SEAO2 CDR

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Ensuring consistency and completeness when conducting Life Cycle Assessments (LCA) of marine Carbon Dioxide Removal (mCDR)

EXECUTIVE SUMMARY

To understand the environmental implications of marine carbon dioxide removal (mCDR) approaches, we need clear guidelines that ensure consistency and completeness of Life Cycle Assessment (LCA) applications.

However, caution is required in the interpretation of LCA results until more research reduces the remaining uncertainties.

- **(mCDR) approaches are an emerging solution for achieving global climate targets and could complement significant emission reductions**. However, the environmental side-effects of large-scale mCDR deployment remain largely unknown, and it is essential to assess whether their carbon removal benefits come at the expense of other environmental impacts, particularly on marine environments.
- **(LCA) is a methodology used to evaluate the environmental performance of mCDR approaches along its entire life cycle, helping to identifying both their environmental benefits and unintended side-effects**. Until recently, no common procedure existed for conducting LCAs of mCDR, limiting the consistency and completeness of such assessments. A comprehensive guideline has now been developed for LCA practitioners on mCDR.
- **Results from different LCAs of mCDR approaches should not be used for public comparisons or policy decisions for deployment**. This is due to high technological uncertainty and current methodological limitations associated with LCAs on mCDR. Additionally, LCAs often vary in study context and assumptions, often precluding meaningful equivalence and potentially leading to misleading comparisons of carbon removal performance and environmental side-effects. Comparison of LCA results should be restricted to the same mCDR approaches conducted under comparable conditions, for example large-scale deployments of ocean alkalinity enhancement that differ only in the type of alkaline material used.
- **For a more comprehensive understanding of the environmental impacts of mCDR, LCA should be complemented by other environmental assessment methods, such as Risk Assessment (RA)**. While LCA informs on the overall environmental performance of an mCDR approach across its life cycle, RA evaluates the site-specific environmental safety and potential risks associated with technology deployment.
- **To reduce current uncertainties and limitations in LCAs of mCDR, support should be given to research aimed at enhancing LCA methodologies for better assessments of mCDR environmental effects.**

BACKGROUND

To limit global warming, the Intergovernmental Panel in Climate Change (IPCC) expects carbon dioxide removal (CDR) approaches, which remove carbon directly from the atmosphere and store it durably, to complement significant emission reductions. So far, CDR approaches deployed on land have received the most attention. However, the ocean is the world's largest carbon reservoir and could potentially be an important location for the implementation of what is known as mCDR. mCDR approaches are increasingly being studied, but the environmental implications of deploying these technologies on a large scale remain poorly understood and could be significant, notably on marine species and ecosystems. It is thus important to be well-informed on how mCDR could affect the environment before widely deploying them.

LCA is a methodology commonly used to evaluate the environmental impacts of a technology at every stage of its life cycle (e.g., from cradle to grave), from raw material extraction and manufacturing to use, disposal, or recycling. LCA typically considers a large range of environmental issues, including global warming, ecosystem effects, and human health impacts. This methodology is already embedded in several EU regulations aimed at promoting product sustainability, such as the Construction

Fig. 1. The different mCDR approaches assessed in this review, namely: (1) Macroalgae cultivation and sinking; (2) Ocean fertilisation; (3) Blue CDR; (4) Ocean alkalinity enhancement (OAE); (5) CDR with deep-sea storage; (6) Bioenergy production using marine biomass with carbon capture and storage (mBECCS); (7) Marine biomass for biochar production; (8) Electrochemical mCDR; (9) Artificial upwelling and downwelling; and (10) Terrestrial biomass sinking.

