Eion Corp White Paper

Methodology for Carbon Dioxide Removal by Enhanced Mineralization on Farmland in the United States

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1 Sources

This methodology is informed by the following methodologies:

- VCS methodology VM0043, Methodology for CO_2 Utilization in Concrete Production
- 40 CFR Part 98, Subpart RR, Geologic Sequestration of Carbon Dioxide
- 40 CFR Part 98, Subpart HH, Municipal Solid Waste in Landfill

2 Summary Description of Methodology

Enhanced mineralization (EM) is an approach to carbon dioxide capture that results in the permanent sequestration of CO_2 as dissolved inorganic carbon (DIC) (Figure 1). On farmland, defined as all cropland, farmstead land, government program land, idle land, orchards, pasture, wasteland, wetland, and woodland, the carbon captured by EM originates largely as respiration within the pore space of soils. In this soil pore space, the CO_2 concentration is greatly elevated compared to the atmosphere, which accelerates the process. In this context, the process is commonly called enhanced rock weathering (ERW), because it mimics the natural process by which rocks weather into secondary minerals, resulting in a flux of cations and DIC into the ocean. The weathering process is thermodynamically irreversible, and results in the permanent storage of DIC in saline marine environments with a lifetime of carbon on the order of 500,000 years. Inventories of appropriate minerals suggests that the potential scale of carbon removal is ~35,000 Gt of CO_2 (~500 years of current global emissions)(1). Recent studies focused narrowly on land application of silicates suggests the US, China, and India could each be capable of 0.5Gt CO_2 removal per year (2). This methodology is specifically focused on farmland in the United States, due to vast availability of federal data that is required to constrain the methodology. More specifically this means that the rock application on farmland needs to be within the United States, but other project activities, e.g. related to such as quarry or processing, may be outside of the United States.

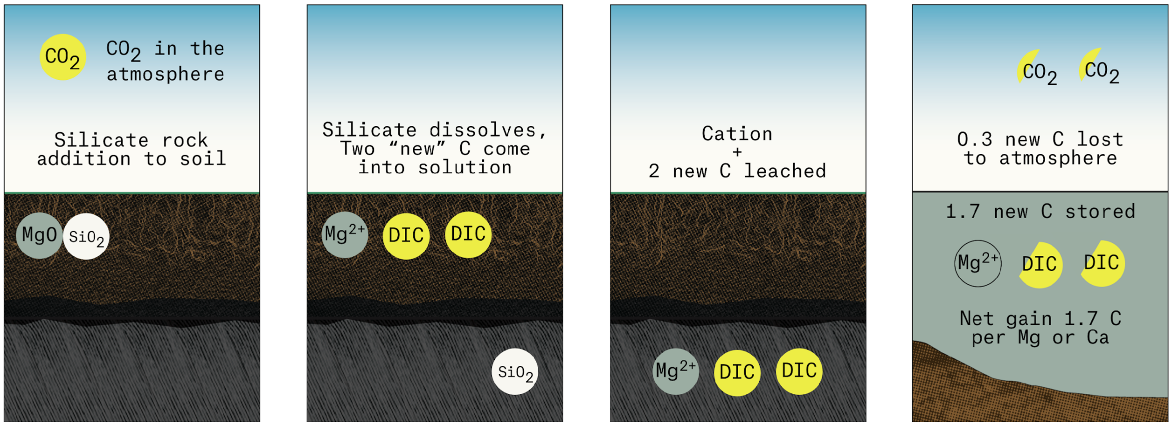


Figure 1: Chemical transformations in carbon capture by enhanced mineralization on croplands.

The key processes in ERW include:

1. Extraction of minerals from a quarry, including primary crushing activities
2. Transportation from the quarry to a processing facility (“mill”)
3. Processing of minerals to a fine particle size with high surface area (>1m^2/g) that represents a sensitized sorbent with high reactivity for CO_2 removal
4. Transportation from the mill to a field
5. Application of the mineral sorbent onto the field
6. The carbon capture, utilization, and sequestration process of mineral weathering in soils (CCUS)
7. Downstream transport of captured carbon from the field to the ocean

Among these seven distinct stages, the first five emit CO_2 as industrial processes. These processes demand energy from the grid (as a mill) or fuel (for transportation), and as such are readily accounted for by conventional lifecycle analyses (NETL cite or 40CFR Part 98 cite) that utilize direct measurements to account for their greenhouse gas emissions. These processes may also have one time capital expenditures, for example for equipment manufactured from steel, or facilities that use concrete, which is also accounted for using conventional methodologies.

The sixth step, the CCUS step in the weathering process, has been the limiting factor for ERW to be accounted for in carbon accounting, because methodologies have either been developed for quantifying (a) weathering rates in the solid phase, or (b) weathering rates at basin or watershed scales, but never at the individual field scale. The present methodology largely focuses on this step.

