

Guidance for assessing quantification plans and deliveries for enhanced weathering

Reviewer rubric for Frontier's 2023 Purchase Cycle | Summer 2023

Context

Accurately quantifying the carbon removal resulting from enhanced weathering (EW) deployments and accounting for system leakages in open field environments is challenging for a number of reasons.

Frontier partnered with Noah Planavsky¹ and Chris Reinhard² to propose a set of requirements that would give us high confidence an enhanced weathering project is responsibly, conservatively, and rigorously demonstrating removal from field weathering deployments, despite these measurement challenges.

This document is *not* a credit program protocol. Rather, it is an interim tool Frontier reviewers can use to evaluate the measurement, modeling and sampling approaches of offtake candidates today while formal protocols develop.

This document contains:

- A summary of the criteria enhanced weathering projects must meet to be eligible for offtake
- An excerpt of the measurement, reporting, and verification (MRV) questions from Frontier's offtake application and the rationale of why each matters
- Proposed reviewer scoring based on applicants' submitted answers

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Summary of enhanced weathering measurement requirements

Frontier has high confidence an enhanced weathering project is responsibly, conservatively, and rigorously crediting tons for their deployment if they:

- Measure feedstock dissolution with redundant measurement techniques
- Have a spatial and temporal sampling strategy that is deployment-location-specific
- Quantify soil and river leakages and discount delivered volume accordingly
- Quantify the re-release of captured CO₂ in the coastal ocean and from long term carbonate formation, and discount delivered volume accordingly
- Use agronomic measurements to assess historical pH management practices and explicitly remove any baseline emissions/capture associated with liming
- **Quantify structural and parametric model uncertainty**, transparently publish modeling parameters, and share anonymized field-level climatological and geochemical data to allow for verification of results and further the scientific foundations for the field.
- 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 a given field enhanced weathering candidate to be eligible for offtake. Frontier will update the bar periodically as field learning evolves.

		Project Assessment		
	Description Why this factor matters	Fail (1) Not eligible for offtake	Pass (3) Eligible for offtake, with strong safeguards	Best-in-class (5) Eligible for offtake
Initial feedstock dissolution	Rates of feedstock dissolution vary over orders of magnitude and represent the primary uncertainty in quantification of CDR during EW.	 Feedstock dissolution is derived from a model forecast and not empirically measured. This includes projects that "validate" a model at a single site and apply the same model with no empirical crosscheck at other deployment sites. Feedstock dissolution is empirically determined with a single measurement technique (gas phase, dissolved, solid soil), but spatial and temporal sampling strategy is not data-based (emergent). 	- Feedstock dissolution is empirically determined with a single measurement technique (gas phase, dissolved, solid soil), and spatial/temporal sampling strategy is data-based and explicitly justified based on prior field data or will be evaluated as such through the course of the project.	- Feedstock dissolution is empirically determined with redundant (and independent) measurement techniques. Spatial and temporal sampling strategy is tailored to each technique based on a data-based evaluation of needed sampling density, either through prior field data from deployment sites or through the course of the proposed project.

Soil & catchment leakage	Re-release of initially captured CO ₂ ("leakage") is known to occur in low-pH soils and in river/stream systems during transport to the ocean, and this must be incorporated into estimated project CDR.	Soil and catchment leakage are not explicitly quantified, and are assumed to be a relatively minor "haircut" that is applied across the board for all project deployments.	Soil leakage determined through thermodynamic calculations with no treatment of cation exchange. River leakage estimated thermodynamically (conservatively assuming equilibration with atmospheric pCO_2) with a dynamic river network for segments downstream of deployment locations. All estimated leakage to be removed from delivered tonnage.	Soil leakage estimated based on measured soil properties (CEC, target soil pH) and a soil biogeochemistry model that includes cation exchange or through robust quantification of solute fluxes. River leakage estimated thermodynamically (conservatively assuming equilibration with atmospheric pCO_2) with a dynamic river network for segments downstream of deployment locations. All estimated leakage is removed from delivered tonnage.
Ocean storage	Equilibration of the carbonate system in the shallow ocean can lead to release of initially captured CO_2 — this is the final hurdle before durable storage, and must be incorporated into any robust estimate of project CDR.	Ocean storage is not explicitly quantified, and shallow ocean CO ₂ leakage is assumed to be a relatively minor "haircut" that is applied across the board for all project deployments.	Ocean storage is quantified through back-of-the-envelope estimates of carbonate system re-equilibration and the long-term response of the ocean carbonate system. Re-release of captured CO ₂ in the shallow ocean is removed from delivered tonnage, while long-term re-release due to marine carbonate formation is ignored.	Re-release of captured CO_2 in the coastal ocean is explicitly quantified, either through conservative thermodynamic assumptions or with an ocean biogeochemistry model. Gradual, long-term CO_2 release from carbonate formation is explicitly quantified and included as a discount on delivered tonnage. In both cases, parametric model uncertainty is explicitly evaluated.
Lifecycle assessment & additionality	Claimed CDR for any project must be on a net lifecycle basis, and must be additional removal relative to the counterfactual case.	No (or only anecdotal) constraints on historical pH management practices. Any reduction in liming rates taken as avoided emissions, with all estimated CDR assumed to be additional.	Clear constraints on historical pH management practice. Previous liming taken as avoided emissions, with all additionality of CDR estimated based on agronomic target pH.	Historical pH management practices evaluated based on previous agronomic measurements. If there is no history of pH management, estimated CDR is considered fully additional. If there is a history of pH management, baseline emissions/capture associated with liming explicitly estimated thermodynamically and either classified as avoided emissions or removed from delivered tonnage.
Model validation & Standards of practice	Developing robust empirical and modeling approaches hinges on transparency and openness in deployment data and model code. Current models are not capable of accurately forecasting CDR, making transparent and rigorous model validation an essential near-term goal for suppliers that use modeling as a part of their approach.	Proprietary model code evaluated through comparison to lab, greenhouse, and/or mesocosm results. All model/optimization code and field deployment data are strictly confidential.	Proprietary model code evaluated through ongoing comparison with field deployment data. Field deployment results aggregated at the field scale are linked to a permanent DOI following delivery.	Open-source model code continuously evaluated with field data during the course of the project. Structural and parametric model uncertainty explicitly quantified. All field climatological and geochemical data (anonymized at the county level) linked to a permanent DOI following delivery.



