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STATE OF THE PLANET Discussions

Climate targets, carbon dioxide removal and the potential role of Ocean Alkalinity Enhancement

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Abstract. The Paris Agreement to limit global warming to well below 2°C requires ambitious emission reduction and the balancing of remaining emissions through carbon sinks, i.e. the deployment of carbon dioxide removal (CDR). While ambitious climate protection scenarios until now consider primarily land-based CDR methods, there is growing concern about their potential to deliver sufficient CDR, and marine CDR options receive more and more interest. Based on idealized theoretical studies, Ocean Alkalinity Enhancement (OAE) appears as a promising marine CDR method. However, the knowledge base is insufficient for a robust assessment of its practical feasibility, of its side effects, social and governance aspects as well as monitoring, reporting and verification issues. A number of research efforts aim to improve this in a timely manner. We provide an overview on the current situation of developing OAE as marine CDR method, and describe the history that has led to the creation of the OAE research Best Practices Guide.

1 Climate Goals and the need for Carbon Dioxide Removal

Achieving the Paris Agreement's goal of limiting global warming to well below 2°C, and ideally 1.5°C, requires ambitious reductions in anthropogenic greenhouse gas emissions and the balancing of remaining emissions through carbon sinks in the second half of the 21st century (UNFCCC, 2015). The balance to be achieved is also called net zero and is a qualitatively new element compared to previous climate protection agreements. The net-zero requirement for avoiding further temperature rise derives from a key finding of climate research in recent decades, namely that the increase in global mean surface air

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temperature since the beginning of industrialization is proportional to cumulative emissions of carbon dioxide (CO_2), the major anthropogenic greenhouse gas (Matthews et al. 2009).

Arresting global warming will thus require net-zero CO_2 emissions. Non-CO_2 greenhouse gases (GHGs), in particular nitrous oxide and methane, also contribute to current warming. However, because their lifetime in the atmosphere is considerably shorter than that of CO_2, arresting global warming does not require net-zero non-CO_2 GHG emissions (Allen et al., 2022). Nevertheless, increases in non-CO_2 GHG emissions may lead to further temperature rise, whereas a decrease in non-CO_2 GHG emissions will relatively quickly reduce atmospheric concentrations of the respective non-CO_2 GHG and thus radiative forcing and global warming. In order to achieve the long-term temperature goal, parties to the Paris Agreement agreed to reach global peaking of GHG emissions as soon as possible, to undertake rapid reductions thereafter and to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century. Since it is not foreseeable that all greenhouse gas emissions can be avoided by mid-century, the net-zero target set in the Paris Agreement implies the deployment of CO_2 removal methods and explicitly refers to enhancing carbon sinks. The Paris Agreement adopts the UNFCCC definition of "sink," which refers to "any process, activity or mechanism which removes a greenhouse gas . . . from the atmosphere," and thus encompasses both ecosystem-based and more technological or engineered removal approaches. Presently, no viable methods for large-scale non-CO_2 greenhouse gas removal exist, so carbon dioxide removal (CDR) will likely have to balance hard-to-abate residual emissions of non-CO_2 GHG emissions from, e.g., agriculture, in addition to hard-to-abate residual CO_2 emissions, e.g. from cement production, waste incineration, aviation and maritime transport.

The amount of these residual emissions needs to be politically and socially viable. In principle, all 'hard-to-abate' emissions are technically avoidable, e.g. by switching from fossil to renewable energy, by capturing and safely storing CO_2 from process emissions (e.g. cement production with renewable energy), or by avoiding the processes that lead to emissions. Particularly in the agricultural sector, avoiding all emissions appears impossible without critical societal impacts: rice production and the raising of livestock are associated with methane production, and any use of nitrogen fertilizer is associated with nitrous oxide production, which are both potent non-CO_2 greenhouse gases. The exact amount of residual emissions is thus largely an issue of economic and social costs and society's ambition to avoid emissions. Which emissions are deemed unavoidable also varies across historical and political contexts and is influenced by claims as to what is regarded as legitimately possible (Lund et al. 2023). Ultimately, decisions about the amount of residual emissions depend on values, norms and interests. Current scenarios assume that, by mid-century, residual emissions will amount to close to 20% of today's emissions, i.e. to several Gt CO_2 per year globally (Buck et al., 2023).