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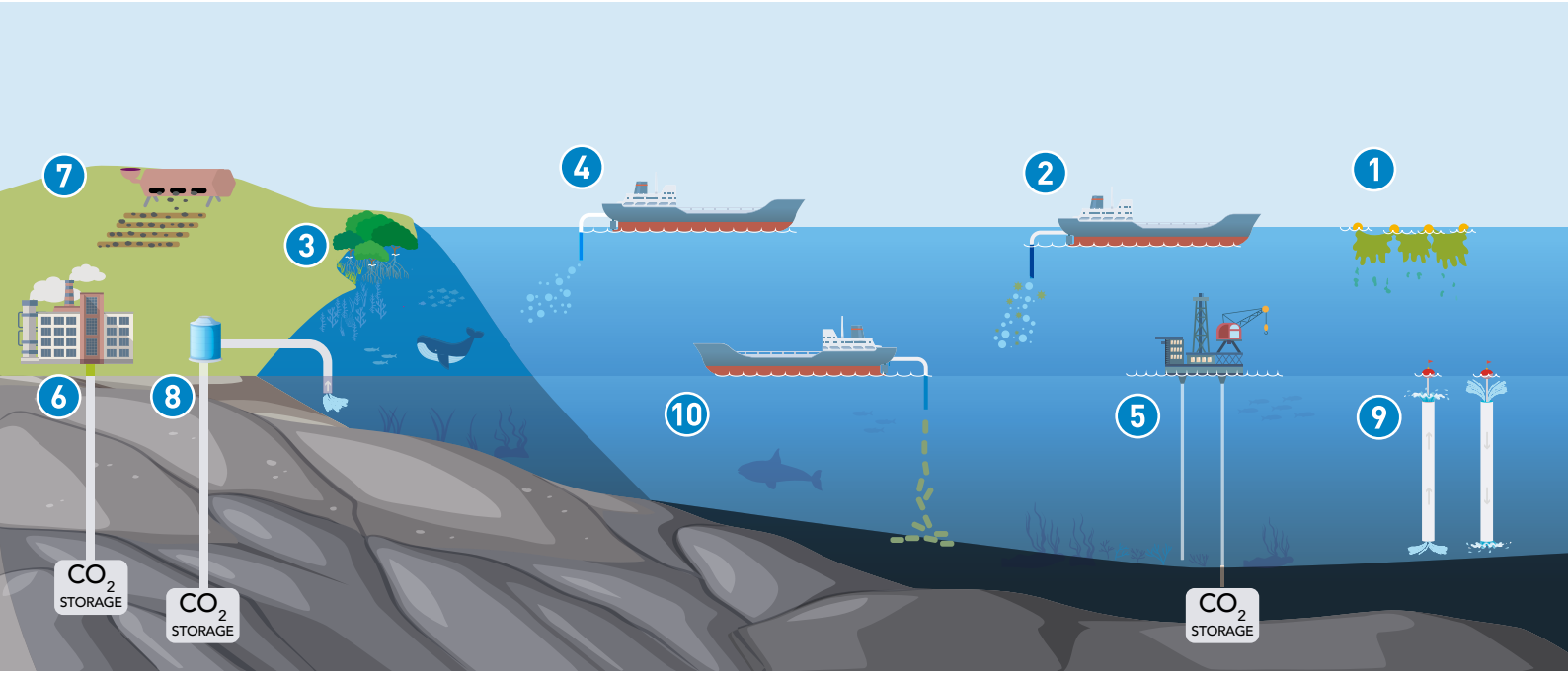

Products Regulation (CPR) and the Ecodesign for Sustainable Products Regulation (ESPR). Applied to mCDR, LCA can quantify the net carbon removal potential, by deducting carbon emitted across the technology's life cycle from carbon removed, and identify potential environmental issues while the technology is still in early development, when there are still opportunities to improve the technology design and reduce negative environmental effects.

However, standardised guidelines to conduct LCA of mCDR are currently lacking. Standardised is essential to ensure consistency, reproducibility, and comparability of the LCAs. For instance, current LCAs do not systematically evaluate mCDR approaches across their entire life cycle, yet only by accounting for all the processes of the technology thoughout its full life cycle can we accurately determine the net carbon removal potential and overall environmental performance. Additionally, important environmental indicators, such as marine ecotoxicity or marine eutrophication, are often omitted. As a result, the environmental benefits of mCDR may be overestimated, potentially leading to flawed conclusions in decision-making.