Responses are, with some targeted exceptions, scored numerically on a 1 - 5 scale. Prompt categories are weighted according to the following table:

Factor	Weighting	
Initial feedstock dissolution	40%	
Standards of practice	15%	
Catchment leakage	10%	
Life cycle assessment	10%	
Model validation	10%	
Soil leakage	5%	
Ocean storage	5%	
Additionality	5%	



Assessment rubric for enhanced weathering MRV application questions

Below is an excerpt of the MRV questions from Frontier's 2023 offtake application with proposed reviewer scoring in the text box in orange based on applicants' submitted answers. For a subset of questions, we have included an explanation of why this is a critical component to factor into our assessment of a project's MRV plans.

2023 Application Supplement: Field Enhanced Weathering MRV Technical Details

This technical addendum contains detailed questions on how companies doing enhanced weathering in fields address various MRV uncertainties.

Initial feedstock dissolution

These questions are intended to help us assess your approach to quantifying weathering of material spread in fields.

1. Will you empirically quantify initial feedstock dissolution or rely solely on modeling?

There is general consensus in the academic community that the rates and extent of rock weathering is one of the largest uncertainties associated with enhanced weathering. Feedstocks used for enhanced weathering have reactive surface areas — which control the weathering reaction — that are much higher than natural rock grains of a similar size (often by an order of magnitude or more). How this high reactive surface area evolves with dissolution of the material under different conditions and deployments is poorly constrained. This uncertainty is more pronounced for coarser grained feedstocks. Estimates of the rates and extent of weathering on a 10-to-100-years-time scale significantly vary if surface roughness is annealed or maintained. The extent and mode of secondary clay formation — which is notoriously difficult to model given strong kinetic inhibition on clay precipitation — will also dictate both the rate and the extent of weathering on a 100-year time scale. Given the current state of the art, this seriously undermines a model-based weathering estimate or a use of a weathering curve to generate carbon credits. At a recent enhanced weathering workshop at Yale 42 of 45 people directly working on enhanced weathering responded in a poll that they did not think that weathering rates could be confidently predicted with a model.

Example answer and scores.

Model-only quantification of initial feedstock dissolution:
 We will quantify dissolution through a state-of-the-art soil chemistry model extensively validated with mesocosm experiments. | We will use empirical data on rainfall and temperature to drive a biogeochemical model that predicts initial feedstock dissolution rates. | 1

 Empirical quantification of initial feedstock dissolution: We will empirically quantify dissolution through (solid/dissolved/redundant) measurement technique(s). | 5

A failing score on this question (Score = 1) would mean the project is not fundable.

2. Describe the method(s) you will employ to empirically quantify initial feedstock dissolution. including assessment of spatiotemporal variability in dissolution rates. For example, if you are using a dissolved-phase measurement, how will you account for temporal variability in discharge, solute concentrations, and cation exchange? If you are using a solid-phase measurement, how will you account for spatial variability in background soil chemistry and feedstock spreading rate? Include the sampling resolution and frequency for this project.

Empirical constraints are a requirement — there is clear consensus that models are not ready to generate credits. A failing score on this question (Score = 1) would mean the project is not fundable.

