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LETTER

A holistic assessment framework for marine carbon dioxide removal options

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Abstract

Marine carbon dioxide removal (mCDR) options could potentially play an important role in future CDR policy portfolios. They include, for example, ocean alkalinity enhancement, blue carbon projects such as mangrove cultivation, as well as sub-seabed storage of captured atmospheric CO_2. In this paper we present a novel assessment framework designed for mCDR options. The framework provides important conceptual advancements to existing frameworks currently used to assess climate options: It clearly distinguishes between and allows for the assessment of both the feasibility and desirability of mCDR options, it makes explicit the evaluative standards upon which the assessment is based and it separates the descriptive listing of information from the evaluation of said information. The assessment framework aims to advance the debate on what role mCDR can and should play in responding to the climate crisis by providing a tool for both policymakers and stakeholders to assess mCDR options in a transparent and comprehensive way.

1. Introduction

Carbon dioxide removal (CDR) techniques capture CO_2 from the atmosphere and store it for decades to millennia (Vaughan *et al* 2024). Their envisaged role in achieving climate goals has drastically changed in the last decade, from being considered speculative (IPCC 2007, Lawrence *et al* 2018) to having a key role in reaching the net-zero targets (IPCC 2022b). Acknowledging this role is consistent with saying that emissions reductions should remain our top priority and must account for most of the effort to achieve net-zero emissions (Ho 2023). The role of CDR might thus not be large in purely quantitative terms, but could be crucial for counterbalancing residual emissions to reach net-zero and returning from a potential overshoot (Schenuit *et al* 2022, Schneider 1996).

A multitude of proposed approaches for removing carbon from the atmosphere exist, and new ideas are constantly being developed (Fuss *et al* 2018, Minx *et al* 2018, Nemet *et al* 2018, Vaughan *et al* 2024). Different methods could be implemented in a variety of scenarios involving different actors, in different locations, and at different points in time. But not everything that is imaginable will—upon closer inspection—turn out to be feasible or desirable. The research community is called upon to sort the actually feasible from the merely imaginable and to contribute to the debate about which CDR methods, implemented in which ways, if any, are desirable (Tank *et al* 2025). In this paper, we present a tool to help decision makers address these questions: a holistic assessment framework with which to evaluate marine CDR (mCDR) options, together with a list of indicators (see annex 2) upon which the assessment process can build.

mCDR includes a wide variety of methods. Some of them, like blue carbon management, which includes restoring, and expanding of blue carbon ecosystems such as mangroves to increase the amount of carbon stored in coastal ecosystems (Krause-Jensen and Duarte 2016, Macreadie *et al* 2021), are well-established. Others like ocean alkalinity enhancement, i.e. adding alkaline substances such as silicate or lime to the ocean's surface water (Oschlies *et al* 2023), are currently receiving increasing attention. Yet others like open ocean seaweed farming with biomass sinking are still in their infant stage (Wu *et al* 2023). For overviews of different mCDR methods, see Bach *et al* (2024, Chapter 2), CDRmare (2024) and GESAMP (2019).

A substantial number of assessment frameworks for climate options in general, or for certain categories such as mitigation or adaptation (IPCC 2018; and advanced in, IPCC 2023; see also GESAMP 2019, Nielsen *et al* 2020, Singh *et al* 2020, Brutschin *et al* 2021, Williams *et al* 2021, Steg *et al* 2022, Doshi and Garschagen 2023) have already been published and some proposals for assessment frameworks specifically for terrestrial CDR exist (e.g. McLaren 2012, Bellamy *et al* 2013, Förster *et al* 2022). Bach *et al* (2024) furthermore present an assessment of mCDR options, but their framework is explicitly limited to a few cross cutting issues. NASEM (2022) provides a broader set of questions by which to evaluate mCDR options, but without justifying their choices or naming indicators. Gattuso *et al* (2018) present a highly developed assessment framework for what they call 'ocean solutions', but only some of them fall into the category of mCDR.