To fill this gap, researchers from the EU-funded SEAO2–CDR project performed a critical literature review to develop a comprehensive guideline for LCA practitioners working on mCDR. Additionally, they identified uncertainties arising from both the emerging nature of mCDR approaches and the LCA methodology in current practice. This policy brief summarises the main findings of the critical literature review and outlines several priority areas for policy action related to LCA in the context of mCDR.

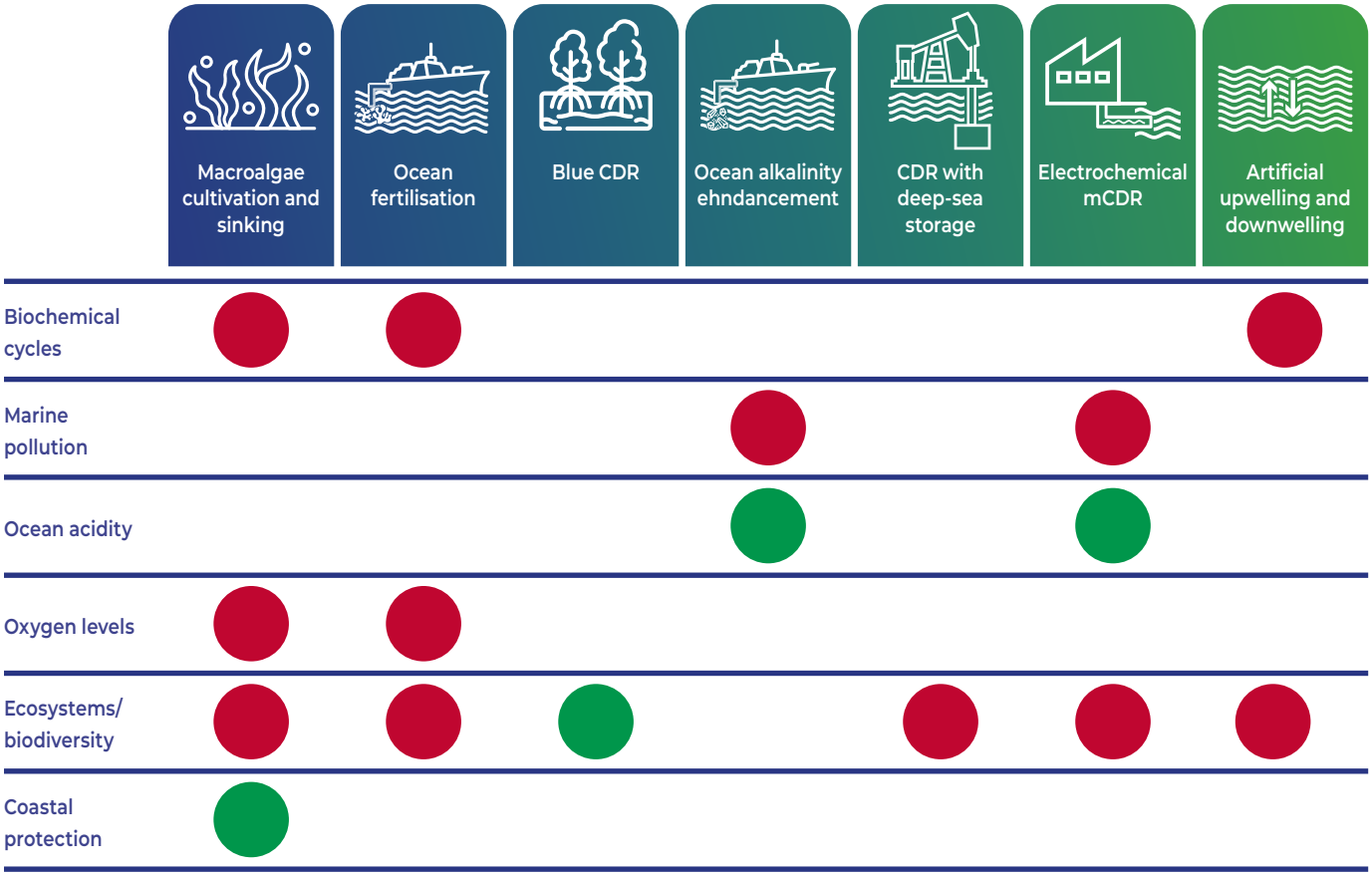

Fig. 2. Potential environmental side-benefits (in green) and side-effects (in red) of mCDR approaches. Only some major points mentioned, more complete information in Deliverable 2.1. on the webpage of SEAO2-CDR.