By mid century, all remaining CO_2 emissions will have to be balanced by CDR in order to reach net-zero CO_2 and thereby arrest global warming. In order to reach net-zero GHG emissions as stated in the Paris Agreement and in national legislation of a number of countries, also residual emissions of non-CO_2 GHGs will have to be balanced by CDR unless atmospheric removal of non-CO_2 GHG should become possible. Current global CDR deployment has been estimated near 2 Gt CO_2 per year mostly by conventional management of land, primarily afforestation and reforestation and with only 0.002 Gt CO_2 yr^{-1} by 'novel' CDR schemes comprising bioenergy with carbon capture and storage (BECCS), direct air capture with carbon storage (DACCS), enhanced weathering, and marine CDR, also sometime called ocean CDR, including ocean alkalinity enhancement (OAE) as a subcategory (Smith et al., 2023). According to the 'State of CDR' report (Smith et al., 2023), deployment of novel CDR approaches will have to increase by three orders of magnitude by mid century in order to reach net-zero emission even in most ambitious emission reduction scenarios. Note that many scenarios used in the recent IPCC's 6th Assessment Report assume that emissions turn net negative after having reached net zero (Fig.1), which would allow a net cooling and is also deemed necessary for so-called temperature overshoot scenarios (Geden and Löschel, 2017) that receive more attention the longer it takes to drastically reduce emissions. It is, however, currently unclear how to incentivise and govern net negative emissions.

While the current climate goal of the UNFCCC is to limit the temperature rise to 2°C or 1.5°C, one could also envisage climate targets that aim to reduce global temperatures further toward pre-industrial levels, and much faster than the tens to hundreds of millennia that planetary feedbacks would take to do so (Archer et al., 2009). Should humanity aim for a faster restoration of the planetary thermal balance to pre-industrial times, CDR would be a prime mechanism with deployment required well beyond the current 'net-zero' targets.

2 CDR approaches and the role the ocean could play

Traditionally, the focus of CDR has been on land-based methods such as reforestation and afforestation or BECCS. While these approaches certainly have some potential, there are unresolved issues related to land-use competition and associated political and societal feasibility challenges, and it is currently unclear if and how their combined deployment will be possible at scales sufficient to meet the net zero target by mid century (The Land Gap Report, Dooley et al., 2022). It is thus unlikely that such ecosystem-based solutions alone will be sufficient to achieve net-zero (Smith et al., 2023) and therefore 'novel' approaches will also have to be applied to a considerable extent. None of these are ready for large-scale deployment today. Transparent research into the efficacy, risks, and benefits of different approaches is urgently needed, and the societal debate on what counts as residual emissions and whether and how to deploy different CDR approaches must begin quickly so that appropriate processes can be developed in time, well-informed decisions can be made about research, development, and deployment, and mechanisms can be devised to regulate such use responsibly. Importantly, deployment at scale could compete with other societal demands for land, water and energy (Lawrence et al., 2018). Marine CDR has the potential to reduce the need for land and freshwater resources. Large-scale marine CDR approaches, however, may struggle to achieve public acceptance (Bertram and Merk 2020, Nawaz et al. 2023).

Marine CDR options are receiving more and more interest, acknowledging that the ocean has already absorbed more than a quarter of anthropogenic CO_2 emissions and would, on timescales of thousands to hundreds of thousands of years, take up most of the remaining emissions (Archer and Brovkin, 2008), as it has done with natural high-CO_2 excursions in the Earth's geological past. The ocean holds more than 50 times as much inorganic carbon as the pre-industrial atmosphere and about 20 times as much as the carbon stored in global terrestrial plants and soils (Carlson et al., 2001). Its theoretical carbon storage potential appears large compared to the atmospheric and terrestrial carbon pools. However, increasing the oceanic carbon pool will affect the marine environment and may put additional pressure on marine ecosystems. The current level of scientific understanding of marine CDR is low, Monitoring, Reporting, and Verification (MRV) is challenging, and more research is required to comprehensively assess the diverse portfolio of proposed options (e.g. NASEM, 2021).

Currently considered marine CDR approaches include: (1) biological methods such as photosynthetic carbon fixation by microalgae, macrophytes or mangrove trees and subsequent storage of carbon in the deep ocean or in coastal sediments, and (2) abiotic methods that aim to alter ocean carbonate chemistry in a way that enhances air-to-sea flux of CO_2 and subsequently stores atmospheric carbon as dissolved inorganic carbon in seawater. Also, hybrid biological, physical and/or chemical marine CDR approaches are considered (artificial upwelling/downwelling, marine BECCS, bio-enhanced alkalinity generation, hybrid ocean-geochemical approaches, etc.).

