# Appendix 2:

## Foundations research and development (R&D) priorities

Cascade Climate

# Context

Throughout the *Foundations for Carbon Dioxide Removal Quantification in Enhanced Rock Weathering Deployments* publication (henceforth referred to as "Foundations"), there are three primary groupings of guidance present. The first are areas where there is ‘no recommendation at this time’ due to the lack of clarity in the literature and state of ERW. The second is a ‘recommendation’, which is the current suggested path forward out of the provided approaches. The final is 'best practice’, which is presented when there is an established best practice that should clearly be followed.

Additionally, "Foundations" includes both 1) ‘calls to action’ that indicate high-priority areas where scientific and technical advancements could be made to reduce substantial uncertainty or open questions in ERW quantification, and 2) nods to direct opportunities for Research and Development.

This appendix represents a summary of both of the categories of research priorities described above that are present throughout the "Foundations" document, and is not intended to be a comprehensive list of all ERW research that is needed. R&D areas identified are presented in chronological order as they appear in "Foundations", not in order of prioritization or importance to the field.

We intend for this appendix to be a reference to–and inspiration for–additional targeted ERW research and funding. For additional context on a particular research area listed, including references, please refer to the cited section of “Foundations”.

# R&D priorities identified

## 4.3 Operational Considerations and Challenges with Deeper Measurements

- High sampling densities of deep soil measurements will be needed to detect field-scale changes in key parameters (e.g., cation concentrations on the exchangeable fraction, soil inorganic carbon, and more) above baseline soil variability. A large number of deep samples may be required to constrain each component of the Near Field Zone (NFZ) term balance at the field scale.
    - Note: In the context of commercial deployments, "Foundations" provides a strong recommendation that in the near-term, a deeper NFZ should be used on a small subset of the deployment area. This should be included in the MRV cost of a given deployment, given the central importance of deep-soil processes to the ultimate netCDR quantification. This is included as an R&D priority in addition to a commercial consideration given that there are currently no public datasets that estimate field-scale changes in these deeper soil parameters in the context of ERW, but developing these datasets will be critical to understanding NFZ loss pathways and developing predictive models of the system.

## 4.4 Synthesis and Call to Action (within the “Defining the Near-Field Zone” section)

- In some cases, the decision of how to define the NFZ may have substantial impacts on overall netCDR quantification, both in terms of the magnitude of tonnes quantified and the time horizon over which these tonnes are achieved. Comparative analyses that demonstrate the implications of choosing different definitions of the NFZ on the same field would be a helpful step to guide decision making and future protocols and methodologies.

## 5.3.1 Near-Field Zone time accounting frameworks (a comparison of proposed approaches 1 and 2)

- Pursuing method intercomparison–i.e., comparing solid-phase mass balance results with those from aqueous phase monitoring of DIC and weathering products at a range of well-instrumented sites–should be considered a key near-term priority.
    - Independently constraining potential CDR associated with alkalinity release from the feedstock, alongside changes in any transient or permanent sinks

of alkalinity within the NFZ should in theory yield an equivalent mass balance to directly measuring the time-dependent export of dissolved-phase weathering products and associated DIC from the NFZ. However, this has yet to be rigorously demonstrated in an ERW field trial or deployment.

## 5.6 Statistical Methods, Uncertainty Quantification, and Discounting

- The datasets needed to quantify CDR in ERW deployments can be highly complex, often with many different parameters measured at several points in time. Parameters can also co-vary with complex spatial correlation structures. It is therefore likely that more simplistic statistical tests, like Student t-tests or simple parametric confidence intervals, will not be able to accommodate this high-dimensional data, and that closed-form expressions for the standard error or statistical power will be difficult or impossible to develop analytically. Instead, some degree of simulation, re-sampling, or novel statistical model development may be required.