METHODS

To develop a guideline for conducting LCA on mCDR, researchers conducted a critical literature review, which comprised three parts:

1. a review of previous recommendations in the literature for performing LCA on related technologies, such as CDR on land or carbon capture and utilisation (CCU) technologies;
2. a review of recommendations in the literature for performing LCAs on the future environmental performance of emerging technologies;
3. a review of previous LCAs on mCDR in the literature. These main mCDR approaches were covered: macroalgae cultivation and sinking, ocean fertilisation, blue CDR, ocean alkalinity enhancement, CDR with deep-sea storage, bioenergy production using marine biomass with carbon capture and storage, marine biomass for biochar production, electrochemical mCDR, artificial upwelling and downwelling, and terrestrial biomass sinking.

Fig. 3. Methodology for developing a guideline for conducting LCA on mCDR.

POLICY RECOMMENDATIONS

1 For now, avoid comparative assertions between LCAs of different mCDR approaches

At this stage, LCA is best used to determine environmental hotspots and opportunities for design improvement, identify knowledge gaps, and guide future research. Until data quality, temporal and spatial resolution, and methodological consistency are significantly improved, investment and regulatory decisions should not be based on comparative LCA results. Comparison of LCA results should be restricted to the same mCDR approaches conducted under comparable conditions, for example large-scale deployments of ocean alkalinity enhancement that differ only in the type of alkaline material used.

2 Encourage the use of the guideline for more standardised LCAs on mCDR

Based on the critical literature review, a set of guidelines has been developed. Key recommendations to support more standardised LCAs on mCDR are:

- To broaden the scope of environmental issues. Current LCAs often focus narrowly on carbon emissions quantification to quantify the net carbon removal potential of mCDR approaches. However, it is essential that LCA also evaluates a wider range of environmental impacts, particularly those affecting the marine environment, where mCDR technologies will be deployed. Neglecting these impacts could result in incomplete environmental assessments and decisions made on partial information.
- To address uncertainty. Uncertainty is inevitable due to the emerging nature of mCDR and can also stem from data limitations, assumptions, and modelling choices made by the LCA practitioner. Uncertainty should be appropriately handled in uncertainty analyses. At present, such assessments are often missing or insufficient in LCAs on mCDR, which can lead to misinterpretation of the LCA results and weak policy conclusions.
- To use consistent and precise terminology. Inconsistency in terms used across LCAs on mCDR can lead to misinterpretation of results and undermine their credibility. One key example is the confusion between *negative emissions*, which refer to emissions directly removed from the atmosphere through CDR, and *avoided emissions*, which refer to a reduction of emissions by using one technology instead of another. These two concepts are not interchangeable, as avoided emissions prevent further emissions but do not reduce current

levels of atmospheric carbon. They must thus be treated separately in LCA and carbon accounting. Terminology clarity is essential for producing transparent and scientifically sound LCA results that can reliably inform policy and investment decisions.

Applying the proposed guideline in future LCAs will help modelling methodologies, ensure more comprehensive environmental assessments of mCDR, and promote greater transparency regarding data, method, modelling choices and limitations to inform decision-making.

3 Address current limitations in LCA for mCDR

Fundamental limitations remain in existing LCA methodologies that hinder accurate environmental assessment of these technologies:

- Several environmental impacts, notably key stressors responsible for marine biodiversity loss, such as ocean acidification and seabed damage, are insufficiently integrated.
- The spatial variability of ocean environments is inadequately represented in LCA models.
- The temporality of carbon emissions and removal is usually not accounted. For example, emitting carbon all at once today does not have the same environmental effect as slowly releasing those emissions over decades. Yet, LCA handles them as equivalent.