- Dissolved-phase | soil-based approach | arbitrary spatial resolution | no discharge:
 We will deploy wick lysimeters at a depth of 20cm and a density of one sampler per hectare. Soil waters will be sampled twice monthly and analyzed for dissolved alkalinity, inorganic carbon, and base cations. Water flux will be quantified based on regional precipitation. Uncertainty will be quantified as propagated analytical uncertainty on geochemical measurements. |1
- Dissolved-phase | drainage approach | arbitrary temporal resolution | no discharge:
 We will deploy feedstock exclusively on fields that are tile drained. Drainage waters will be sampled twice monthly and analyzed for dissolved alkalinity, inorganic carbon, and base cations. Water flux will be quantified based on regional precipitation. Uncertainty will be quantified as propagated analytical uncertainty on geochemical measurements | 1
- Solid-phase | arbitrary spatial resolution | discrete sampling:
 We will take individual soil core samples at a density of one per hectare. The upper 10cm of each core will be homogenized, exchangeable base cations will be extracted with a weak Na-acetate leach, and residue will be digested with a multi-acid technique. Soil samples will be analyzed for [immobile tracer] and [dissolution tracer] via [analytical technique]. Individual cores will be interpolated to yield field-scale feedstock dissolution estimates. Uncertainty will be quantified as propagated analytical uncertainty. | 1
- Gas-phase | arbitrary spatial/temporal resolution | no productivity measurement:
 We will measure soil-air CO₂ fluxes with an automated chamber system linked to a cavity ring-down spectrometer. Measurements will be taken continuously for a full day twice

monthly at a resolution of one chamber per hectare. Uncertainty will be quantified as propagated analytical uncertainty on gas flux measurements. | **1**

- Gas-phase | constrained spatial resolution, arbitrary time resolution | productivity:
 We will measure soil-air CO₂ fluxes with an array of automated chamber systems linked to a cavity ring-down spectrometer. Measurements will be taken continuously for a full day twice monthly at high per-hectare density (two chambers per acre), and we will explicitly evaluate the performance of our sampling array through rarefaction of field data. Aboveground primary productivity will be measured via [technique]. Uncertainty will be quantified as propagated analytical uncertainty on gas flux measurements. | 1
- Dissolved-phase | soil-based approach | constrained time/space resolution | no discharge:
 We will deploy wick lysimeters at a depth of 20cm and a high per-hectare density (two samples per acre), and will explicitly evaluate the performance of our sampling array through rarefaction of field data. Soil waters will be sampled at a frequency interval that is justified with reference to the fact that carbon and alkalinity throughput will be pulsed and unpredictable, and analyzed for dissolved alkalinity, inorganic carbon, and base cations. Water flux will be quantified based on regional precipitation. Uncertainty will be quantified as propagated analytical uncertainty on geochemical measurements | 3
- Dissolved-phase | drainage approach | constrained temporal resolution | discharge:
 We will deploy feedstock exclusively on fields that are tile drained. Drainage waters will be sampled at a frequency interval that is justified with reference to the fact that carbon and alkalinity throughput will be pulsed and unpredictable, and analyzed for dissolved alkalinity, inorganic carbon, and base cations. Discharge will be continuously monitored with a flow meter at the outflow point. Uncertainty will be quantified as propagated analytical uncertainty on geochemical measurements and discharge measurements. | 4

- Gas-phase | constrained spatial and temporal resolution | productivity:

We will measure soil-air CO₂ fluxes with an array of automated chamber systems linked to a cavity ring-down spectrometer. Discrete daily measurements will be taken six times throughout the day throughout the deployment period at high per-hectare density (two chambers per acre), and we will explicitly evaluate the performance of our sampling array through spatial and temporal rarefaction of field data. Aboveground primary productivity will be measured via [technique]. Uncertainty will be quantified as propagated analytical uncertainty on gas flux measurements. | **4**

- Solid-phase | arbitrary spatial resolution | pooled/paired sampling:

We will take pooled and spatially paired soil core samples before and after deployment at a density of one per hectare. The upper 10cm of each core will be homogenized, exchangeable base cations will be extracted with a weak Na-acetate leach, and residue will be digested with a multi-acid technique. Soil samples will be analyzed for [immobile tracer] and [dissolution tracer] via [analytical technique]. Paired data will be interpolated to yield field-scale feedstock dissolution estimates. Uncertainty will be quantified as the

larger of: (1) propagated analytical uncertainty; (2) uncertainty in individual paired estimates resulting from variability in controls. | **3**

- Solid-phase | constrained spatial resolution | pooled/paired sampling:

We will take pooled and spatially paired soil core samples before and after deployment at a high per-hectare density (two samples per acre), and will explicitly evaluate the performance of our sampling array through rarefaction of field data. The upper 10 cm of each paired/pooled sample will be homogenized, exchangeable base cations will be extracted with a weak Na-acetate leach, and residue will be digested with a multi-acid technique. Soil samples will be analyzed for [immobile tracer] and [dissolution tracer] via [analytical technique]. Paired data will be interpolated to yield field-scale feedstock dissolution estimates. Uncertainty will be quantified as the larger of: (1) propagated analytical uncertainty; (2) uncertainty in individual paired estimates resulting from variability in controls. | **4**

 Redundant (solid+dissolved phase) | arbitrary spatial/temporal resolution | discrete sampling:

We will deploy wick lysimeters at a depth of 20 cm and take individual soil core samples at a density of one per hectare. Soil waters will be sampled twice monthly and analyzed for dissolved alkalinity, inorganic carbon, and base cations, while solid samples will be homogenized analyzed for [immobile tracer] and [dissolution tracer] via [analytical technique]. Uncertainty will be quantified as propagated analytical uncertainty on geochemical measurements. | **4**

 Redundant (two independent solid phase methods) | constrained spatial resolution | pooled/paired sampling:

We will take pooled and spatially paired soil core samples before and after deployment at a high per-hectare density (two samples per acre), and will explicitly evaluate the performance of our sampling array through rarefaction of field data. The upper 10 cm of each core will be homogenized, exchangeable base cations will be extracted with a weak Na-acetate leach, and residue will be digested with a multi-acid technique. Soil samples will be analyzed for [Dissolution Tracer 1] and [Dissolution Tracer 2] via [analytical technique]. Paired data will be interpolated to yield field-scale feedstock dissolution estimates. Uncertainty will be quantified as the larger of: (1) propagated analytical uncertainty; (2) uncertainty in individual paired estimates resulting from variability in controls. | **4**

Redundant (solid+dissolved phase) | constrained spatial/temporal resolution | discharge measured for dissolved phase | paired/pooled sampling for solid phase:
 We will deploy wick lysimeters at a depth of 20 cm and take paired and pooled soil core samples at a high per-hectare density (two samples per acre), and will explicitly evaluate the performance of our sampling array through rarefaction of field data. Soil waters will be sampled at a frequency interval that is justified with reference to the fact that carbon and alkalinity throughput will be pulsed and unpredictable, and analyzed for dissolved

alkalinity, inorganic carbon, and base cations. The upper 10 cm of each paired/pooled sample will be homogenized, exchangeable base cations will be extracted with a weak Na-acetate leach, and residue will be digested with a multi-acid technique. Soil samples will be analyzed for [immobile tracer] and [dissolution tracer] via [analytical technique]. Lysimeter data and pooled/paired soil data will be interpolated to yield field-scale feedstock dissolution estimates. Uncertainty will be quantified as the larger of: (1) propagated analytical uncertainty; (2) uncertainty in individual paired estimates resulting from variability in controls. **5**

3. Describe how you will constrain the fraction of feedstock dissolution that is driven by carbonic acid versus other potential acid interactions (e.g. acidity from fertilizer).

There should be constraints on the extent of strong acid weathering. Carbonic acid and strong acids can both fuel dissolution of rock feedstock. Strong acid silicate weathering can lead to CDR or can be carbon neutral. If there is significant carbonate alkalinity in the weathering system—relative to the acid load—strong acid weathering of silicates is reducing CO₂ evasion and driving CDR. The strong acid load needs to be constrained. There are multiple empirical and model-based ways to provide reasonable constraints on the portion of strong acid weathering that should be considered part of CDR.

Example answer and scores.

- Charge balance by carbonic acid assumed, with no justification for why strong acid removal results in CDR:
 - We will assume that all feedstock dissolution is charge balanced by carbonic acid. | 1
- Dissolution explicitly corrected for acidity from fertilizer, but implied CDR retained: We will use documented fertilizer application rates and measured nitrogen use efficiency to quantify the fraction of feedstock dissolution attributable to strong acid production from fertilizer. We will use a soil reaction-transport model and a dynamic river network to construct a counterfactual for strong acid release in the absence of feedstock application, and will retain in our delivery any CDR associated with buffering fugitive acidity at the catchment scale. | 1-5 (depending on quality of counterfactual method)
- Robust measurement of alkalinity and DIC export from the system:
 We will simultaneously quantify initial feedstock dissolution and charge balance with carbonic acid through robust, time-integrated measurement of alkalinity flux from the soil column (or at the field scale). | 1-5 (see score for description of solute flux quantification)
- Conservative removal of fertilizer acidity from feedstock dissolution:

We will use documented fertilizer application rates and assume that all ammonium nitrogen in applied fertilizer is nitrified with attendant strong acid production. This fraction of the overall charge balance from feedstock dissolution will be removed from delivery. | **5**

Dissolution explicitly corrected for acidity from fertilizer with implied CDR removed:
 We will use documented fertilizer application rates and measured nitrogen use efficiency to quantify the fraction of feedstock dissolution attributable to strong acid production from fertilizer. This fraction of feedstock dissolution will be removed from delivery. | 5

4. Will you make redundant measurements of initial feedstock dissolution? If not, how will you verify the accuracy of your measured initial feedstock dissolution?