In contrast to existing frameworks for assessing climate response options, the framework presented here clearly distinguishes between listing information on mCDR options and evaluating this information, and lays out the underlying 'evaluative standards' upon which the assessment is based. This approach provides transparency with regard to norms and values which play a role in the evaluation. Relatedly, our assessment framework takes up a distinction reflected in earlier work—the distinction between feasibility ('could we?', e.g. Schneider 1996, Williamson 2011) and desirability ('should we?', ibid.). The framework builds on this by being the first to systematically distinguish between a feasibility and a desirability domain of assessment[9]. The explicit inclusion of desirability enables the better integration of issues of justice, governance, societal and environmental impacts into the framework. Existing frameworks evidently see the importance of such issues because they tend to include them in some way (Singh *et al* 2020, Williams *et al* 2021, Förster *et al* 2022, Steg *et al* 2022, IPCC 2022a, 2022b) and consider it a research priority to include socio-political and economic concepts in assessments (see Bellamy *et al* 2013, GESAMP 2019). Inclusion of the desirability domain allows their explicit consideration without asserting questionable correlations with feasibility (see section 4, see also Tank *et al* 2025).

Our framework is 'holistic' in that it can be applied both to mCDR methods in general and to concrete mCDR projects of different scales and in different locations, and in that it evaluates both feasibility and desirability. While this framework was developed within the European context, it does not involve any criteria that are specific to it. Whether the criteria proposed for the evaluation of desirability in particular would need to be adjusted for other contexts is an open question (see section 4 for details on the need to be transparent about the normative foundation of desirability assessments). The framework is specific to mCDR, as some of the indicators are specific to the marine realm, including e.g. indicators on marine water quality and impacts on local ocean circulation. However, much of the approach, including the distinction between feasibility and desirability, as well as the criteria we developed, are also applicable for the assessment of terrestrial CDR.

2. Materials and methods

The framework was developed in a twofold-process. From the bottom–up, we collected, clustered and critically reviewed indicators and criteria from relevant literature assessing CDR (Bellamy *et al* 2013, Gattuso *et al* 2018) and other CDR assessment frameworks (The Royal Society 2009, U.S. GAO 2011, McLaren 2012, Williamson and Bodle 2016, GESAMP 2019, Energy Futures Initiative 2020, Jeffery *et al* 2020, Förster *et al* 2022, NASEM 2022, Bach *et al* 2024). From the top down, we analyzed strengths and weaknesses of existing assessment frameworks for different climate options (IPCC 2018, 2022a, 2022b, 2023, GESAMP 2019, Singh *et al* 2020, Roe *et al* 2021, Brutschin *et al* 2021, Williams *et al* 2021, Förster *et al* 2022, Tirado *et al* 2022, Borchers *et al* 2024) based on

[9] Though the feasibility-desirability distinction is reflected in earlier work on what was then called geoengineering, see e.g. Schneider (1996) ('Geoengineering: Could? or should? we do it?'), Williamson (2011) ('Climate geoengineering: Could we? Should we?').