The final step is analogous to the estimation of hydrologic loss of CO_2 from subsurface reservoirs from carbon captured and injected from point sources. The system loss within monitoring areas in the United States can be evaluated by using historical data from federal sources (e.g. USGS) with models developed at National Labs. Subsequent to project implementation, current data may be monitored to evaluate whether conditions exist for actual system losses exceeding anticipated losses.

3 Definitions

Aglime: Calcite ($CaCO_3$) or dolomite (($CaCO_3$)($MgCO_3$)), generally with a high concentration of Ca and/or Mg, and with a particle size distribution meeting agricultural requirements to be readily dissolved over a 2-4 year time horizon. Aglime is generally a waste product from limestone extraction for the building and transportation industries.

Alkalinity: The charge balance of proton acceptors (which include carbonate species) over proton donors OR the charge balance of cations (which include calcium and magnesium) over anions. These two expressions are by definition equal, and sum to zero net charge of a solution.

Carbonate System: The pH-dependent speciation of H_2CO_3, HCO_3^- , and CO_3^{2-} . The carbonate system parameters that define the equilibrium between these species is determined by temperature and salinity.

DIC: Dissolved Inorganic Carbon, consisting of $H_2CO_3 + HCO_3^{-} + CO_3^{2-}$.

Enhanced Mineralization: Mineralization of CO_2 is a process that reacts alkaline material with CO_2 to form solid carbonate minerals, for CO_2 removal from air, for stable and permanent carbon storage, or for post-processing, where the alkaline agents are separated, and the CO_2 is stored elsewhere. Sources of alkalinity (i.e., Mg- and Ca-rich silicate materials) can be naturally occurring minerals (such as olivine) or waste material from industry or quarry operations.

Farmland: All cropland, farmstead land, government program land, idle land, orchards, pasture, wasteland, wetland, and woodland.

Hydrologic Loss: In the context of ERW, hydrologic loss is the loss of captured CO_2 to the atmosphere due to a change in the carbonate system, due to changes in pH, salinity, or temperature.

LCA: Life Cycle Analysis, meeting ISO 14040 and 14044 standards, and optionally meeting additional DOE NETL CO2U requirements.

Mineral Trapping: Mineral trapping refers to a reaction that can occur when the Ca and HCO_3^{-} dissolved in alkaline water is precipitated inorganically or calcified by aquatic organisms into calcite. In marine environments, the calcite may be deposited at the bottom of the ocean, where it persists for millenia. In these settings, the calcium may be substituted by magnesium, forming dolomite.

Solubility Trapping: In solubility trapping, captured CO_2 will dissolve into alkaline water that is present in soils, freshwater, and marine waters. At the CO_2/water interface, some of the CO_2 molecules dissolve into the alkaline water within the soil's pore space. When CO_2 dissolves in water it forms a weak carbonic acid (H_2CO_3) and eventually bicarbonate (HCO_3^{-}).

System Loss: System loss is the reversal of CO_2 captured.

4 Applicability Conditions

This methodology is specifically focused on farmland in the United States, due to vast availability of federal data that is required to constrain the methodology. More specifically this means that the rock application on farmland needs to be within the United States, but other project activities, e.g. related to such as quarry or processing, may be outside of the United States.

The applicability conditions are built around some basic principles, namely that the project genuinely removes CO_2; that this removal is empirically verifiable; that the project does not cause harm; and the project conforms to applicable law. Projects shall be in farmland with initial circumneutral pH (5.5 - 7.5) where carbon is more likely to be maintained in the aqueous phase and flow into the ocean; this methodology specifically addresses CDR associated with alkalinity generation (and flushing from soils) rather than from the accumulation of solid carbonates in soils.

Projects must meet the following conditions:

- The emissions from the project activity itself must not exceed its life cycle emissions. The system boundaries for accounting the carbon footprint of the project must include seven process stages: extraction, transport from the quarry to the mill, processing, transportation from the mill to the field, application, and capture/sequestration, and storage.
- The silicate mineral used for this project must have sufficient concentration of alkaline elements (Ca, and Mg) to exceed potential crop uptake, and result in capture of dissolved CO_2.
- The soil type of the system must be considered. Only soils where the field-average of pre-project pH is within the range of 5.5 - 7.5 are eligible. Sites with Histic epipedons such as inland basins, peat bogs, mangrove swamps, are not eligible until more information on their full greenhouse gas budgets are available.
- For farmland with soil pH > 7.0, the $CDR_{potential}$ of the project (calculation described below) shall be 3 orders of magnitude greater than the CO_2 sink of an alternative aglime application (e.g. historic best-practice lime application for the region where the project is implemented) predicted by aqueous speciation modeling, e.g. (3,4), in order for the baseline to be considered 0. For soils with pH < 7.0 the baseline can be considered 0.
- The land use must be farmland: all cropland, farmstead land, government program land, idle land, orchards, pasture, wasteland, wetland, and woodland.
- The geography of the applied material must be considered to account for the fate of captured carbon and cations: (a) into marine environments, (b) into acidic lakes, (c) into alkaline lakes (or evaporated). These settings determine the magnitude of hydrologic or system loss. Hydrologic catchments must have higher pH than the soil region, and drain into the ocean.
- The agronomic application of minerals must not lead to a reduction in plant productivity, which would lead to expansion of crop production elsewhere, creating leakage.
- When minerals are applied on a farm, the project developer must have agreements from the farmers that transfer ownership of any carbon offsets to the project developer. These agreements should be made available to an independent verifier.
- A given field may only participate in a single EW project.