3 Ocean Alkalinity Enhancement

Ocean alkalinity enhancement (OAE) is a marine CDR method with high (> Gt CO_2 yr^{-1} scale) theoretical sequestration potential (Renforth and Henderson, 2017). Alkalinity, the excess of proton acceptors over donors, is a chemical concept that largely determines the storage capacity for CO_2 in seawater. OAE aims to enhance alkalinity by adding alkaline material to the surface ocean or by removing acid from seawater via electrochemistry. Alkalinity enhancement results in the consumption of protons, a corresponding increase in the pH, which results in a decrease of the partial pressure of CO_2 in seawater. If applied to the surface ocean, and depending on the initial air-sea CO_2 gradient, it would promote CO_2 uptake from - or lessen CO_2 release to - the atmosphere, in both cases leading to a net reduction in atmospheric CO_2 at the expense of an increase in the oceanic carbon pool. The atmospheric CO_2 absorbed via OAE-induced air-sea gas exchange is essentially stored in the form of dissolved bicarbonate and carbonate ions that do not exchange with the atmosphere.

When applied within the surface ocean, OAE can rely on air-sea gas exchange to at least partially restore the OAE-induced decrease in partial pressure of CO_2. Air-sea gas exchange of CO_2 can take months to years (Jones et al., 2014) and poses specific challenges to MRV (He and Tyka, 2023). OAE can also be applied by adding alkalinity in chemical reactors upstream, that could at least partially pre-equilibrate the alkalized seawater with CO_2 taken either from ambient air or from CO_2 waste streams. If CO_2 is taken from waste streams, this would, technically, correspond to emissions avoidance and not CDR. Also,

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if this CO_2 was taken from ambient air via, e.g. direct air capture facilities or bioenergy plants, CDR would be termed according to the process that removes CO_2 from the atmosphere and not the process that provides terminal carbon storage. OAE qualifies as marine CDR if CO_2 is transferred directly from the atmosphere into seawater, either in chemical reactors or in the surface ocean. Hybrid schemes that combine emission reduction by dissolving minerals with acidic CO_2 waste streams in chemical reactors to generate dissolved alkaline solutions to be added into the ocean for subsequent marine CDR can also be envisaged.

OAE was positioned in the "Concept Stage" cluster of a recent assessment of ocean-based measures for climate action (Gattuso et al., 2021). This cluster was defined for measures with potentially very high effectiveness but with feasibility and cost-effectiveness which have yet to be demonstrated. The assessment highlighted the urgent need to improve knowledge on "Concept Stage" measures because the full implementation of proven measures runs the risk of falling short of providing enough cost effective CDR capacity. Attractive aspects of OAE compared to many other methods, in particular those that store carbon in biomass, are its potential to reduce ocean acidification at least locally (at the expense of imperfect CDR), and the theoretical durability of storage over several tens to hundreds of thousand years. An effective leakage of CO_2, either via enhanced CO_2 flux back to the atmosphere or by reduced CO_2 uptake from the atmosphere compared to a baseline scenario, can result from enhanced formation and reduced dissolution of carbonate minerals in the water column or at the sea floor. Frequently mentioned drawbacks of OAE are (i) the amount and the quality of alkaline material that is needed (whether mined in the case of mineral-based approaches or generated from waste brine in electrochemical approaches) and the energy required (whether mining, grinding, and transport for mineral-based approaches or low-carbon electricity of electrochemical approaches), and (ii) the difficulty of reliably quantifying CDR (MRV). Regarding (i), all known CDR methods require, at climate-relevant scales, the movement of large amounts of matter. In addition to abundant carbonate and silicate minerals, a number of industrial waste products or artificial minerals can also be considered as alkalinity sources (Renforth, 2019, Caserini et al., 2022). Overall, there is no shortage of alkaline materials on the planet. Regarding (ii), MRV is indeed a challenge and will be addressed in chapter 6 of this best practices guide.