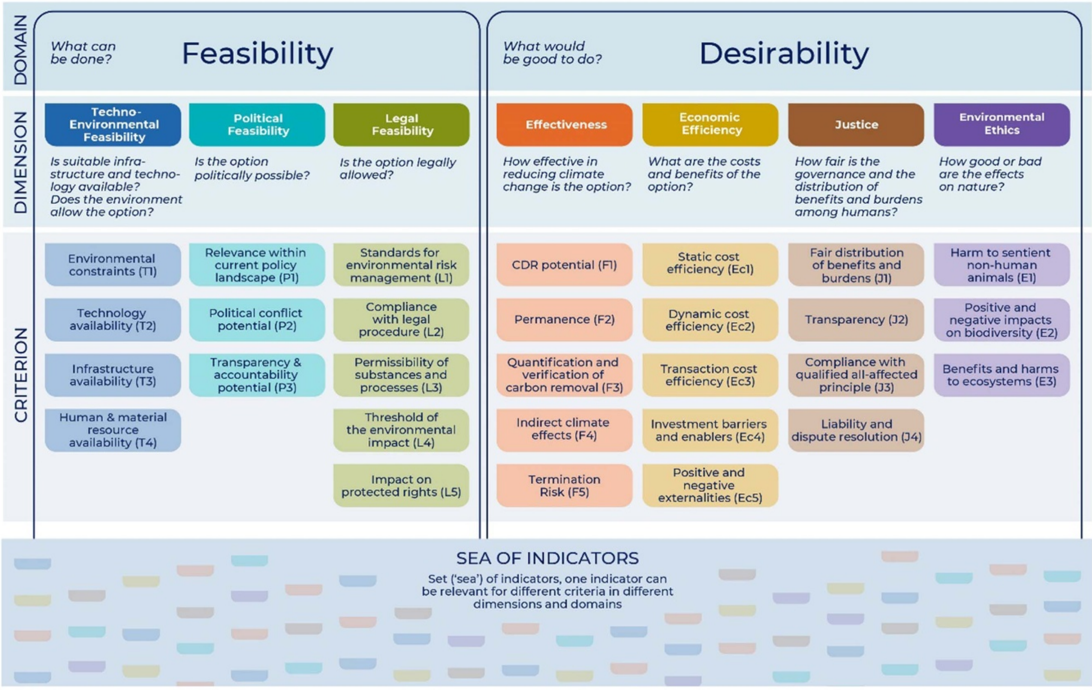

Figure 1. An assessment framework for evaluating mCDR options. From bottom to top, a set ('sea') of indicators informs a structured collection of criteria. Indicators provide relevant information, criteria comprise standards used to evaluate (i.e. assess) this information. Criteria are informed by several indicators and indicators are often relevant for more than one criterion. Criteria are grouped into assessment dimensions that feed into two overarching domains addressing which mCDR options can be implemented (Feasibility) and whether it would be good or bad (or better or worse) if certain mCDR options were to be implemented (Desirability). There is no predetermined sequence or ranking between the domains, dimensions or criteria. Neither the placement of a dimension in the visual presentation of the framework, nor one dimension having more or less criteria, implies any special relevance.

conceptual work on feasibility (Gilabert and Lawford-Smith 2012, Jewell and Cherp 2020, Nielsen *et al* 2020, 2023) and in normative theory (Roser 2015, Baatz 2018, Heyward 2019, Lenzi and Kowarsch 2022).

Since the framework aims to offer guidance to a wide array of possible users in academia, politics and the wider society, we gathered input from potential users of the framework such as public policy makers, representatives from regulatory agencies, and NGOs at interactive workshops (see section 5). This co-productive, transdisciplinary approach helped to bridge the gap between academia and policy makers, made sure that the assessment framework addresses questions that stakeholders find relevant, and allowed us to develop an assessment framework format that is suitable for end-users (Maas *et al* 2022, Clancy *et al* 2023).

3. An assessment framework for mCDR

The assessment framework (see figure 1) consists of a set ('sea') of indicators informing a structured collection of criteria. Indicators provide relevant information. Criteria express standards used to evaluate (i.e. assess) this information. These 'evaluative standards' also make explicit the relation between the criteria and the overall notions of feasibility and desirability. The political feasibility criterion 'Relevance within the current policy landscape' (P1), for example, spells out that being further along in the policy cycle positively influences political feasibility. Desirability criteria furthermore entail and express values and norms as evaluative standards—they are thus value-based.

The criteria are grouped into a total of seven assessment dimensions, which in turn inform two overarching assessment questions (domains): one on how feasible the mCDR options assessed are and one on how desirable the mCDR options assessed are (see figure 1). The purpose of the framework is to support users in reaching a verdict on which mCDR options can be implemented (feasibility) and whether it would be good or bad (or better or worse) if certain mCDR options were to be implemented (desirability).

