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Carbon to Sea Initiative

# OAE and mCDR priorities for the EU Ocean R&I Initiative

**OVERVIEW**

The European Scientific Advisory Board on Climate Change (ESABCC) estimates that between 390 and 1,165 million tonnes of CO2e will need to be removed annually in Europe by 2050 to achieve climate neutrality, in addition to aggressive efforts to reduce greenhouse gas emissions. To achieve carbon dioxide removal (CDR) at this level, the EU and member states will need to rapidly expand the array of reliable approaches and technologies.

Marine CDR (mCDR) pathways show considerable promise in contributing to this goal but further research is needed to demonstrate their safety and efficacy. A research strategy to advance the technological readiness of these approaches will be most effective if fully integrated into the broader Ocean Research and Innovation Initiative being developed by the Commission. Such an approach will allow mCDR research funding and programming to be directed within the larger framework of European ocean R&I priorities. A coordinated and integrated approach to ocean research and innovation in Europe is needed because today's challenges to ocean health and productivity increasingly require interdisciplinary and transboundary solutions.

Carbon to Sea (CTS) is the largest non-commercial initiative evaluating if and how marine carbon dioxide removal could be part of the global response to climate change. We explored multiple potential carbon removal solutions before deciding to focus on accelerating the evaluation of ocean alkalinity enhancement (OAE), which, in the view of leading scientists, offers high potential for safety, efficacy, and scale.

We have committed more than US$30 million in research and technology development projects across the globe to address whether OAE is safe for people and the environment, effective at removing legacy carbon from the atmosphere, and can scale to be a climate-relevant solution. Our grantees include dozens of world-leading experts at academic institutions and companies on subjects ranging from geochemistry to ecotoxicology to physical oceanography. We also engage civil society and coastal communities. After several years of intensive work on the interplay of research, technology, and governance related to OAE, we believe governments have a critical, time-sensitive role in ensuring the quality and integrity of carbon removals by OAE and other mCDR pathways.

To rapidly explore the potential for OAE and other marine CDR pathways, coordinated, strategic research to explore and develop these technologies should be incorporated into

the proposed Ocean R&I strategy. OAE may prove to be highly scalable because of the ocean's vast carbon storage and absorption capacity, but before governments and society sanction the development of OAE and other mCDR technologies at a large scale, significant scientific questions must be addressed, including:

1) Whether and which of these technologies are safe for people and the environment?
2) How effective is mCDR at removing legacy carbon from the atmosphere?
3) Can mCDR safely and efficiently scale to be a climate-relevant solution?

Current research on the environmental impacts of ocean alkalinity enhancement (OAE) focuses on improving understanding of the main types of perturbations that may affect marine organisms. These include changes to seawater carbonate chemistry, the introduction of feedstock impurities (e.g., heavy metals or nutrients), and interactions between feedstock particles and organisms. Through targeted laboratory and mesocosm experiments, recent studies have identified critical thresholds (e.g., alkalinity levels at which impacts occur) and are beginning to provide mechanistic insight into how different OAE feedstocks and dosing strategies cause these perturbations. This work is helping to identify feedstock-specific deployment approaches that can minimise undesired ecological impacts during field research.

The theoretical efficiency of OAE is well understood from decades of research, but real-world processes affect its overall effectiveness. Current research is focusing on quantifying the potential loss of efficiency from processes like incomplete dissolution of mineral feedstocks and air-sea gas exchange, loss of alkalinity to precipitation, and indirect effects on biogeochemical cycles. Significant progress has been made through laboratory and mesocosm studies on each of these impacts, but data is lacking on how they interact, and affect, overall OAE efficiency in the field.

**CRITICAL RESEARCH NEEDS FOR OAE**

In its efforts to address fundamental questions about the safety, efficacy, and scalability of OAE, Carbon to Sea has identified the following research priorities. These recommendations are not an exhaustive compendium of knowledge gaps but we believe they provide a strong basis for a focused, strategic programme to support research and innovation on OAE. Although our recommendations are focused on Ocean Alkalinity Enhancement (OAE), most of the broad areas of research discussed below are applicable to other forms of abiotic mCDR.

***Field research***

Funding for well-designed, intercomparable field studies is a need that cuts across research areas. It is a critical next step to evaluate hypotheses identified in laboratory, mesocosm, and early pilot studies under real-world conditions. Such studies must follow regulatory compliance, include extensive monitoring for carbon removal and environmental effects, and adhere to safe environmental thresholds from best-practice ecotoxicological and pilot studies.