5 Project Boundary

As illustrated in Figure 2, the spatial extent of the project boundary encompasses all of the stages identified in Section 2, which are analyzed in the Eion Whitepaper "Life Cycle Analysis and Full Carbon Accounting of Enhanced Rock Weathering".

These stages include:

1. The quarry where the product is extracted
2. Transportation from the quarry to the mill
3. The mill where the product is pulverized to an appropriate particle size
4. Transportation from the mill to the field
5. Application on the field
6. Chemical transformations within the field resulting in carbon capture and sequestration

7. Hydrologic transport of cations and DIC to its ultimate sink, with attendant system losses.

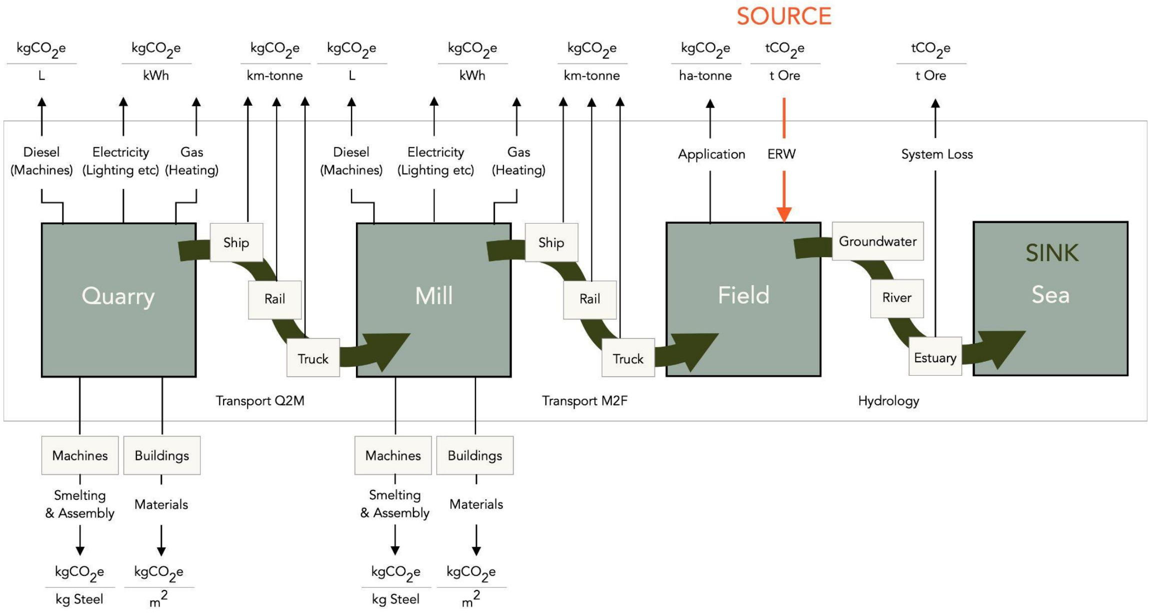


Figure 2: Project Boundary for Enhanced Rock Weathering Life Cycle.

To the extent that emissions factors for fuel and grid power account for non-CO_2 greenhouse gasses, then these are included in the LCA; however in Stages 6-7 other GHGs are ignored (Table 1). Note however that there is evidence that N_2O emissions are reduced with application of alkaline silicates in agricultural settings (5).

Table 1: Boundary Table

	Gas	**Included?**	**Explanation**
Material Source	CO_2	Yes	Equipment and power usage
	CH_4	No	Excluded for simplicity, emissions are negligible
	N_2O	No	Excluded for simplicity, emissions are negligible
	Other	N/A	Other GHGs are not involved
Material Transport	CO_2	Yes	Equipment and power usage
	CH_4	No	Excluded for simplicity, emissions are negligible
	N_2O	No	Excluded for simplicity, emissions are negligible
	Other	N/A	Other GHGs are not involved
Farmland application	CO_2	Yes	Equipment and power usage
	CH_4	No	Excluded for simplicity, emissions are negligible
	N_2O	No	Excluded for simplicity, emissions are negligible

	Other	N/A	Other GHGs are not involved
In-situ removal	CO_2	Yes	Primary removal mechanism
	CH_4	No	Not involved
	N_2O	No	Not involved
	Other	N/A	Other GHGs are not involved
Hydrologic transport	CO_2	Yes	Natural release at ocean interface
	CH_4	No	Not involved
	N_2O	No	Not involved
	Other	N/A	Other GHGs are not involved

6 Baseline Scenario

The baseline scenario is the level of GHG emissions that would take place in the absence of the project activity.