In contrast to prominent assessment frameworks for climate options (e.g. IPCC 2018, 2022a, 2022b, 2023, GESAMP 2019, Förster *et al* 2022), one indicator is not assigned exclusively to one criterion, but may be relevant for multiple criteria in different dimensions and domains (for the full set of indicators and the criteria for which each indicator is relevant see

Annex 2). We use the image of a 'sea of indicators' out of which the criteria 'fish' the indicators they need to describe this feature. For example, indicator I37 asks whether 'necessary infrastructures (e.g. energy grid, roads, pipelines) already exist, and if not, can we create those first?'. It is relevant for criterion T3 'infrastructure availability' which belongs to the techno-environmental feasibility dimension in the feasibility domain. Because lack of necessary infrastructure can act as an investment barrier, it is also relevant for criterion Ec 4 'investment barriers and enablers' as part of the economic efficiency dimension in the desirability domain. This also shows how many pieces of information, i.e. many indicators, are relevant for assessing both feasibility and desirability, i.e. inform criteria in both domains. The indicators can be quantitative or qualitative and serve as the empirical foundation upon which the assessment process is based. Each indicator is accompanied by a specific question for ease of use.

While indicators are formulated exclusively in descriptive terms, criteria propose standards for the evaluation of mCDR options. The criterion J2 'transparency', for example, states that, other things being equal, mCDR options are more just if relevant information surrounding them, including anticipated side-effects, are openly communicated. We acknowledge that transparent communication will often have a secondary influence on other criteria, for example within the political feasibility dimension. We view these cross-connections as a positive feature of the framework that expresses itself through shared indicators, and which does not negate that, to stay with the example, 'transparency' is primarily important as a criterion of justice.

Generally, the framework is designed to be applicable both to mCDR methods as a whole and more concrete mCDR projects of all sizes and in all stages of development. If the object of assessment is a general mCDR method like ocean alkalinity enhancement, the assessment will often be able to do little more than point to the need to look at more concrete scenarios. The assessment will be more informative if it includes information on the scope, context and timing of the mCDR option to be assessed. More elaborate questions the framework aims to answer will typically be something at least as concrete as: 'A private company in New Zealand plans to implement an ocean alkalinity enhancement project before 2050 in New Zealand's exclusive economic zone that is supposed to sequester ten megatons of carbon—how feasible and desirable is that?'. Specifying the assessment to a sufficient degree will limit the number of 'depends on implementation' caveats, and prevent misunderstandings about what precisely is being assessed. In other words, assessment results depend on the specific circumstances of the activity being assessed and will change if these characteristics (e.g. actors, location, scenarios, timescale, etc) change.

Even if applied to concrete mCDR projects, assessments will sometimes come with considerable uncertainty. This is true for both indicators and criteria and across the entire framework. However, it is one purpose of assessment frameworks to highlight what would be important to know to assess an mCDR option, but which can currently not be known with a high degree of confidence because of lack of research or because of inherent deep uncertainty (Adler *et al* 2019). Doing so can indicate where more research is needed. Society might sometimes need to decide whether to proceed implementing an mCDR option, thereby accepting current or inherent unknowns. We do not presuppose one specific method of how to account for lack of confidence, but see the approach outlined by Mastrandrea *et al* (2010) and adopted in later IPCC publications as exemplary[10].

The framework is a tool that supports users in their own assessment process. It is not designed to produce assessment results without the need for human judgment and hence it does not prescribe how certain facts about an mCDR option (say, its effects on biodiversity) result in a certain assessment verdict. We do not presuppose which dimensions or criteria should carry more or less weight in the assessment and how individual assessment results should combine into an overall assessment result. Nor is the number of criteria in any given dimension indicative of their relative importance.

The following sections give short descriptions of the dimensions and criteria addressing feasibility (section 3.1) and desirability (section 3.2). More comprehensive information is provided in annex 1.