In the past decade, research has progressed dramatically through modeling, lab, and mesocosm studies, helping us understand key concepts of environmental impacts, efficiency, scalability and cost-effectiveness. However, real-world evidence is nascent and scattered and remains the major roadblock in our efforts to evaluate the viability of OAE. Ocean-based carbon removal methodologies are highly location-specific, shaped by the unique characteristics of the receiving waters, the materials used, and method of dispersal. As a result, there is a need for considerably higher quantity and quality of field data to build the empirical understanding of OAE's efficacy and safety in different scenarios

***Environmental and human safety***

Understanding OAE's impact on marine life is crucial for regulatory approval, public trust, and long-term pathway viability. Until recently there were few studies on environmental impacts, leading to much speculation and uncertainty about the safety of OAE. Recent studies, primarily conducted in the laboratory and in situ mesocosms, have provided crucial understanding of its safety. Ecotoxicological impacts of various feedstocks as well as the intended changes in carbonate parameters must be identified to set environmental guardrails under which fieldwork or early projects can proceed. Further progress requires rigorous testing of hypotheses and accurate contextualisation of lab-based studies to provide insights needed to inform regulation and future fieldwork design.

There are four main sources of environmental and human safety hazards from OAE:

1. Changes in carbonate chemistry can shift seawater chemistry in ways that matter to organisms, for example by raising alkalinity and pH locally, changing $CO_2$ levels in the water, and altering carbonate mineral saturation states. Changes in these parameters represent a higher risk when they vary drastically over a short period of time, "shocking" the system, or more mildly but over longer durations that exceed ecological thresholds. Certain organisms, life stages, or ecosystem dynamics may be especially sensitive to carbonate chemistry changes.
2. Impurities in alkaline feedstocks can result from sourcing or processing. These include trace metals, nutrients, or other contaminants that could be toxic, accumulate in sediments or food webs, or trigger other water-quality issues.

Therefore the risk is not just the alkalinity, it is what comes along with a feedstock and how readily it dissolves or disperses.

3. Increased turbidity, resulting from incomplete dissolution of alkaline feedstock particles or secondary precipitation, can be an ecological issue as these particles may limit light penetration, be eaten by organisms, or bury benthic fauna.
4. Operational/site hazards that result from the practical risks of doing this work in the real world: storing and moving large volumes of reactive or dusty material, worker exposure (skin, eyes, lungs), heavy equipment and vessel operations, and spills during transport or application.

A literature analysis conducted by Bach et al., 2025 examined 29 relevant OAE experiments in which alkalinity perturbations ranged from 10 - 3,400,000 µmol kg-1, with the upper value likely being well beyond realistic in-water OAE scenarios. The study concluded that raising total alkalinity by up to 300 umol/kg in most cases is both within natural variability and allows for substantial capture of $CO_2$. Impacts in the field can be mitigated by ocean mixing, which dilutes and limits the exposure to alkalinity perturbations. As a result, most of these risks can be minimised by thoroughly characterising the alkalinity source and through controlled dosing and monitoring of the receiving environment.

The next step must be to test and validate these findings in real-world settings through controlled and stage-gated field research. Also important to note is that much of this research has been focused on primary producers (phytoplankton). These are typically some of the most sensitive indicator species for most stressors (Ferderer et al., 2022). But it will be important to close knowledge gaps of potential effects on higher trophic-level organisms to inform application of the "Do No Significant Harm Principle."

***Dissolution, dispersal, and resulting alkalinity enhancement of particulate feedstocks***

For technologies adding particulate alkaline feedstocks, the amount and rate of dissolution of these additions is critical for quantification of carbon removal and staying within safe ecological thresholds. To improve understanding of particle dissolution, realised alkalinity increase, and factors affecting these parameters, research is needed on:

- Characterisation of particulate feedstocks;
- Improving and standardising methods and metrics for deriving dissolution rates in vitro and proxy evidence of dissolution and alkalinity enhancement in situ;
- Understanding additionality effects of OAE on secondary precipitation, biological calcification, and sediment alkalinity flux, as well as knock-on environmental impacts from changes in these processes; and
- Developing improved dispersal and dosing technologies (e.g., particle size control, application rate and pattern, and delivery method) to enhance dissolution and alkalinity release whilst limiting localised environmental impacts.

***Alkalinity enhancement via electrochemical processing***

For technologies generating alkalinity electrochemically from seawater or brine, the efficiency, durability, and by-product profile of the generation process are critical for the economic viability, verifiability, and environmental footprint of carbon removal. To improve understanding of electrochemical alkalinity generation and dispersal, research is needed on:

- Developing durable, selective electrodes and membranes;
- Reducing the energy intensity of alkalinity generation at scale; and
- Identifying viable use or disposal pathways for by-products (e.g., acid).

***Modeling***

Because of the broad spatial and temporal scale involved, models will always be needed to simulate effects of OAE on near-field, regional, and global scales. A suite of models across these scales is required to estimate feedstock dissolution (for those technologies utilising particulate feedstock additions in situ) and subsequent carbonate chemistry responses that lead to oceanic uptake and storage of atmospheric $CO_2$. R&I to improve model representation of these processes in hydrodynamic and biogeochemical models will lead to more accurate quantification of carbon removal and reduced uncertainty in those estimates.