The alternate management of the field would be lime application or no pH adjusting applications. Lime application can be considered a CO_2 sink or source, so a baseline scenario whereby all applied $CaCO_3$ dissolves and liquid-gas exchange occurs between the soil-air interface should be addressed. This may include thermodynamic modeling of the soil pore water and the air reservoir with a calculated output of a CO_2 sink or source (g CO_2/m^2).

For instances where a CO_2 source is observed (positive values of g CO_2/m^2 emitted upon full dissolution of lime), a baseline scenario of 0 is acceptable as a conservative measure. In other words, stopping the application of lime in order to pursue the suggested project's activity would not lead to an increase in CDR estimation.

Under circumstances where a CO_2 sink is observed (negative values of g CO_2/m^2 emitted upon full dissolution of lime), the magnitude of the sink should be compared with the suggested project scope. If the calculated CO_2 sink is estimated as at least 3 orders of magnitude (1000-fold) lower than the CDR project scope (i.e. the CO_2 sink is sufficiently low compared to the CDR scope), or if the pre-project initial soil pH conditions do not exceed 7.0 (i.e. a CO_2 sink is sufficiently rare), a baseline scenario of 0 GHG emissions/removal is considered an acceptable measure to begin accounting for CDR estimation.

The alternate use of the rock used in the proposed project would be to remain in a natural geologic mountain form, where the surface area of the rock is too low to weather at any meaningful rate in comparison with discussed project timelines; thus, no CO_2 would be removed in the absence of the activity.

7 Additionality

If Step 1 and Step 2 are satisfied, the proposed project activity is additional.

Step 1: Regulatory Surplus

The requirements for regulatory surplus are met if there is no mandatory law, statute or other regulatory framework in place at the local, state, or federal level.

Step 2: Barriers analysis

Establish that there are barriers that would prevent the implementation of the type of proposed project activity. Such barriers may include, among others: Investment barriers, institutional barriers, technological barriers, barriers related to local tradition, barriers due to prevailing practice, barriers due to local ecological conditions, barriers due to social conditions and land-use practice, lack of organization of local communities, barriers relating to land tenure, ownership, inheritance, and property rights;

8 Quantification of GHG Emissions and Removals

For a given year (*y*), net Carbon Dioxide removal ($CDR_{net,y}$) is calculated as the actual CO_2 removed ($CDR_{actual,y}$) minus project emissions (PE_y) minus the system loss (SL_y), according to the following equation:

$$CDR_{net,y} = CDR_{actual,y} - PE_y - SL_y \tag{1}$$

The project stages were outlined in Section 2 (Summary) and Section 5 (Boundary). Emissions are represented by Stages 1-5 (Section 8.2); carbon removal in Stage 6 (Section 8.3); and hydrologic equilibration losses in Stage 7 (Section 8.4). Baseline emissions for computing emission reductions is considered in Section 8.1, and accounts for each of these stages under the narrow case of silicate replacing aglime application. In general, the calculations are normalized to a single metric tonne of ore, which may then be integrated to the many tonnes of ore used in the project. This ore may be extracted on different days from the same quarry, follow different transport routes to individual fields, but otherwise have a constant elemental makeup and particle size.

8.1 Baseline Emissions

Baseline emissions are 0 based on the Applicability Conditions (Section 4).

8.2 Project Emissions

Project emissions account for the use of fuel and electricity in the extraction, transport, processing, and field application in Stages 1-5 of the process flow.

Project emissions in year y of the project crediting period will be expressed as follows:

$$PE_y = f_Q \cdot PE_{Q,y} + PE_{TQ2M,y} + PE_{M,y} + PE_{TM2F,y} + PE_{FA,y} \tag{2}$$

where:

PE_y = Project emissions in year y (tCO_2e)
$PE_{Q,y}$ = Total quarry emissions in year y (tCO_2e)
f_Q = Fraction of quarry activities involved in project (unitless)
$PE_{TQ2M,y}$ = Transport emissions from the quarry to mill in year y (tCO_2e)
$PE_{M,y}$ = Mill emissions in year y (tCO_2e)
$PE_{TM2F,y}$ = Transport emissions from the mill to field in year y (tCO_2e)
$PE_{M,y}$ = Field application emissions in year y (tCO_2e)

8.2.1 Stage 1: Quarry

Determining $PE_{Q,y}$: Total quarry emissions from the extraction of minerals, including primary crushing activities, shall be determined using one of the following options:

Option 1: Under certain circumstances, the emissions of the feedstock may be zero if, for example, the emissions have been accounted for in other products coming from the quarry.