Given the level of uncertainty at this stage, redundancy is the clearest path toward ensuring that CDR estimates are robust and widely accepted - all efforts should thus have multiple means of empirically estimating CDR rates.

As we are rolling out various proposed methods of tracking EW there is an obvious appeal in having empirical or empirical + model based CDR estimates. This is one way – with limited extra cost in many cases – to more rapidly move forward our understanding of how to track EW and avoid claims that are poorly founded.

Model-only quantification of initial feedstock dissolution:
 We will quantify dissolution through a state-of-the-art soil chemistry model extensively validated with mesocosm experiments. | 1

Non-redundant empirical measurement of initial feedstock dissolution:
 We will measure initial feedstock dissolution using solid-phase estimates of cation mobility. Although we will not make redundant dissolution rate measurements, our empirical cation mobility estimates will be compared with results from a published/validated and open-source biogeochemical model using measured agronomic boundary conditions. | 3

Redundant empirical measurement of initial feedstock dissolution:
 We will make redundant measurements of initial feedstock dissolution, empirically quantifying: (1) cation mobility from the solid phase; and (2) cation storage/loss from the dissolved phase. Uncertainty in each set of measurements will be quantified as described above/below, and any conflicting estimates from the two methods will be flagged and removed from delivered tonnage. | 5



- 5. Describe how you will constrain or deconvolve signals for background (natural) weathering relative to signals for enhanced weathering.
 - Background (control) weathering not constrained for all deployments at the field scale | 1
 - Constraints on background (control) weathering for all deployments at the field scale: | 5
- 6. Describe how you will quantify uncertainty in feedstock dissolution rates at the field scale, and how this uncertainty will be propagated at the deployment scale and through the duration of the contract delivery period.

There needs to be clear plan for estimating uncertainty in feedstock dissolution rates

The basic idea behind most of the modes of constraining the extent of enhanced weathering are straightforward (e.g., tracking how much basalt was dissolved, tracking how much soluble carbon was produced). In most cases the complicated aspect is going to be ensuring that you have a way of estimating the spatial and temporal variability in your proxy. For instance, it is well established that dissolved fluxes scale with water fluxes and that both vary significantly through a season and with the severity of storms (e.g. Raymond et al., 2016). Any soil-based estimate is going to vary significantly spatially – in part because it is well established that organic matter fluxes vary wildly even within a field (e.g. Pennock et al., 2008). At this stage, field-based protocols cannot reasonably have a fixed uncertainty/error. Uncertainty in field/project-based estimates at this stage need to be linked to variability in observations.

- Uncertainty in feedstock dissolution rates is not explicitly quantified and propagated for all deployments at the field scale | 1
- Uncertainty in feedstock dissolution rates is explicitly quantified and propagated for all deployments at the field scale | 5

7. If rock feedstock chemistry is used to estimate feedstock dissolution, describe how you will constrain uncertainty in feedstock composition.

There should be an estimate of error in feedstock composition.

The carbon dioxide removal potential of a feedstock can be most simply determined by multiplying the concentration of metal cations present in a feedstock (typically Mg^{2+} , Ca^{2+} , Na^+ , K^+) by the generalized stoichiometric ratio of cation: CO_2 consumed in the weathering reaction (e.g. Steinour, 1959; Fernández Bertos et al. 2004; Gunning et al., 2010; Renforth, 2012; Bullock et al., 2021). Here, an assumption must be made about the fate of carbon reaction products (i.e. precipitation of carbonates, export of alkalinity, buffering by the ocean carbonate system; see e.g. Renforth and Henderson, 2017). Depending on the approach, the chemical composition of the feedstock may be used in generating an



enhanced weathering CDR estimate. If this is the case, there needs to be an explicit consideration of uncertainty/error in estimates of the feedstock composition.

- Single pre-deployment sampling/analysis | analytical error propagated:
 We will sample and characterize chemistry for all distinct feedstocks prior to deployment.
 Uncertainty in feedstock chemistry will be assessed based on the reported analytical error on measurement of feedstock chemistry. | 1
- Multiple random pre-deployment samples/analyses | error evaluated explicitly:
 For each feedstock batch defined as an individual feedstock delivery to a field we will take 10 randomly placed samples for chemical analysis. Uncertainty in feedstock chemistry for each field will be assessed based on the reported mean and dispersion of measured feedstock chemistry for the corresponding feedstock batch. | 5

Soil leakage

These questions are intended to help us assess the extent to which soil pH effects on CDR efficiency and pedogenic carbonate formation are taken into account.