Model uncertainties must be rigorously assessed and used to determine appropriate discounting of estimated carbon removal. A significant challenge is that some systemic uncertainties (i.e., how well models represent underlying processes and the real world) cannot be addressed by individual projects. Model capabilities can only be improved when actual project data exist for comparison. As such results become increasingly available, investment in model intercomparison exercises or parametric sensitivity analyses are among the types of analyses that would go a long way to improve our understanding of and confidence in models used to project carbon removal from OAE.

Additional R&I is also needed to:

- Develop and validate OAE modules for integrated assessment models (IAMs) and assess how OAE could fit within a broader CDR and emissions-reduction portfolio.

- Develop and parameterise models to directly simulate biological impacts as biological response data accumulate, enabling more robust safety assessment and regulatory guidance alongside carbon removal quantification.

If funding is available, the field is poised for significant advancements through faster GPU-based modeling, model coupling, and increasing application of AI and machine language for data assimilation and other functions.

***Uncertainty***

Models inherently carry uncertainty from varying sources, including measurements used to force, train, or validate them, as they aim to represent the real world in a simplified way. Development of a shared uncertainty taxonomy for model-based quantification will improve consistency across projects, clarify which uncertainties are not yet adequately represented, and facilitate comparison of results among projects. Use of such a protocol by experimental and commercial projects will generate results that will lead to much more rapid advancements in our knowledge and understanding of uncertainty, and how it might be better constrained and managed. R&I funding will be necessary to conduct such meta-analyses as they are usually beyond the scope (and resources) of individual projects.

It is to be expected that early-stage, small-scale OAE activities will have greater uncertainty associated with carbon removal yet fewer resources to confidently quantify it. Such projects, if properly structured and funded, can yield data to improve carbon removal efficiency and environmental safety in future iterations. To ensure data collection and analysis goes beyond the minimum required for certification and environmental compliance, R&I funding should support collaboration between the research community and the private sector so that project design and implementation generates and makes publicly available information needed to address scientific questions whilst meeting the operational needs of the project operator.

***MRV***

Rigorous monitoring, reporting, and verification (MRV) is foundational for development and certification of safe and effective OAE, and will entail both measurement and modeling. Measurements provide vital evidence for operational outcomes, model validation, and environmental impact assessment. MRV protocols for purposes of environmental compliance and carbon removal certification specify different, but often overlapping measurements and metrics. R&I resources to support sensor and platform improvements and to expand monitoring in current and future small in situ trials will generate additional information that can be used to improve and standardise MRV protocols, thereby facilitating project and technology intercomparisons, and improving confidence in carbon removal estimates and environmental safety. To realise these benefits, accessible data repositories are important so that MRV data and modeling results are readily available in standardised formats.

***Techno-economic and life-cycle assessment***

Robust techno-economic assessment (TEA) and life-cycle assessment (LCA) are essential for evaluating the real-world viability, environmental footprint, and scalability of OAE technologies, yet standardised, OAE-specific methodologies are still lacking. R&I is needed to develop OAE-specific impact categories and

standardised LCA/TEA methodologies. Additionality effects also need to be quantified, and MRV protocols and their associated costs need to be refined across different OAE pathways and included in LCAs and TEAs. Finally, assessment methods for projecting technology performance from pilot to gigatonne scale need improvement, including cost and energy scaling and by-product management strategies, such as acid disposal for electrochemical approaches.

***International Collaboration and Cooperation***

Climate change is a global crisis requiring global solutions. Collaborative, interdisciplinary research is needed to fully explore the potential of OAE as a climate mitigation method. Institutions across the European Union and beyond are well positioned to carry out comprehensive R&I programmes, building on decades of oceanographic research involvement and pioneering work on OAE. In addition, access to Horizon Europe programmes and funding by non-EU states will pay dividends for European and global efforts to address climate change. For example, scientists and research institutions in Canada and Australia are on the cutting edge of OAE research. Their ability to seek funding from and collaborate with the proposed ocean research initiative will greatly enhance their contributions to advancing our knowledge and understanding of this field.

**CONCLUSION**

A quantity of carbon dioxide removal orders of magnitude greater than the current level will be needed to achieve Europe's long-term climate goals. Given the rapidly developing technologies and scaling challenges, a diverse portfolio of CDR approaches will be needed to fill this need. Because of their potential for scale, ocean-based CDR approaches, if shown by rigorous research to be safe, effective, and desirable, could play a substantial role in meeting Europe's CDR needs.

Climate change is having a profound impact on the ocean, its ecosystems, and the coastal communities that depend on them. The ocean also holds promise for climate mitigation via nature-based and technological approaches for CDR. Substantial additional research is needed, however, to demonstrate the safety and efficacy of these approaches. Through a coordinated and comprehensive Ocean Research and Innovation Initiative, Europe has the opportunity to reap the economic and environmental benefits of advancing these technologies. To do so, the Commission needs to make a substantial and sustained commitment to mCDR research by fully integrating it into the proposed initiative.

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