Option 2: A life cycle analysis may be available for the quarry as a whole, or each product coming from the quarry, which assigns a summary emission factor for the feedstock ($tCO_2e/tOre$).

Option 3: Quarry emissions are calculated as follows:

$$PE_{Q,y} = V_{grid,Q,y} \cdot EF_{grid,Q} + \sum_i V_{fuel,i,Q,y} \cdot EF_{fuel,i,Q} \tag{3}$$

where:

$PE_{Q,y}$ = Project emissions from the quarry in year y (tCO_2e)
$V_{grid,Q,y}$ = Quantity of electricity from the grid used by the quarry in year y (MWh)
$EF_{grid,Q}$ = Emissions factor of the electricity used to power the quarry (tCO_2e/MWh)
$V_{fuel,i,Q,y}$ = Quantity of fossil fuel of type i used by the equipment in the quarry in year y (unit of fuel, e.g. L)
$EF_{fuel,i,Q}$ = Emissions factor of the fossil fuel of type i used by the equipment in the quarry (tCO_2e/unit of fuel)

Determining $V_{grid,Q,y}$: The quantity of electricity from the grid used by the quarry in year y shall be determined using one of the following options:

Option 1: Electricity usage records.

Option 2: A bottom-up engineering model, such as Sherpa (6), which has been used to estimate emission in the US aggregate and limestone industry (7). Applied generically, such a model may deviate by 20% or more from actual (per expert consensus in the industry) but can reach errors <5% if it is constrained by site-specific parameters. Site specific parameters that constitute a large fraction of the electricity profile include the size and duty cycle of crushers used in primary size reduction, alongside lighting, water pumps, conveyors, and facility electricity needs.

Determining EF$_{grid,Q}$: Project proponents shall follow one of two alternatives to calculate this parameter:

Option 1: Use country specific grid emissions factors published by a government agency. For countries, such as the United States, Canada, Australia, the eGrid emissions factor for the sub-region (state or province) where the facility is located shall be used (latest available information). Where grid emission factors are not available from a government agency, an emission factor published by a certified or accredited body, and reviewed for publication by an appropriately qualified, independent organization or appropriate peer review group, may be used (if available). Renewable Energy Certificate (REC) or Guarantee of Origin (GO) may be used to demonstrate that electricity was generated and supplied (net) to the shared electrical grid through the use of renewable energy resources.

Option 2: Use the CDM Tool to calculate the emission factor for an electricity system.

Determining V$_{fuel,i,Q,y}$: The quantity of fossil fuel of type *i* used by the quarry in year y shall be determined using one of the following options:

Option 1: Fuel consumption records.

Option 2: As previously referenced for electricity, a bottom up engineering model constrained by site-specific information. Site specific parameters that comprise a large fraction of fuel usage includes Site specific parameters include the number and size of various pieces of equipment, distances traveled, and total ore production.

Determining EF$_{fuel,i,Q}$: Project proponents shall use a fuel emission factor published by a government agency, such as EPA or DEFRA.

8.2.2 Stage 2: Transport Quarry to Mill

Milling involves final comminution (pulverizing) of the mineral feedstock from a top size of 6mm- to a final particle size D50 of ~ 100µm, subsequent to primary and secondary crushing and screening at the quarry. Quarries may or may not have such a facility on-site, which requires transportation to a mill for subsequent processing by a toller to reach the target particle size and agglomeration appropriate for field application and ERW. Thus, transportation may or may not be relevant to the project emissions budget.

Total project emissions for this transportation stage are calculated as:

$$PE_{TQ2M,y} = \sum_{i} PE_{TQ2M,j,y} \tag{4}$$

where:

$PE_{TQ2M,y}$ = Total transport emissions from the quarry to mill in year y (tCO_2e)
$\sum_j$ = Summation over all transport legs *j*.
$PE_{TQ2M,j,y}$ = Transport emissions from leg *j* from the quarry to mill in year y (tCO_2e)

Determining $PE_{TQ2M,j,y}$: Transport emission from quarry to mill for each transport leg *j* in year y shall be determined using one of the following options:

Option 1: Actual Fuel Usage. This is preferred when there is uncertainty as to which emissions factor to use, which varies considerably on the vehicle size and load. This is also relevant where the amount of ore moved is large, e.g. on a cargo vessel.

$$PE_{TQ2M,j,y} = \sum_{i} V_{i,j,y} \cdot EF_{i,j} \quad (5)$$

where:

$PE_{TQ2M,j,y}$ = Transport emissions from leg *j* from the quarry to mill in year *y* (tCO_2e)
$\sum_{i,j}$ = Summation over all fuel types *i* used in leg *j*.
$V_{i,j,y}$ = Quantity of fossil fuel of type *i* used in leg *j* in year *y* (unit of fuel, e.g. L)
$EF_{i,j}$ = Emissions factor of the fossil fuel of type *i* used in transport leg *j* (tCO_2e/unit of fuel)