1. Will you account for the impact of agronomic target pH on soil CDR efficiency? If so, how will the magnitude and uncertainty of this be quantified?

The product of weathering (reaction of carbonic acid and a silicate mineral) is bicarbonate (HCO_3). However, that bicarbonate will be in equilibrium with other forms of dissolved inorganic carbon (e.g. Dickson, 1981; Zeebe and Wolf-Gladrow, 2001; Wolf-Gladrow et al., 2007; Middelburg et al., 2020). At a low pH, re-equilibration with the carbonic acid system will lead to conversion of bicarbonate to carbonic acid (which is in equilibrium with aqueous CO_2 , and ultimately atmospheric CO_2). Focusing only on tracking the bicarbonate from weathering will suggest there is extensive carbon leakage from acidic soils (see Dietzen et al., 2023). However, this process is also going to deacidify soils – changing the carbonic acid speciation of soil waters after weathering has occurred. The cation from weathering (e.g., Ca^{2^+}) will move into the sorbed fraction of soils replacing a proton (H^+ , acidity), changing the soil pH. As the system reacidifies (which can take, depending on the deployment, months to decades) there will be a re-exchange of the sorbed Ca^{2^+} and H^+ . The dissolved Ca^{2^+} will then be charge balanced by production of bicarbonate. Therefore, if you frame the weathering reaction through the lens of the cation and charge balance, weathering in acidic soils can deliver efficient CDR, albeit with a lag from when the initial weathering reaction occurs. Therefore, to demonstrate CDR the MRV framework has to account for the effects of soil pH on the timing and efficiency of CDR.

- No consideration of soil pH:
 We will not quantify the impact of agronomic target pH on soil CDR efficiency. | 1
- Thermodynamic estimate with no consideration of cation exchange or uncertainty in soil CO₂:

We will use the method of <u>Deitzen + Rosing [2023]</u> to estimate CDR efficiency at our measured agronomic target pH values. | 1

- Thermodynamic estimate with no consideration of cation exchange but quantification of uncertainty in soil CO₂:

We will use the method of <u>Deitzen + Rosing [2023]</u> to estimate CDR efficiency at our measured agronomic target pH values, accounting for uncertainty in the impact of soil pCO_2 on this approach by directly measuring soil pCO_2 . | **3**

- Reaction-transport model estimate considering cation exchange, soil CO₂, and back reactions:

Using measured agronomic target pH and field-scale climatology as boundary conditions, we will use a published/validated and fully open reaction-transport code to estimate soil CDR efficiency at each field location sampled for pH analysis. These locations will be interpolated for field-scale CDR efficiency, with uncertainty being bounded by comparing multiple interpolation schemes. | **5**

- Robust measurement of alkalinity and DIC export from the system:
 We will quantify initial feedstock dissolution through robust, time-integrated measurement of alkalinity flux from the soil column (or at the field scale), obviating the need to explicitly quantify local soil CDR efficiency. | 1-5 (depending on description of solute flux quantification)
- 2. Describe how you will incorporate soil leakage into unit cost, and how this information will be communicated to purchasers of your delivered tonnage.

The utilized framework for accounting for the carbonic acid system in soils needs to not only have a conceptual framework – there needs to be a clear set of guidelines of how leakage is accounted for quantitatively and translated into a monetary framework.

- There is clear accounting of soil leakage and removal from delivery:
 We used a joint model and empirical approach (as described) to ensure that soil leakage is subtracted from initial CDR rates. | 5
- Soil leakage is already accounted for in our estimate of initial CDR rates: We will quantify initial feedstock dissolution through robust, time-integrated measurement of alkalinity flux from the soil column (or at the field scale), obviating the need to explicitly quantify local soil CDR efficiency. | 1-5 (depending on description of solute flux quantification)



3. Describe how you will empirically constrain or otherwise account for the possibility of pedogenic carbonate formation and its impact on estimated CDR.

There need to be constraints on the extent of soil carbonate formation.

When carbonate formation occurs, it drives CO_2 evasion. From a carbon point of view carbonate formation results in the removal of carbonate ion — and thus a drop in pH and increase in carbonic acid (which is proportional to aqueous CO_2). From a cation point of view, calcium is removed from the dissolved phase—thus less carbonate alkalinity is needed to drive charge balance in the system. In many regions, the foremost example being the west of the "liming line" of the middle of the US, upper soils are heavily acidified because of nitrogen fertilizer application but the lower portion of the soil column is still very alkaline. In these cases, you could have rapid weathering near the surface but extensive carbonate precipitation within the upper portion of the soil column, leading to a significant drop in CDR inefficiency. Oklahoma and Oregon are two of the obvious places where this is a concern. On top of the induced soil leakage, extensive carbonate precipitation in the soils can dramatically change soil properties and result in long term damage for the land holder (e.g. formation of fragipans can have multiple negative agronomic effects). Given the potential for long term soil damage, secondary carbonate formation needs to be explicitly considered.