As a result, LCA, in its current form, does not fully capture the environmental performance of mCDR approaches. There is an urgent need for methodological advancements to ensure that LCA tools can more accurately assess these

technologies, especially regarding marine-specific impacts, spatial variability, and the temporality of emissions and removals. Policymakers should actively support this progress through continued investment in methodological research and development, ensuring that LCA becomes a more robust and reliable tool for evaluating mCDR approaches.

4 Conduct LCA alongside complementary environmental assessment tools, such as Risk Assessment (RA)

While LCA provides important insights into the overall environmental performance of mCDR across its life cycle, it does not capture all relevant environmental impacts, particularly local or short-term risks. Complementary environmental assessment tools, such as those which are the focus of other active projects (e.g. **Hourglass's FEMM Framework**, **Ocean Visions mCDR EIAF, Carbon to Sea's OAE EIM framework**) should be applied. RA evaluates potential hazards and site-specific environmental risks that LCA alone may overlook. Combining these approaches offers a more comprehensive understanding of mCDR's environmental effects and supports more informed decision-making.

This brief presents findings and policy lessons identified in a deliverable of the EU-funded SEAO2-CDR project. The SEAO2-CDR project, funded by Horizon Europe, aims to develop consistent and robust assessment frameworks to support the safe and effective deployment of mCDR. **More details about this particular topic are available in the Deliverable 2.3.**

(https://seao2-cdr.eu/seao2-cdr/sites/seao2-cdr/files/documents/SEAO2-CDR%20D2.3%20A%20common%20LCA%20framework.pdf)

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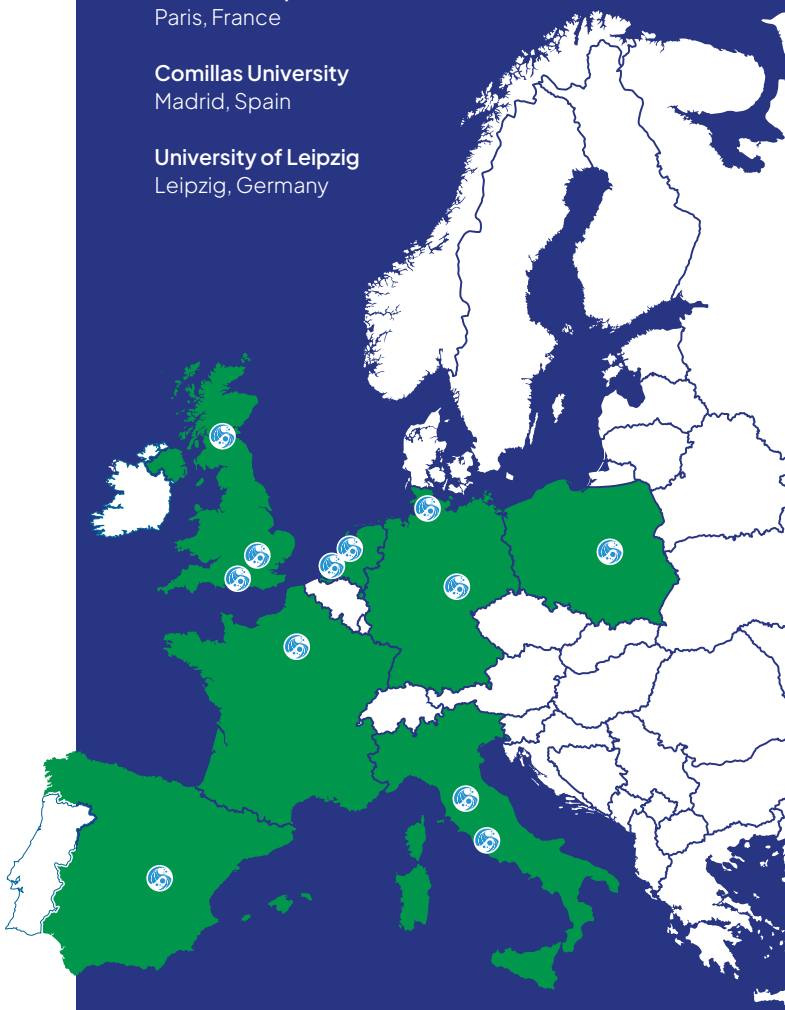

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