## 5.5.3.1 Counterfactual Near-Field Zone CDR

- Using reactive transport models of the soil profile coupled to models of downstream processes is not currently an acceptable method for quantifying the netCDR of counterfactual liming practices due to a lack of fully validated or benchmarked models (and accepted validation/benchmarking frameworks). Progress on model development and validation against field data could allow for this approach to be a quantification option in the future.

## 7.5 Aqueous Phase Measurement Guidelines

- While there is a decades-long history of collecting measurements of porewater, groundwater, and surface waters across the soil science and low-temperature geochemistry communities that practices employed for ERW quantification can build upon, there is a need to further develop context-specific best practices for quantifying dissolved carbon and cation fluxes for ERW deployments.

## 7.5.3 Temporal variability and frequency of aqueous measurements

- In computing estimates of time-integrated fluxes of weathering products, instantaneous aqueous measurements of the concentrations of weathering products need to be assigned to specific time intervals of fluid flow, potentially using a temporal interpolation method to fill in the data gaps. Such temporal interpolation might best be done with process-based models which can predict the response of the soil water chemistry to fluctuating soil water dynamics (e.g., since

concentrations will vary with net infiltration and evaporation), which is a key area of R&D moving forward.
- Proxy measurements or novel sensor development that allow for the use of in-situ soil sensors (e.g., using electrical conductivity as a proxy for total alkalinity), and which are sufficient validated to be used in place of standard analytical measurements, could allow for the production of a continuous time-series of a given variable of interest. This could also serve to reduce or eliminate the need for temporal interpolation.

## 8.2 Feedstock Dissolution

- There is a need for better prediction and modeling of mineral dissolution rates in soil systems–particularly silicate dissolution rate.
    - There are many complex and interrelated processes that can exert a strong influence on dissolution kinetics in soils, such as temperature, pH, variable water content and fluid residence time, kinetic inhibitors and dissolved phases that enhance rates, the formation of secondary phases, and the impacts of biological processes. It is also extremely well documented that dissolution kinetics observed in field settings can diverge from those predicted from laboratory measurements by several orders of magnitude.

## 8.4 Cation Sorption

- Cation sorption can act as a transient alkalinity sink; when base cations exchange for acidic cations on exchange sites (e.g., $H^+$, $Al^{3+}$), the addition of acidic cations to the soil solution will reduce alkalinity and pH and drive $CO_2$ evasion, reducing CDR efficiency. There is a need to gather multi-annual datasets of how cation exchange capacity and base saturation evolve over the course of an ERW deployment, including measurements of deeper soils.
- Ultimately, the ERW community will need to develop and validate models that can predict the lag time between feedstock dissolution and the released alkalinity exiting the near-field conformance zone.

## 8.5.2 Approaches to monitoring and accounting for potential soil carbonate formation in netCDR quantification

- There is a need to gather long term (i.e., multi-annual) datasets of soil inorganic carbon (SIC) accumulation in ERW contexts, including measurements of deeper soils. These datasets are needed to develop validated modeling frameworks that can predict pedogenic carbonate formation over annual-to-decadal timescales.

### 8.6.1.1 Fe and Al oxy-hydroxides

- It is recommended that pedogenic Fe and Al oxy-hydroxides and associated base cation content are assessed via a variety of extraction methods for near-term ERW deployments in an R&D capacity, as in certain conditions the formation of Fe and Al oxy-hydroxides may reduce CDR efficiency.

### 8.6.1.2 Secondary silicates

- Direct quantification of newly formed secondary clays (e.g., via quantitative XRD) could be extremely challenging, particularly over the short timescales of reporting periods and given that the secondary phases most likely to form rapidly in the field are non-crystalline or short-range order phases that cannot be identified via XRD. Given their importance to soil organic matter stabilization, the detection and quantification of such short-range order phases (both silicates and Fe/Al oxy-hydroxides) are considered a key research priority.
- Building an improved predictive understanding of the timing and magnitude of secondary silicate formation in both the soil profile and along the long fluid residence time flow paths of the lower vadose zone and groundwater systems is also a key R&D priority.