3.1. Feasibility

When we assess the feasibility of an mCDR option, we assess whether an agent *could* implement that mCDR option upon trying (Gilabert and Lawford-Smith 2012). In our framework, the feasibility domain encompasses techno-environmental, political and legal feasibility. Such a subdivision of the feasibility assessment, including the proposal of criteria and indicators, is compatible with different methods of assessing whether an mCDR option is feasible or not (see Jewell and Cherp 2023 for a recent proposal for such a method).

3.1.1. Techno-environmental feasibility

The dimension of techno-environmental feasibility is concerned with the technical means to carry out the mCDR option and whether there are any environmental constraints that could prevent the mCDR option from functioning fully or partly. This dimension goes beyond previous assessments, which often

[10] See Bindoff *et al* (2019), 521 for an application to, among other things, mCDR options and Bach *et al* (2024) for an explicit discussion of issues of predictability in relation to mCDR and an identification of which forms of mCDR are easier to predict than others.

(primarily) focus on the technical maturity level, also known as technology readiness level (United States Government Accountability Office (U.S. GAO) 2011, GESAMP 2019, IPCC 2022b). Technical means and environmental constraints will be of different relevance for different mCDR methods. The feasibility of alkalinity enhancement through electrolysis, for example, will crucially depend on questions of technological maturity, while planting mangroves is relatively technology-independent but highly dependent on environmental conditions (Gattuso *et al* 2018, 2021).

In addition to criteria on environmental constraints (T1) and technology availability (T2), techno-environmental feasibility also contains criteria on the availability of infrastructure (T3) (e.g. pipelines to underground storage sites), and resources (T4) (including skilled workers and material). Techno-environmental feasibility does not ask about the general availability of these things, but about the availability under the circumstances specified in the assessment (e.g. location, scenario, time-scale, etc) for the actors who seek to implement the option. The lower these constraints are and the more relevant technologies, infrastructure and resources are available, the higher the techno-environmental feasibility of the option.

3.1.2. Political feasibility

Even the most technologically mature forms of mCDR can be highly unfeasible if they do not stand a chance in the political arena. In democratic systems mCDR options must find some level of support (or at least lack of opposition) among elected officials and their electorates. The extent to which mCDR fits within the existing climate policy landscape of a given country or region will affect its political feasibility (P1). The same is true for the level of political contestation or even conflict between groups who support and those who oppose certain mCDR options (P2). Lastly, whether there are policy instruments in place to ensure the transparency and political accountability of a given mCDR activity (P3) will also play a large role in determining its political feasibility.

Overall, the more deeply embedded mCDR is in the wider climate policy landscape, the lower the political conflict potential and the higher the political accountability and transparency is for a given mCDR option, the more politically feasible it will likely be. Moreover, public perception of the mCDR option will influence and be influenced by the three political feasibility criteria.

3.1.3. Legal feasibility

Legal feasibility evaluates whether implementing an mCDR option will be legally permissible at the time and the location of the activity. In contrast to existing work which examines the feasibility of mCDR techniques solely through the prism of current law and treaties (e.g. GESAMP 2019), we propose taking an abstract approach to ensure its adaptability to future changes of the law. While the details of regulating mCDR operations (i.e. applicable regulations) may change, high-level concerns represented by our criteria will remain and should be regarded as legal fundamentals in assessing legal feasibility. The abstract approach also has the merit of applying equally to international, regional and national levels.

The criteria of the dimension represent five areas of concerns typically found in the regulation of hazardous activities. Standards for environmental risk management (L1) relates to the handling of risks before and during an mCDR activity. Compliance with legal procedure (L2) involves procedures specifically addressed to mCDR and procedures applicable to environmentally hazardous projects in general, e.g. the procedural rights of persons affected by the project. Permissibility of substances and processes (L3) addresses substances and processes involved in mCDR operations that are subject to legal regulations. Threshold of the environmental impact (L4) concerns the prohibition of significant transboundary harm. Impact on protected rights (L5) captures the potential harm an mCDR activity can have on non-environmental interests such as economic activity, navigation or cultural value insofar as these harms may challenge the mCDR's legality.