Option 2: Transport Emissions Factor.

$$PE_{TQ2M,j,y} = D_j \cdot EF_j \quad (6)$$

where:

$PE_{TQ2M,j,y}$ = Transport emissions from leg *j* from the quarry to mill in year y (tCO_2e)
D_j = Distance of transport leg *j* (km)
$EF_{tonne\text{-}km,j}$ = Transport emissions factor of conveyance used for transport leg *j* (tCO_2e/tonne-km)

Determining D_j: Distance for each transport leg *j* shall be determined using one of the following options:

Option 1: GPS tracking of the vehicle, such as the AIS ship/barge tracking system or rail locator systems . This is particularly relevant when there is uncertainty as to the route taken, and is helpful in assessing proof of origin of a mineral.

Option 2: Automated route calculations for the vehicle, such as the Google Directions API or Bing Maps Directions API. This is more appropriate for short-haul truck deliveries, for which GPS tracking may be impractical or inaccurate and the emissions impact of deviations from the idealized route is low.

8.2.3 Stage 3: Mill

Mill emissions are calculated as follows:

$$PE_{M,y} = V_{grid,M,y} \cdot EF_{grid,M} + \sum_{i} V_{fuel,i,M,y} \cdot EF_{fuel,i,M} \tag{7}$$

Definitions for these parameters, and guidance for estimating their values, are directly analogous to those for the quarry. More details on the drivers for these emissions, including the energy used for particle size reduction, can be found in the accompanying life cycle analysis.

8.2.4 Stage 4: Transport Mill to Field

Transportation emissions from the mill to the field are calculated as follows:

$$PE_{TM2F,y} = \sum_{i} PE_{TM2F,j,y} \tag{8}$$

Definitions for these parameters, and guidance for estimating their values, are directly analogous to those for transport from the quarry to the mill.

8.2.5 Stage 5: Field Application

Mineral application is generally done by the same farm equipment as for limestone.

$$PE_{FA,y} = FPT \cdot TPMPA \cdot EF_{i} \tag{9}$$

where:

$PE_{FA,y}$ = Field application emissions (tCO_2e)
FPT = Fuel usage per unit time (e.g. L/h)
$TPMPA$ = Application time per mass of mineral applied per area (e.g. h/tOre/ha)
EF_i = Emissions factor of the fossil fuel *i* used for field application ($kgCO_2e/L$)

FPT can be determined by conventional engineering calculations or retrieved from an officially designated OECD tractor test laboratories, e.g. a 150HP motor uses approximately 28.6 L/h. If available, an actual fuel survey is preferred.

TPMPA can be determined by conventional engineering calculations, else an as-applied map can be used to determine the total time spent, divided by the total area covered and the total mass of mineral applied.

EF_i is determined as above for transportation emissions.

8.3 Carbon Dioxide Removal

The process of silicate rock weathering is well understood, but the impacts of enhancement on the kinetic rates of the process are subject to uncertainty. The enhancement is achieved by first increasing the surface area of minerals through pulverizing the minerals, and subsequently adding these minerals to environments with elevated CO_2, acidity, moisture, and temperature. In agricultural systems these conditions can be quite dynamic, owing to plant growth, microbiological activity, and weather impacts on soil moisture and temperature regimes. Furthermore, there are spatial variations in soil physical properties (mineralogy, texture) and human management (application of fertilizer and other inputs). The following methodology is designed to constrain by direct measurement those elements of the system that are most variable (such as weathering rate), and to use the existing supply chain infrastructure to provide useful boundary conditions (e.g. amount delivered to the field and applied) wherever possible. An accompanying Project Design Document shall provide a theoretical rationale and empirical evidence for a Project Developer's approach to verifiability.

8.3.1 Potential CDR

Potential CO_2 removal shall be estimated as follows:

$$CDR_{potential} = A \cdot AR \cdot \frac{1}{tOre} \cdot MP \cdot DUI_{soil} \tag{10}$$

where:

$CDR_{potential}$ = Maximum potential CO_2 removal ($tCO_2/tOre$)
A = Area of mineral application (ha)
AR = Application rate of mineral (tOre/ha)
$tOre$ = Total metric tons of mineral applied over area A (tOre)
MP = Mineral potential of the applied silicate ($tCO_2/tOre$)
DUI_{soil} = DIC Uptake Index of the soil, equivalent to $\frac{dDIC}{dAlk}$, the moles of DIC taken up by soil solution per marginal unit of added alkalinity