## 8.7 Alkalinity Loss due to Biomass Uptake

- There is a need to develop sufficiently robust predictive frameworks to estimate element-specific plant uptake for different crop types under different growing conditions, as accounting for base cation uptake into plant biomass is important for a holistic accounting of netCDR. Currently, sufficient data (or at the very least, sufficient synthesized data) does not yet exist to develop these frameworks.

## 8.8 Changes to the Net Organic Carbon Balance

- Our understanding of a given ERW intervention's potential impact on soil organic carbon stocks and the net organic carbon balance is nascent, and we do not yet have enough data and sufficient predictive understanding of the underlying mechanistic drivers of interactions between SOC and ERW to consider the potential for SOC mobilization resulting from an ERW deployment to be sufficiently de-risked.
    - Continuing to build out the evidence base for how shifts in soil biogeochemistry and physical conditions due to ERW deployments can influence different aspects of soil organic carbon cycling (productivity, respiration, stabilization, or destabilization of existing organic carbon stocks) would be a valuable addition to the fields' understanding of organic-inorganic soil dynamics.

## 8.8.7 Future research priorities (within the "Changes to the Net Organic Carbon Balance" section)

*This section of "Foundations" contains preliminary recommendations on the outlook and R&D path forward to build a better predictive understanding of SOC-ERW interactions.*

Suggested near-term areas of focus include:

- Incorporation of ERW interventions into models of SOC dynamics–e.g., building on the CORPSE (Carbon, Organisms, Rhizosphere, and Protection in the Soil Environment) framework. Measurement approaches, particularly for long-term monitoring sites, should consider data needed for model parameterization and model-data comparison.
- Probing the microbial community response to ERW interventions.
- Understanding the biological, mineralogical, and chemical effects of ERW on different pools of SOC.
- Investigating the evolution of mineral-organic and Ca-bridging SOC stabilization pathways across different ERW deployment contexts.

## 8.9 Potential Changes to other Greenhouse Gas Emissions

- Building a broader understanding of potential feedback between ERW interventions and non-$CO_2$ greenhouse gas fluxes in different environments is a key R&D priority and should be subject to regular meta-analyses. Specifically, a focus on expanded monitoring for interactions between ERW interventions and soil $N_2O$ emissions and $CH_4$ production in methanogenic systems, field and mesocosm studies, as well as model development.

## 8.10 Modeling the Near-Field Zone: Validation and Uncertainty Quantification

- There is a need for the development of third-party, impartial systems for model validation and uncertainty analysis, such that we can evaluate the predictive skill and sensitivity of ERW models, and understand how and when they can play an increasing role in robust CDR quantification.
    - It is highly likely that geochemical soil models will eventually need to be a central component of CDR quantification as ERW reaches greater scale, such that monitoring and verification can become less reliant on high density measurement and sampling for every deployment. However, given the early stage of the application of such models to ERW contexts and the need for stronger frameworks and datasets for calibration and validation, there is currently strong consensus in the community that soil models

should not be used today in place of direct measurements and empirical constraints to quantify CDR.

### 8.10.3 Benchmarking for ERW

- While there is an established literature describing benchmarks for geochemical reactive transport codes comparing model results for a range of subsurface applications to known analytical solutions or to lab or field data, there is likely a need for the development of ERW-specific benchmarks to evaluate the predictive skill of a range of ERW models in the unique ERW context.

### 8.10.3.2 Model intercomparison

- While initial efforts for ERW model intercomparison have begun, additional efforts are needed to develop the infrastructure for ongoing intercomparison with a higher degree of inclusion of both academic and private-sector models.
    - This could include creating a shared set of model scenarios and boundary conditions for spin-up, a list of parameters to vary and ranges to vary them over, and infrastructure and documentation to automate and streamline the process of including additional models.