So far, the CDR potential of OAE has essentially been inferred from modeling and techno-economic studies (Kheshgi, 1995; Harvey, 2008), including spatially resolved global or regional models (e.g., Ilyina et al., 2013; Keller et al., 2014, Hauck et al., 2016; Wang et al., 2023). Such models employ simplified representations of marine biogeochemistry, rudimentary descriptions of marine ecosystems, and typically simulate OAE as the addition, often instantaneously, of 'pure' alkalinity or of olivine minerals consisting of silicate, iron and alkalinity. The first experimental studies have started only recently and have already generated novel insight into issues regarding the actual delivery of alkalinity (Fuhr et al., 2022; Moras et al., 2022; Hartmann et al., 2023) and ecological impacts (Ferderer et al., 2022), and further research efforts are underway. Some information on the biogeochemical and ecological impacts of OAE might be gained from experimental work on ocean acidification that has been carried out during recent decades. Indeed, a first ocean acidification field experiment employed alkalinity addition to demonstrate that ocean acidification is detrimental to coral reef calcification (Albright et al., 2016).

Issues to be researched include the method of deployment of alkalinity, the alkaline materials to be used as well as their processing, the key attributes of ideal locations for deployment, the CDR potential that can be realized on given timescales, durability of the carbon storage, biogeochemical and ecological side effects, and also MRV and economic, legal, social, and ethical aspects of OAE.

4 Motivation for developing a best practices guide

Given the urgency of establishing a portfolio of CDR options, a rapid improvement of our understanding of the carbon storage potential and of the co-benefits and risks of OAE is needed. This requires responsible, efficient and transparent scientific research in order to generate new and reliable information, allowing for rapid sharing, testing and synthesis of results. With the first publicly funded research projects having started in several countries, philanthropy funding a number of research projects to accelerate scientific progress, and start-ups working on enhancing technological readiness, this has motivated us to develop a best practices guide for OAE research.

The chapters presented here describe current knowledge regarding strengths and weaknesses of different OAE approaches, scientific uncertainties, biological and ecological impacts, knowledge gaps and research needs. Recommendations for experimental set-up of laboratory, pelagic and benthic mesocosms and field experiments, as well as for modeling scenarios are provided. The guide also discusses the legal context in which research occurs and offers recommendations for responsible research and innovation, public engagement, data reporting and sharing, MRV and attribution.

The best practices guide aims at fostering intercomparison and synthesis efforts of different studies evaluating the potential, effectiveness and durability of OAE. This will help to improve knowledge sharing and information gain, and thereby speed up scientific progress in a situation where robust information about OAE as a carbon dioxide removal option is urgently needed. We have to widen the space of options and also to enable society to define and design appropriate science-based options in order to reach the agreed-upon climate targets.

We note that this research field is in its infancy and rapidly evolving. The broader legal and social contexts in which research occurs are also undergoing change. What we designate as “best practice” in this guide today may not be considered best practice in the future. As such our guide comprises our currently available understanding around OAE, but also requires the user to remain up to date with the available literature. There will almost certainly be improvements in our protocols as the field develops and everyone is invited to contribute to this process.

5 Development of this best practices guide

Best practices guides have proven useful when new areas of research open up, often bringing together scientists from different fields and with different methodological backgrounds. One example is the Guide to Best Practices in Ocean Acidification Research and Data Reporting (Riebesell et al., 2010), in which the project lead, Jean-Pierre Gattuso, the scientific coordinator, Andreas Oschlies, and a number of authors of this guide were involved. The ocean acidification guide had an enormous catalytic effect in growing the field of ocean acidification research by lowering the barrier to entry and making comparison of different studies and the generation of synthesis products more straightforward. The expectation is that the present guide on OAE research will have a similar impact on the OAE community and ocean CDR field at large, and also provide guidelines for ensuring that OAE research is conducted responsibly and most efficiently for the public good.

In summer 2022, Jean-Pierre Gattuso and Andreas Oschlies sent a proposal to the ClimateWorks Foundation with a request for funding to create a detailed guide that outlines all the relevant approaches available for ocean alkalinity enhancement (OAE) as a Carbon Dioxide Removal approach. The requested funding for a part-time project manager, a 3-day in-person workshop of chapter lead authors, as well as costs for production, publication and printing of the guide (total amount 170.000 US$) was approved. A steering committee consisting of the authors of this chapter was established and had several online meetings to develop the chapter outline and a personal information form that all authors would have to sign in order to ensure transparency, and best scientific knowledge and the absence of conflicts of interest. Lead authors for each chapter were chosen by the steering committee based on experience, scholarship, and diversity. In consultation with the steering committee, all lead authors then chose co-leads and additional authors of their respective chapters.