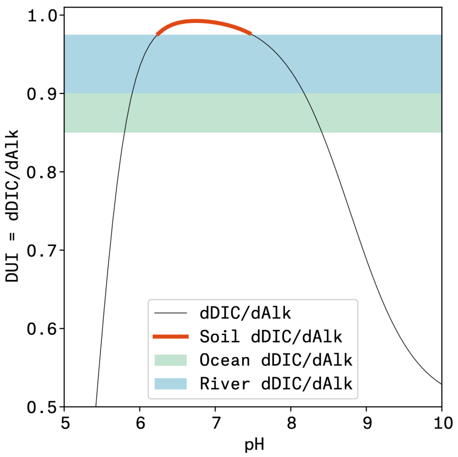


Figure 3: DIC Uptake Index (DUI) showing ideal range for soil uptake

At first glance, *A*, *AR*, and *tOre* all cancel, *DUI* is 1, and the equation reduces to simply the value of *MP*. This is slightly misleading however, because each of these phenomena can be accounted for by sources of information within the ERW supply chain.

Determining *A*: The area of mineral application shall be determined by a prescription for the area to be applied; or from an as-applied map provided by the applicator; or even from satellite imagery if taken on a cloud free day immediately after application.

Determining *AR*: The application rate shall be determined by a rate prescription, supported by an as-applied map, and ultimately corroborated by pre- and post- application soil measurements.

Determining *tOre*: The total amount of mineral applied to the field shall be assessed by shipping records, ultimately traceable to the mill or quarry to achieve mass balance closure for the total amount of mineral applied in the project. An as-applied map may complement this record of mineral applied. Moisture content shall be accounted for, as water is typically a binder to reduce dust in handling and spreading.

Determining *MP*: A large body of literature traceable to the DOE and National Labs [2, 7–9] provides a simple expression for the mineral potential (MP) for CO_2 removal based on feedstock elemental composition in terms of MgO% and CaO%, shown in Equation 31.

$$MP \equiv \frac{tCO_2e}{tOre} = \frac{MW_{CO2}}{100\%} \cdot \left(\frac{MgO\%}{MW_{MgO}} + \frac{CaO\%}{MW_{CaO}} \right) \cdot V \tag{11}$$

where:

$MgO\%$ = Mass fraction of magnesium oxide in the mineral
MW_{MgO} = Molecular weight of magnesium oxide (40g/mol)
$CaO\%$ = Mass fraction of calcium oxide in the mineral
MW_{CaO} = Molecular weight of calcium oxide (56g/mol)
MW_{CO2} = Molecular weight of CO_2 (44g/mol)
V = Valence of the cations (2 for Mg and Ca)

Analytical labs typically provide calibrations and validations against traceable standards as a standard set of quality assurance documentation for elemental analysis used to determine *MP*.

Determining *DUI*: This value shall be estimated as approximately 1 *if* the soil can be shown to be at a pH where $\frac{dDIC}{dAlk}$ is within an appropriate range (that is, between 6.2 and 7.5, Figure 3). Aglime additions are often used to bring acidic soils into this pH range. The amount of aglime to add to reach a pH target is known as the lime requirement (*LR*). The *LR* of soils is commonly determined by use of a soil test; an example of such a calculation is provided in Appendix D.

Thus, determining *DUI* shall be achieved by a combination of (a) a baseline soil test that quantifies soil and buffer pH, (b) a prescription by an agronomist for the lime requirement (*LR*) of the soil, and (c) an application rate (*AR*) for the silicate mineral that meets this LR, making use of the *CCE* of the product applied, which can be determined from (d) an elemental analysis.

8.3.2 Actual CDR

Potential CDR from ERW can be known at the time of application, but actual CDR takes place over time as the acidity in the soil weathers the mineral, bringing cations into solution and taking up DIC in the soil (Figure 1).

Actual CDR shall be computed as:

$$CDR_{actual,t} = CDR_{potential} \cdot f_{captured,t} \tag{12}$$

where:

$CDR_{actual,t}$ = Actual CO_2 removal at time t ($tCO_2/tOre$)
$CDR_{potential}$ = Maximum potential CO_2 removal ($tCO_2/tOre$)
$f_{captured,t}$ = Fraction sequestered of potential CDR at time t (unitless)

In this context, $f_{captured,t}$ quantifies the cations and associated DIC that has been leached below a plane in the soil at time t as a fraction of the total cations represented in $CDR_{potential}$:

$$f_{captured,t} = \frac{DivAlk_{captured,t}}{DivAlk_{added}} \tag{13}$$

$DivAlk_{added}$ corresponds to the equivalents of charge in divalent cations (Mg and Ca) (i.e. divalent alkalinity) per unit mass of soil $\frac{eq}{g_{soil}}$, following the equation:

$$DivAlk_{added} = \left(\frac{MgO\%}{MW_{MgO}} + \frac{CaO\%}{MW_{CaO}}\right)_{added} \cdot V \cdot AR \cdot \frac{1}{d \cdot \rho} \tag{14}$$

Where d (units m) represents the soil depth, and ρ (units g/cm^3) represents soil bulk density. The units of this expression for DivAlk$_{added}$ is therefore as follows:

$$\frac{equivalents}{mass\ soil} = \frac{mass\ oxide}{mass\ ore} \cdot \frac{mol\ oxide}{mass\ oxide} \cdot \frac{equivalents}{mol\ oxide} \cdot \frac{mass\ ore}{area\ soil} \cdot \frac{1}{depth\ soil} \cdot \frac{volume\ soil}{mass\ soil} \tag{15}$$

where *oxide* refers to MgO or CaO as in Equations 31, 33, 20.

