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# Guidance for assessing abiotic marine carbon dioxide removal monitoring, reporting, and verification plans

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#### Context

Accurately quantifying the carbon removal resulting from abiotic marine carbon dioxide removal (mCDR) deployments and accounting for system leakages in open environments is challenging for a <u>number of reasons</u>.

Frontier partnered with scientists at the nonprofit [C]Worthy<sup>1</sup> to propose a set of requirements that would give us confidence that an abiotic mCDR project is responsibly, conservatively, and rigorously demonstrating removal from deployments, despite these measurement challenges.

This document is *not* a credit program protocol. Rather, it is an interim tool that Frontier and other buyers can use to evaluate the measurement, modeling and sampling approaches of offtake candidates today while formal protocols develop. It only covers abiotic approaches, and is generally not intended to be used to assess biotic mCDR such as marine or terrestrial biomass sinking.

mCDR includes a number of subpathways including mineral ocean alkalinity enhancement, electrochemical ocean alkalinity enhancement, inland water alkalinity enhancement, and direct ocean removal. While this guidance focuses on some of the most common uncertainties, subpathways will have additional specific MRV considerations that should be assessed on a project-by-project basis.

 $<sup>^{1}</sup>$  [C]Worthy team and organizational details: https://www.cworthy.org/team

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#### Summary of abiotic mCDR measurement requirements

In order to build confidence in the climate impact of abiotic mCDR activities, Frontier requires that suppliers have methods to effectively:

- **Measure alkalinity added** or carbon dioxide removed from ocean systems with a high level of accuracy.
- **Robustly account air sea gas exchange** dynamics specific to the site of the mCDR activity, and any resulting lags in effective carbon removal.
- Take steps to **minimize risks of secondary carbonate precipitation** that could re-release captured CO2, and ensure local conditions do not exceed thresholds under which precipitation might occur.
- Account for any change in biotic calcification response in the environment in which mCDR operations are occurring. Any increases in biotic calcification could effectively reverse a portion of carbon removal.
- Account for any reduction in natural alkalinity release. The addition of alkalinity can impact natural weathering of alkaline materials, particularly in sediments, and any change as a result of the project should be assessed.
- Ensure minimal reversal risks of removed acid or CO2. mCDR approaches that remove acidity or CO2 from the water must ensure they are not re-released.
- Accurately assess ocean storage of bicarbonate from upstream interventions. The addition of alkalinity or removal of carbon from freshwater systems can result in leakage during carbonate chemistry equilibration upon reaching the ocean.
- **Robust data sharing.** Developing robust empirical and modeling approaches hinges on transparency and openness in deployment data and model code. mCDR should not rely on black-box models developed using proprietary datasets.
- Robustly **monitor ecosystem impacts** and follow Frontier's ecosystem safeguards.

The rubric below outlines the practices for quantifying deliveries that Frontier expects to see from abiotic mCDR projects to be eligible for offtakes. As mCDR is still a relatively nascent approach, Frontier will update the bar periodically as field learning evolves.

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		Project Assessment				
	<b>Description</b> Why this factor matters for verification confidence	Fail	Acceptable for offtake	Best-in-class		
Air-Sea Gas Exchange	<ul> <li>The effective carbon removal associated with mCDR occurs when pCO2 depleted seawater resulting from either direct removal of DIC or from a shift of DIC to bicarbonate induced through an enhancement in alkalinity absorbs CO2 from the atmosphere. If alkalinity-enhanced or DIC-depleted water is mixed into the deeper ocean prior to equilibration, then a portion of the atmospheric drawdown could be delayed for decades or even centuries.</li> <li>Note: Air sea gas exchange models are an evolving area of science, but suppliers will lock in the models they use at the time of the offtake. Model updates will not retroactively affect credits issued.</li> </ul>	Project fails to acknowledge that atmospheric drawdown requires air-sea gas exchange with the surface ocean, and instead assumes that removal of CO2 from seawater is quantitatively equivalent to removal from the atmosphere.	Project uses scientifically sound arguments to determine the rate of CDR following air-sea gas exchange. Models used are reasonable, though the models' certainty is low at the relevant deployment sites.	Projects quantitatively assess the amount of re-equilibration via air sea gas exchange, including accounting for regional, seasonal, and model-based variations in air-sea gas exchange. Sources of uncertainty are identified and the total uncertainty is assessed using an approach that is scientifically justified.		
Alkalinity Addition Efficiency	The total useful alkalinity released in seawater is a function of particle size, dissolution rates, and sinking rates. Larger particle sizes may reduce dissolution rates or result in material sinking to depth or being buried in sediment, complicating the assessment of alkalinity released and potentially resulting in a reduction of net atmospheric CO2 uptake.	No direct means of quantitatively assessing the amount of alkalinity added (or carbon removed) from the ocean as a function of time.	The release of alkalinity or dissolution rate is expected to be fast based on modeling and mineralogy. Measurement of alkaline material dissolution is possible but subject to sampling and temporal uncertainties. For DOR, quantification of the amount of carbon that has been removed is directly measured from the CO2 stream, not modeled from the process run parameters.	Projects directly control and verify the rate of pre-dissolved alkalinity release (or DIC-depleted water release). In the case of mineral OAE, release of alkalinity is precisely quantified (e.g. via a containerized reactor).		
Secondary Carbonate Precipitation	If too much alkalinity is present in a particular parcel of seawater, it can cause existing bicarbonate in the seawater to precipitate out as carbonate, consuming alkalinity, and releasing half of its stored CO2. This secondary	Aragonite saturation states are not modeled or measured. Or local dilution rate is slow and creates a risk of localized secondary precipitation.	Conditions for runaway precipitation are well understood <i>locally</i> through experiments. Reasonable set of thresholds established through pre-deployment trials <i>locally</i> .	Conditions for runaway precipitation are well understood <i>locally</i> through experiments. Reasonable set of thresholds established through pre-deployment trials <i>locally</i> . MRV discount is determined by direct		

