the seafloor there. As a result, even weathering on the seafloor can result in increased CO_2 uptake at the water's surface. If silicates are to be used, warmer regions would offer ideal conditions, as the chemical dissolution reactions proceed faster in warm water than in cold.

Distributing lime powder on the seafloor produces the best results (a) when the deep water is highly acidic, which is particularly the case in oxygen-poor regions of the Baltic Sea, and (b) when the upper seafloor layer is especially muddy, i.e., fine-grained and rich in organic material. In contrast, if ground silicates are to be used on the seafloor, the upper seafloor layer should be highly permeable and the deep water should be continuously exchanged by currents – conditions that can be found in sandy areas, for example. But even there, it would take several decades for the added silicates to be completely weathered.

In the German North Sea and Baltic Sea, there are a number of regions that meet the criteria for the accelerated weathering of finely ground lime on the seafloor. One example: parts of Eckernförde Bay on Schleswig-Holstein's Baltic coast. Its seafloor is muddy and extremely rich in organic material (animal and plant matter). In addition, oxygen-poor zones form on the seafloor in summer and autumn. When, under these conditions, organisms on and in the seafloor release CO_2, e. g. by breaking down organic material, the deep water acidifies. In turn, lime dissolves faster in mildly acidified water. Consequently, the targeted input of mineral powder in the oxygen-poor zones could be used to reverse the acidification on the seafloor and to chemically bind the CO_2 released by these organisms.

It remains unclear, however, whether the targeted dissolution of added limestone powder would slow down the natural dissolution of mussel shells and other biogenic carbonates on the seafloor, and whether mussels would grow better as a result of increased alkalinity – potentially offsetting part of the intended CO_2 removal through the CO_2 released during shell formation. Both questions are at the core of RETAKE research efforts in Funding Phase II, which is ongoing and will end in summer 2027.

Key message 6

By applying two or three alkalinity enhancement methods in its waters, Germany could remove several million metric tons of CO_2 from the atmosphere per year – well before the year 2045, by which time the nation plans to be greenhouse-gas-neutral.

All findings from the RETAKE project to date indicate that the assessed ocean alkalinity enhancement methods work; but also, due to a range of limiting factors, that they work on a lower scale than theoretically presumed. Nevertheless, alkalinity enhancement represents a promising approach for permanently removing substantial amounts of CO_2 from the atmosphere and storing them in the water masses of the North Sea as well as the Baltic Sea.

For example, if two or three particularly well-suited methods were combined, Germany could fix more than 15 million metric tons of CO_2 in its North Sea and Baltic Sea waters a year. In this regard, the candidates include methods explored in RETAKE, such as the accelerated weathering of finely ground lime on the seafloor of the Baltic Sea; the deployment of numerous weathering reactors along Germany's major rivers; and distributing quicklime solution in the North Sea.

According to our estimates, accelerated weathering on the seabed of seasonally oxygen-poor regions throughout the Baltic Sea could chemically bind around 3.2 million tonnes of atmospheric CO_2 per year, assuming no subsequent effects in seawater chemistry (currently being studied in RETAKE) reduce the efficiency of the method. However, the lime powder would need to be regularly distributed in the corresponding zones for weathering for at least 10 years.

Erecting weathering reactors on a large scale along its rivers and coastlines would afford Germany an estimated additional capture and storage potential of 10 million metric tons of CO_2 per year. Another 5 million metric tons of CO_2 could theoretically be fixed by distributing a lye made of quicklime and freshwater along the shipping routes of the German North Sea. However, this approach would consume considerable energy and, above all, require the capture and geological storage of the CO_2 generated by the production of the quicklime: manufacturing sufficient lime for the ocean-based removal of 5 million metric tons of CO_2 would generate 3.5 million metric tons of CO_2 emissions – which would need to be captured and geologically stored.

Nevertheless, their technical feasibility is only one of many prerequisites for deploying marine CO_2 removal methods; a robust legal framework and the necessary level of political and societal support are also essential. Further, established monitoring and control systems are called for, so as to ensure that the methods are applied as sustainably as possible, and that their use also achieves the intended results and delivers the outcomes it promised.

Key message 7

Quantifying and verifying the additional CO_2 removal achieved through alkalinity enhancement is problematic.

The sheer size of the world's oceans, their complex seawater chemistry, and the substantial natural fluctuations within the ocean system would make it extremely difficult for experts to prove how much the seawater's alkalinity rose following the addition of minerals, and how much additional carbon dioxide the ocean took up as a result; the corresponding CO_2 signals would be diluted and carried away by the waves, wind and currents far too quickly. As such, in many waters, it could take a few decades before the ocean's additional CO_2 uptake were actually detectable.

In the interim, for the purposes of short-term reports and inspections, as would be needed e.g. for certificate trading, it would be necessary to rely on theoretical estimates and small-scale experiments, or on the results of numerical simulations. However, doing so would involve considerable uncertainty.

This uncertainty could make it more likely that some mineral-based ocean alkalinity enhancement methods will not be used for CO_2 removal, as their effectiveness would be difficult to verify. Interested actors could then resort to weathering reactors, or to methods in which CO_2 is captured and stored underground, instead. Though these approaches are resource-intensive, their effects can be precisely measured, documented and verified.

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