While legal criteria are ultimately binary, their fulfillment typically results from the accumulation of measures taken to meet them. The more steps taken to satisfy these criteria, the more likely the project is to meet the threshold of legality.

3.2. Desirability

Not everything that can be done is something that would be good to do. And some of the things that currently cannot be done are nevertheless so attractive that we should work to increase their feasibility. There are evidently important questions to be answered in the debate about mCDR that are not questions of feasibility, but rather of desirability (Tank *et al* 2025). Our framework makes these questions explicit and discusses them in the dimensions of effectiveness, economic efficiency, justice and environmental ethics.

3.2.1. Effectiveness

The fundamental aim of mCDR measures is to generate climate benefits. Whether an mCDR option is desirable or not is thus heavily, albeit not exclusively, determined by its direct and indirect contribution to reducing climate change. These are evaluated in the effectiveness dimension[11].

The Effectiveness dimension encompasses five criteria: CDR potential (F1) and permanence (F2)

[11] See IPCC (2022a) for another proposal that does not subsume 'effectiveness' under feasibility.

provide basic information about the amount of carbon captured by a CDR option and the duration of carbon storage. Quantification and verification of carbon removal (F3) covers efforts to monitor, report and verify (MRV) carbon sequestration. Higher CDR potential and higher permanence render an mCDR option more effective and hence more desirable. While better MRV by itself does not make an mCDR option more effective, it gives us a better insight into its (lack of) effectiveness, which in turn is desirable. Indirect climate effects (F4) evaluates all effects apart from the intended beneficial effect (i.e. sequestering CO_2), such as additional avoidance of fossil CO_2 emissions. Negative indirect effects like a co-emission of GHGs would undermine the intended effect of an mCDR option (i.e. climate change mitigation), thus more negative indirect climate effects render an mCDR option less effective and hence less desirable. Termination risk (F5) asks whether the mCDR option in question can be terminated without detrimental effects on its original intent. Lower Termination risk renders an option more desirable.

3.2.2. Economic efficiency

When evaluating mCDR options, the question of the cost effectiveness, i.e. the efficiency, of a proposed action inevitably arises. In general, economic efficiency is the allocation of all goods and production factors to their most valuable uses. It explicitly considers not only the financial cost to the implementing actor, but also the cost in terms of societal welfare. From an economic perspective, an option is most desirable if it is the efficient solution, i.e. if it minimizes the cost per unit of CDR. Thus, we see economic efficiency in the realm of desirability.

The dimension economic efficiency highlights the benefits and costs related to mCDR options, including static costs (Ec1), i.e. the cost of CDR incurred by a private or public actor at a given point in time, dynamic costs (Ec2), i.e. potential cost developments over time that may change the relative performance of an mCDR option, and the public or private transaction costs (Ec3) generated by the application of an mCDR option. Investment barriers and enablers (Ec4), which can block or promote mCDR options that would be considered cost-efficient (or not) after a review of static, dynamic and transaction costs, also need to be considered. The same holds for external costs and benefits (Ec5) (external effects, externalities), i.e. financial impacts of an mCDR implementation on third parties who did not choose to take the action.

Higher static (Ec1), dynamic (Ec2) and transaction cost efficiency (Ec3) and the existence of investment enablers (cf Ec 4) make an option more desirable. More and higher barriers (cf Ec4) and higher negative and lower positive externalities (Ec5) make an option less desirable for a society.

Most mCDR options are at a very early stage of development. Data on cost functions and market prices are not yet available. Nonetheless, we include these criteria because looking beyond operational costs can raise the awareness about mCDR's broader implications for welfare.

3.2.3. Justice

Beyond the climate benefits resulting from a reduced atmospheric CO_2 concentration (see Effectiveness dimension), implementing mCDR will entail a diverse array of other benefits and burdens. While their extent is assessed in the economic efficiency dimension (Ec5), distributive justice (J1) focuses on their distribution.

Beyond distribution, the procedures used in decision-making processes leading up to mCDR implementations and during the governance of mCDR projects are also subject to demands of justice. Criteria relating to procedural justice encompass transparency (J2) and the matter of who gets a say in the decision making process (J3).