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	carbonate precipitation can "run away" and result in significantly more total alkalinity to be removed from the system than was initially added. This appears to be triggered by an aragonite saturation state ( $\Omega A$ ) of 7 or above in ocean water.		Injection rate is set to match with modeled dilution timelines. MRV discount is determined by location, dilution speed, and modeled alkalinity impact.	measurement of the max alkalinity added/reached, or operational control is possible based on models or measurement: injection rates are dynamically updated based on quantified dilution and/or alkalinity.
Biotic Calcification Response	Since calcification consumes alkalinity, leading to a release of CO <sub>2</sub> , any changes to the rate of biotic calcification in response to shifts in pH and dissolved inorganic carbon (DIC) concentrations driven by ocean alkalinity enhancement or direct ocean removal process must be considered. Changes in biotic calcification rates could occur in both coastal and open ocean waters, and at the level of individual calcifiers or calcifier populations.	Projects do not take biotic calcification responses into account in their assessment of project net CDR.	Biotic calcification discount has been estimated quantitatively and determined to result in less than 5% of net CDR reductions at reasonable confidence. Projects apply this flat discount rate in credit issuing.	Projects have a robust approach to track changes to calcifying organism populations, both through controlled laboratory trials and in actual deployments. Any observed increase in calcification response is subtracted from project net CDR. Alternatively, the supplier has offered a quantitative argument that the discount is negligible for a specific deployment.
Natural Alkalinity Reduction	Increasing the alkalinity of coastal waters can potentially reduce the rate of natural alkalinity generation through calcium carbonate dissolution from sand and other marine sediments. This effect is important in enclosed areas, coastal systems, etc, but not for deep ocean deployments.	Projects do not take any baseline measurements and are unable to effectively account for changes in natural alkalinity release that result from the project.	Discount is based on scientifically sound models of natural alkalinity feedback. Projects are designed to ensure rapid dilution to minimize impacts on local natural alkalinity sources.	Natural alkalinity discount rate is based on quantitative, experimental data local to the deployment. Alternatively, the supplier has offered a quantitative argument that the discount is negligible (e.g. project is not in a coastal or enclosed environment).
Reversal Risks of Removed Acid or CO2	For approaches that remove acid or CO2 from the ocean, the effective removal only occurs if the acid or CO2 remains out of the ocean (or atmosphere). A re-release of acid removed during electrochemical OAE would effectively undo the CDR, as would a release from a CO2 reservoir in the case of DOR.	Projects lack a clear plan for long-term stable storage of removed CO2 or acid, or plan to use removed acid to neutralize alkalinity in a way that would inhibit counterfactual carbon removal.	Responsibility for storage and reversal risk is assigned to a third-party.	The project has robust long-term safeguards for geologic storage of CO2 or acid, with a high likelihood of functional stability of storage over observable timescales (e.g. through mineralization). Any use of acid for neutralization of alkalinity is carefully assessed to ensure no reduction in counterfactual CDR occurs. Alternatively, the project does not require storage (e.g. mineral OAE).
Ocean storage of bicarbonate from upstream interventions	In cases where alkalinity is added to rivers or other upstream systems, equilibration of the carbonate system in the shallow ocean can lead to rapid	Ocean storage is not explicitly quantified, and river/shallow ocean CO <sub>2</sub> leakage is not discounted.	Outgassing in river/shallow ocean is discounted using a flat rate that isn't specific to local conditions.	Outgassing in river/shallow ocean is simulated or measured for local conditions. A dynamic discount rate is applied for CO2 re-released based on deployment specifics.

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