### 8.10.4 Sensitivity analysis and model uncertainty quantification

- There would be value in the creation of a shared, automated system for running the same multivariate sensitivity analyses and assessments of parametric uncertainty across both process-based and machine learning ERW models. While the parameters that matter most for driving model output will be different depending on model implementation, a shared platform could vary model inputs for a common set of agreed upon parameters that will likely be present and important in a majority of models.

### 9 Components of the Far-Field Zone Term Balance

- The development of publicly available, benchmarked models that have been developed and/or validated by the broader scientific community would be of high utility for downstream ecosystems (groundwater, surface water, and the ocean).

### 9.2 Lower Vadose Zone and Groundwater Systems

- Considering ERW interventions in the context of models that simulate relevant critical zone biogeochemical processes (e.g., ion exchange, mineral dissolution and precipitation, and redox reactions) is a key R&D priority, as it is not currently feasible to require monitoring or modeling of processes occurring in the deep vadose zone and along groundwater flow paths in commercial ERW deployments.

- In addition, undertaking deep vadose zone monitoring or installing groundwater monitoring wells in a select subset of commercial deployments would assist in understanding the need for a counterfactual assessment in projects underlain by a deep vadose zone, and would support efforts to develop models that simulate relevant critical zone biogeochemical processes.

## 9.3 Surface Water Systems

- The development of catchment-scale models capable of simulating the site-specific proton, alkalinity, and carbon balance as a function of time for a counterfactual and deployment scenario would increase the accuracy of CDR quantification and replace conservative accounting buffers.

### 9.3.1 Fluxes that should be considered in surface water systems

- There is a need to better understand and constrain the impact of an ERW deployment on organic matter respiration and metabolic activity in the surface water system, including the influence on aquatic vegetation that directly takes up bicarbonate.

### 9.3.2 Recommended approach for constraining downstream evasion from surface water systems in early deployments

- There is a need to build towards improved process-based frameworks for explicitly modeling the fluxes in surface water systems, new data products for the validation of predictive modeling frameworks, and open-source community tools that enable the generation of catchment-specific conservative loss estimates that would account for the relative vulnerability of a given catchment to downstream loss (but may not require the level of data necessary to parameterize process-based models for all systems).

#### 9.3.2.2 Estimating carbon loss due to carbonate precipitation and burial in surface water systems

- Opportunities for practitioners working in data-poor regions to draw analogies to other catchments with better representation in global databases (e.g., GLORICH) that have similar underlying bedrock lithology and land use characteristics in order to produce first-order estimates of saturation state should be explored in early-stage deployment and R&D efforts.

#### 9.4.1.2 Changes to the net carbon balance due to reactions in marine sediments

- The potential magnitude of reductions in CDR efficiency due to authigenic clay formation in marine environments and timescale over which that reduction in efficiency would be incurred remains poorly understood.
- In addition, potential changes to counterfactual baseline alkalinity fluxes due to various forms of open-system alkalinity enhancement (inclusive of both ERW and ocean alkalinity enhancement (OAE), amongst others) should be a consideration for additional R&D, as shifts in the alkalinity and carbonate saturation state of overlying waters of shallow marine and marginal marine sediments could decrease the natural or counterfactual baseline alkalinity flux, thereby decreasing net additional CDR.

### 9.4.2 Constraining $CO_2$ evasion due to carbonic acid system equilibration in the surface ocean

- More research is needed to determine whether results from relatively coarsely gridded Earth Systems Models continue to hold with more finely resolved models, especially as coastal biogeochemical and diagenetic models are integrated into ERW quantification.

### 9.4.3 Potential netCDR losses due to ocean carbonate burial over long timescales

- Looking forward to ERW deployment at regionally and globally impactful scales, the community will need tools with which to confidently assess the long-term stability of CDR stored as DIC in the global oceans. Notably, this is an area of overlap with the research and tool development needs of the Ocean Alkalinity Enhancement community, and as such, we strongly recommend that cross-pathway collaborations are undertaken accordingly.