Finally, directly or indirectly, mCDR options could result in people being burdened, maybe even harmed. If that happens, regulations of liability and dispute resolution (J4) are key to restoring justice.

Overall mCDR options are more desirable the closer they come to meeting the demands of distributive, procedural, and compensatory justice.

3.2.4. Environmental ethics

Many impacts on the natural world will have knock-on effects on humans and will therefore feature in the justice and economic efficiency dimensions. Mangrove restoration, for example, could result in increased food security and extreme weather protection for local land users (Fuchs and Noebel 2022, Sasmito *et al* 2023). The environmental ethics dimension acknowledges the widespread intuition that certain effects on the natural world are important beyond their effects on humans, namely harm to sentient non-human animals (E1), impacts on biodiversity (E2), and benefits and harms to ecosystems (E3).

Accordingly, beneficial impacts on non-human animals, biodiversity and ecosystems increase desirability, while negative effects lower desirability.

4. Assessing desirability without being policy-prescriptive

Assessment frameworks collect and organize the questions one must ask in order to evaluate, in this case, mCDR as a potential response to climate change. They aim to create transparency by explicitly naming and systematizing criteria and indicators for assessment, making assessment processes comprehensible and comparable. Transparency prevents assessments from becoming a 'black box' where expert judgments are offered in a way not open to critical scrutiny. Instead, it allows users to pinpoint where exactly different agents disagree in the assessment of mCDR options, making such disagreements open for discussion both within and beyond the research community. By explicitly covering desirability as a separate domain (rather than incorporating desirability judgments in feasibility assessments) the proposed framework allows for discussion about what mCDR options, if any, fit our norms and values—and what relevant norms and values are.

By naming dimensions, criteria and indicators by which to judge whether an mCDR option is more or less desirable, one commits oneself to certain normative ideas about desirability. We hold that such value judgments are compatible even with a strict constraint against policy prescriptiveness, as long as they are made explicit and thus open to debate (Tank *et al* 2025). Statements about desirability resulting from our assessment framework have a conditional character. By way of example, if the user or addressee of an assessment accepts the polluter pays principle, then an mCDR option A, where those who have contributed more to climate change bear a bigger share of the costs, qualifies as more desirable than option B, where the majority of the burdens falls on the contemporary poor and future generations. However, if the polluter pays principle is not accepted, option B might be evaluated as more just, depending on the alternative normative principles that are used. Explicitly naming the value judgments that underpin an assessment of mCDR options facilitates a discussion about what is considered desirable—and what mCDR options best fit these criteria of desirability.

In this paper, we propose assessing the desirability of mCDR options against the background of well-justified and widely shared values, norms or basic principles such as the UN's Sustainable Development Goals (SDGs) (informing e.g. the Environmental Ethics dimension, see Annex 1) and widely-held principles of climate justice (informing the Justice dimension, see Annex 1). Further SDG targets and indicators inform the choice of indicators underlying the various criteria in our framework. For instance, the indicators underlying the fair distribution of benefits and burdens were chosen with SDG 1–3 and 10 in mind, among others.

5. Example application of the framework

The framework has been developed in a way that does not prescribe how it should be applied. There is no predetermined sequence or ranking between the domains, dimensions or criteria included in the framework, and no predefined rules for weighting or aggregating the results[12]. The framework is designed to bring together the wide range of expertise needed to holistically assess mCDR approaches. As such, its use requires inter- or transdisciplinary cooperation, but there is more than one way in which this could be carried out. In the following, we describe how we have used it so far and draw out some general guiding principles for applying the framework.

To test the assessment framework, we organized a series of workshops to bring together scientists, members of NGOs, representatives from various German ministries and government agencies to jointly apply the assessment framework to hypothetical mCDR scenarios (Kreuzburg *et al* 2024). Each of the scenarios presented a rich 'story' about a hypothetical mCDR activity which included information about potential technical and environmental risks and benefits, but also information about environmental and procedural justice implications, political and societal context conditions. For each of the scenarios, the transdisciplinary participants were asked to imagine they were tasked with assessing the hypothetical activity to inform the decision as to whether it should go ahead.