There need to be constraints on the extent of soil carbonate formation. Scoring of 1 - 5 based on the extent of constraints built in.

Catchment leakage

This question is intended to help us assess the extent to which evasion from rivers and streams are accounted for.

 Will you explicitly quantify the magnitude of leakage of CO during river/stream transport on a per-deployment basis? If so, provide a full description of the sources, spatiotemporal resolution, and uncertainty in any data used to construct a pre-deployment counterfactual, along with any required model details.

There will be CO_2 evasion from rivers, and this leakage needs to be discounted from the initial carbon captured.

When bicarbonate from weathering enters rivers it will drive re-equilibration of the carbonic acid system. In many segments this will drive CO_2 evasion. However, in some portions of rivers this will lead to a decrease in the extent of CO_2 outgassing.

It is possible to estimate the extent of CO_2 evasion during an enhanced weathering deployment with a fixed river network (e.g. Zhang et al., 2022). But it is more accurately done with a dynamic river network (where there are water and alkalinity fluxes that can vary over time and interact with the atmosphere). In other words, there are multiple ways of tackling the problem of CO_2 evasion in surface waters, but protocols need to explicitly address how river leakage will be constrained, how that will factor into CDR estimates, and how uncertainty in their estimate is quantified and incorporated into delivery/cost.



- Dynamic per-deployment quantification of catchment leakage:
 We will use existing data on river/stream chemistry for river segments downstream from our deployment to construct a counterfactual case, then run a dynamic river network to estimate changes in CO₂ storage at the catchment scale for each of our deployments. | 4
- Static per-deployment quantification of catchment leakage:
 We will estimate the thermodynamic transport efficiency of all stream/river segments downstream of each deployment, and any implied leakage at equilibrium will be removed from delivery. Transport efficiency will be conservatively estimated based on equilibration with current atmospheric pCO₂. | 5

Ocean storage

These questions are intended to help us assess your approach to estimating leakage due to both river-ocean mixing and leakage in the ocean from marine carbonate precipitation during the first 1,000 years after deployment.

1. Describe how you will constrain the extent of CO₂ leakage from river-ocean mixing due to carbonic acid system equilibration in the coastal ocean.

There will be CO_2 evasion from rivers, and this leakage needs to be discounted from the initial carbon captured.

When bicarbonate derived from weathering enters oceans it will drive re-equilibration of the carbonic acid system and evasion. Alkalinity entering the ocean from weathering is not equivalent to ocean alkalinity enhancement—any statement implying so represents a fundamental misunderstanding of the carbonic acid system.

Similar to rivers, it is possible to estimate the extent of CO_2 evasion during an enhanced weathering deployment with a static ocean model, but this is more accurately done with a dynamic ocean model.

- No explicit quantification of coastal ocean leakage:
 We will assume roughly 10% of captured carbon is lost through leakage in the coastal ocean. | 1
- Dynamic per-deployment quantification of catchment leakage:
 We will use the alkalinity and dissolved inorganic carbon outputs from our estimate of river/catchment leakage as inputs to a coastal ocean biogeochemistry model. Estimated leakage due to equilibration of the coastal marine carbonic acid system will be removed

from delivery. Uncertainty will be quantified through model ensembles in which key parameter values controlling sea-air gas exchange are stochastically varied. | **4**

Static per-deployment quantification of coastal ocean leakage:
 We will estimate the thermodynamic storage efficiency of the coastal ocean proximal to outflow regions for each deployment as a worst-case scenario, and any implied leakage at equilibrium will be removed from delivery. Transport efficiency will be conservatively estimated based on equilibration with current atmospheric pCO₂. | 5

2. Describe how you will constrain the extent of CO₂ leakage from the oceans on a 1,000-year timescale due to marine carbonate precipitation.

There should be a discount for long-term marine carbonate precipitation.

As described above, carbonate precipitation will drive CO_2 evasion. Eventually carbonate precipitation in the oceans will lead to a 50% inefficiency in silicate enhanced weathering CDR. However, this takes thousands of years. Nonetheless, a specified timescale for permanence and method of tacking carbon leakage from this process needs to be noted in any protocol.

- Assumption that long-term leakage due to carbonate formation is negligible:
 We will not incorporate long-term leakage due to marine carbonate formation into our estimated CDR. | 1
- No explicit quantification of long-term leakage due to carbonate formation:
 We will assume that roughly 20% of captured CO₂ is regenerated via burial of calcium carbonate in shallow marine sediments on a 1,000-year timescale. | 2
- Explicit per-deployment quantification of coastal ocean leakage:
 We will use a (global/regional) Earth system model that mechanistically represents formation and burial of calcium carbonate in marine sediments in order to quantify long-term CO₂ regeneration through carbonate formation in the ocean. This leakage will be appropriately discounted in any delivery contract. | 5



Additionality

These questions are intended to help us assess the extent to which the potential effects of displacing ag lime and soil background weathering rates are taken into account.