In early 2023, a 3-day in-person workshop of the steering committee and lead authors took place in Villefranche-sur-Mer, France. Chapter outlines were discussed, gaps identified and the timeline agreed upon. Lead authors were responsible for developing their chapters, with support from the scientific project manager. A public website (https://oae-best-practice.carbondioxide-removal.eu) with list of chapters and lead-authors was set up and advertised via social media and the carbon-dioxide-removal news stream (www.carbondioxideremoval.eu). An internal review was initiated in May 2023. All chapters were submitted to ‘*State of the Planet*’ in order to allow for public review to ensure that the guide provides state-of-the-art information.

Author Contributions

AO conceived and all authors wrote and edited the paper

Competing interests

The authors declare no competing interests

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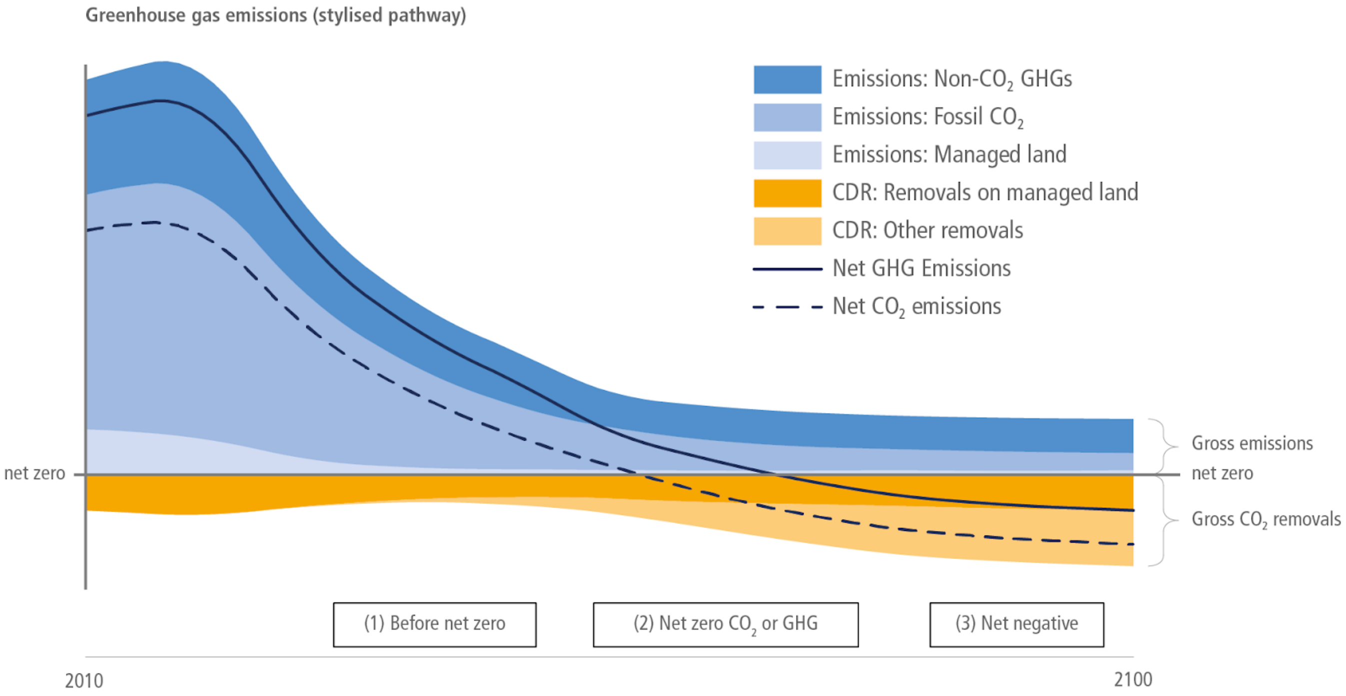

Figure 1: The role of CO_2 removal ("CDR") in a stylised pathway of ambitious climate action. Dark green illustrates CO_2 removals from land management and light illustrates removal from other CDR methods, including ocean methods. Note that net-zero CO_2 is reached well before net-zero greenhouse gas (GHG), and the the amount of CDR required for net-zero CO_2 can be substantially smaller than the amount of CDR required for non-zero GHG. Any contribution of ocean alkalinity enhancement would be included in 'CDR: Other removals'. Source: IPCC (2022) Cross-Chapter Box 8, Figure 2.