To allow the assessment framework to be applied in a participatory, interactive manner at these workshops, we developed a question guide, with each question corresponding to one indicator from the framework (see Annex 2). To apply the question guide, we took a bottom–up approach, focusing on answering indicator level questions for each dimension first, then moving on to use the information gained to address the bigger picture questions about feasibility and desirability. We went through the question guide with the workshop participants step-by-step. We documented all discussions, disagreements and decision-making processes as the assessment was jointly carried out. We did not impose any weighting or aggregation rules on the assessment process, but rather asked those participating to describe and document the reasons for the resulting assessment outcomes. The end result was a shared understanding among those in the room about the feasibility and desirability of the hypothetical scenario being assessed, and how this assessment result had been jointly achieved.

The workshop participants were asked to provide feedback on this process. Amendments to the framework were made based on these responses. The participants responded that they found the framework to be a useful and productive way to forefront the key interrelations between the various dimensions of mCDR assessment. It was also emphasized that applying the framework required a wealth of background

[12] For pragmatic reasons, it might make sense to start with those dimensions where one might suspect 'show stopper' results that would eliminate the need for further assessment. We thank an anonymous reviewer for pointing this out.

information on the whole life-cycle of a planned mCDR activity, input and expertise from a wide range of academics and practitioners, and clear documentation of assumptions made during the assessment process.

Overall these exercises helped to distill the following guiding principles for the application of the framework:

- For a comprehensive assessment, include interdisciplinary experts and practitioners with expertise relevant for each dimension of the framework.
- As far as this is possible, make sure representatives of all (directly) affected parties are involved in the assessment process from the beginning (i.e. local community members, but potentially also actors representing those who stand to benefit from the climate effects of an mCDR option).
- Clearly communicate all aspects of the planned mCDR activity to those involved in the assessment process.
- Jointly work through the assessment framework dimension by dimension, starting from the indicator level, and collecting all information needed to answer criteria and dimension level questions.
- Clearly document disagreements, discussions and decision-making processes.

6. Conclusion

We have presented a holistic assessment framework for mCDR options. Compared to frameworks currently used for assessing CDR or other climate mitigation and adaptation options, it clearly distinguishes between listing information on mCDR options at the indicator level and evaluating this information via criteria, and it lays open the underlying evaluative standards upon which the assessment is based.

A further strength of the framework is that it synthesizes knowledge from a wide range of academic disciplines, including both natural, engineering and social sciences, laws and economy, as well as the humanities. Indicators are not limited to a specific criterion; rather the same indicator can be relevant to multiple criteria and consequently dimensions. In this way the assessment framework bridges the boundaries between disciplines. In addition, it was developed with input from a range of transdisciplinary stakeholders, including members of NGOs and representatives from various national government agencies.

We as society need a debate not just about which forms of mCDR can be done, but also about which mCDR options would be good to do according to key societal goals and norms. Assessment frameworks focusing on feasibility alone are not sufficient to support this debate. Science and humanities have much to offer in analyzing how mCDR options facilitate or hinder the achievement of these societal goals and in reflecting upon the values behind them. In order to be truly holistic tools to assist decision-making, we believe assessment frameworks should also cover desirability (Tank *et al* 2025). The framework presented here is the first within the climate assessment literature to do so explicitly.

The assessment results produced using the framework presented here can help inform future decision-making and governance by identifying the key aspects that hamper the feasibility and desirability of a given mCDR option. Based on these outcomes, framework users can discuss how to make comparatively desirable options more feasible and how to mitigate the undesirable aspects of feasible options.

Data availability statement

The data cannot be made publicly available upon publication because no suitable repository exists for hosting data in this field of study. The data that support the findings of this study are available upon reasonable request from the authors.

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