1. Describe how you have constrained historical soil pH regulation practices on the acres in your deployment(s).

There is not an obvious right answer to this prompt. But it is important to collect background information on liming or organic amendments (e.g., chicken manure can increase soil pH and provide nutrients) as we consider how these processes fit into enhanced weathering purchases. As noted above, liming can be a carbon source, carbon neutral, or a carbon sink — depending on the deployment. The most straightforward case to argue for no additionality (but still decade-scale delivery) is likely silicate weathering as a replacement for sparse limestone addition in acidic cropland soils.

- No constraints on deployment site past pH modifications | 1
- Anecdotal records of deployment site past pH modifications | 3
- Single year record of previous liming history, including initial pH conditions | 4
- Decade scale records of previous liming history, including initial pH conditions | 5
- 2. Describe how you will ensure that your deployments are leading to additional CDR, and specifically how the modified land-use practice associated with your deployment will augment or modify emissions/removals due to liming and/or background soil weathering rates.

It is easy to make a case that liming can be a form of CDR. However, there are other factors to consider. For instance, it is possible to capture more CDR per acre with silicate mineral addition than limestone addition. Nonetheless, it is likely not an ideal use of funds to transport silicates long distances when limestone is a closer feedstock and the liming deployments are likely to result in CDR.

- No constraints on past deployment site pH modifications | 1
- Previous liming, but no evidence for liming of acidic soils (where the process could be carbon positive or carbon neutral) | 3
- No history of past pH practices | 5
- Previous liming in strongly acidic (pH <6) soil (where the process could be carbon positive or carbon neutral) | 5



Model validation

These questions are intended to help us assess how models used in the course of your MRV are validated against observations and deal with uncertainty.

1. If any models are used during deployment, describe in detail how you will establish model accuracy and demonstrate predictive skill.

Protocols should clearly outline how models are validated against empirical observations. For an offtake, referencing a peer-reviewed paper for validation is insufficient.

- Model evaluated against lab/greenhouse/mesocosm trials | Explicit tuning | 1
- Model evaluated against field-scale data | Discrete/extrapolated | Explicit tuning | 3
- Model continuously evaluated against field-scale data | Explicit tuning: We will use a (global/regional) Earth system model that mechanistically represents formation and burial of calcium carbonate in marine sediments in order to quantify long-term CO₂ regeneration through carbonate formation in the ocean. This leakage will be appropriately discounted in any delivery contract. | 5
- 2. Structural uncertainty Does your model include the following processes? (answer yes or no next to each)

[Any "NO" responses yield an overall score of 1]:

- Full three-phase (solid/liquid/gas) system
- Explicit particle size distribution (PSD) tracking
- Cation exchange
- Strong acid dynamics
- Soil mixing
- 3. Describe how you will assess and quantify parametric uncertainty in any model(s) utilized to quantify initial feedstock dissolution or overall CDR.
 - Parametric uncertainty not assessed |1
 - Parametric uncertainty assessed through one-dimensional sensitivity analysis | 3
 - Parametric uncertainty assessed through inclusive stochastic analysis | 5



Standards of practice

These questions are intended to help us understand how you plan to share data with scientific communities.

1. Describe how you will archive and share:

- Characteristics of your feedstocks in particular particle size distributions (PSDs), specific surface areas (SSAs), and feedstock major and trace element chemistry per deployment
- Analytical and LCA data from field deployments geochemical data, spreading rates, measurement error, feedstock processing and transport emissions
- Model code and parameters

Making feedstock data open is essential.

Reporting feedstock data provides a way for verification organizations or companies to validate CDR estimates (through a data-model comparison). Requiring this information (along with other monitoring and reporting requirements) to be open will also help ensure that investments will move forward the entire field of enhanced weathering (even if an individual company folds).

Characteristics of your feedstocks

- Feedstock data to remain proprietary | 1
- Feedstock data to be partially open (partial and/or per-deployment data) | 2
- Feedstock data to be anonymized but fully open on a per-field basis | 5

Analytical and LCA data from field deployments

- Analytical data to remain proprietary | 1
- Analytical data to be partially open (partial and/or per-deployment data) | 2
- Analytical data to be anonymized but fully open on a per-field basis | 5

LCA Data

- Life cycle data to remain proprietary | 1
- Life cycle data to be partially open (partial and/or per-deployment data) | 2
- Life cycle data to be anonymized but fully open on a per-field basis | 5

Model code and parameters

- Model code and output to remain proprietary |1
- Code for CDR estimation open, optimization code proprietary | 3
- All model code and output open | 5