Determining DivAlk$_{added}$:

The central challenge in this methodology is the estimation of DivAlk$_{added}$, which ultimately determines f$_{captured,t}$, and thus the amount of carbon removal achieved to date at discrete moments in time (*t*). Equation 14 suggests that DivAlk$_{added}$ can be determined by knowledge of an elemental analysis and field application rate, or by measurement of soil after application of the mineral amendment.

Option 1: DivAlk$_{added}$ is estimated by the elemental composition of the mineral amendment and measurements of DivAlk$_{post,t}$, which is defined as the equivalents of the charge in divalent cations (Mg and Ca) as measured in the soil after mineral application. The same analyses used to determine *MP* may be used to determine the abundance of other elements in the mineral - including elemental composition includes not only Mg and Ca and also analysis of some predetermined project-specific tracers, which could be isotopic tracers or immobile trace elements that provide a record of application rates of mineral soil amendment.

The means of estimating the application rate using an immobile trace element follows, where [*Z*] represents the concentration of an immobile trace element:

Mineral Amendment Budget:

$$\left[Z_{post}\right] \cdot Mass_{soil} = \left[Z_{pre}\right] \cdot Mass_{soil} + \left[Z_{rock}\right] \cdot AR_{rock}(kg) \tag{16}$$

where

$$Mass_{soil} = Area_{soil} \cdot Depth_{soil} \cdot \rho(kg) \tag{17}$$

and

$$AR_{rock} = \frac{Mass_{rock}}{Area_{soil}}\left(kg/m^2\right) \tag{18}$$

which rearranges to:

$$AR_{rock} = \frac{\left(\left[Z_{post}\right] - \left[Z_{pre}\right]\right) \cdot Mass_{soil}}{Z_{rock}} \tag{19}$$

From this mineral amendment budget, Equation 20 can be be computed by substituting $\text{DivAlk}_{rock} \cdot \text{AR}_{rock}$ for DivAlk_{added}:

In this expression, [*Z*] in soil and rock can be calculated from an elemental analysis, e.g. from ICP-MS, and Mass_{soil} can be determined from Equation 17, where *Depth* is the depth to which soils are collected for [*Z*] (e.g. 30cm) and ρ is bulk density. Bulk density may be determined using either (Option 1) direct measurement or (Option 2) published records, such as local/regional studies or spatially-explicit databases such as SSURGO. DivAlk_{added} is either measured episodically with soil sampling or continuously with a sensor.

However, because the values for $\text{DivAlk}_{post,t}$ are determined from soil tests ultimately from a small amount of soil, the spatial variation in application rate of the mineral is certain to result in samples where the actual amount of mineral applied deviates from the nominal value. This variation in the actual application rate in the specific sample of soil can in principle dominate the estimate of DivAlk_{added}.

Option 2: DivAlk_{added} is estimated using the nominal application rate and the concentration of Mg and Ca in the rock material. Nominal application rate may be determined using records from an applicator, or from knowledge of the amount of mineral delivered to the field and the area of the field. Concentration of Mg and Ca can be determined using an elemental analysis, e.g. from ICP-MS. When using this option, a conservative correction factor must be applied to take into account the uncertainty of the true application rate.

Determining $\text{DivAlk}_{captured}$: Determining the amount of alkalinity captured and therefore the fraction of weathering that has occurred can be determined in several ways. Some methods have been developed as of the time of this writing and are described below; some methods are yet to be discovered or developed.

Option 1: $\text{DivAlk}_{captured,t}$ is calculated as (Figure 4):

$$DivAlk_{captured,t} = DivAlk_{pre} + DivAlk_{added} - DivAlk_{losses} - DivAlk_{post,t} \quad (20)$$

where:

$\text{DivAlk}_{captured,t}$ = Divalent alkalinity captured (i.e. sequestered) (eq/g)
DivAlk_{pre} = Divalent alkalinity in the pre-application baseline soil (eq/g)
DivAlk_{added} = Divalent alkalinity added in the silicate mineral amendment (eq/g)
DivAlk_{losses} = Divalent alkalinity losses from plant uptake and charge-balance with non-DIC cations (e.g. NO_3^-, SO_3^- or Cl^-) (eq/g)
$\text{DivAlk}_{post,t}$ = Divalent alkalinity in the post-application soil at time *t* (eq/g)

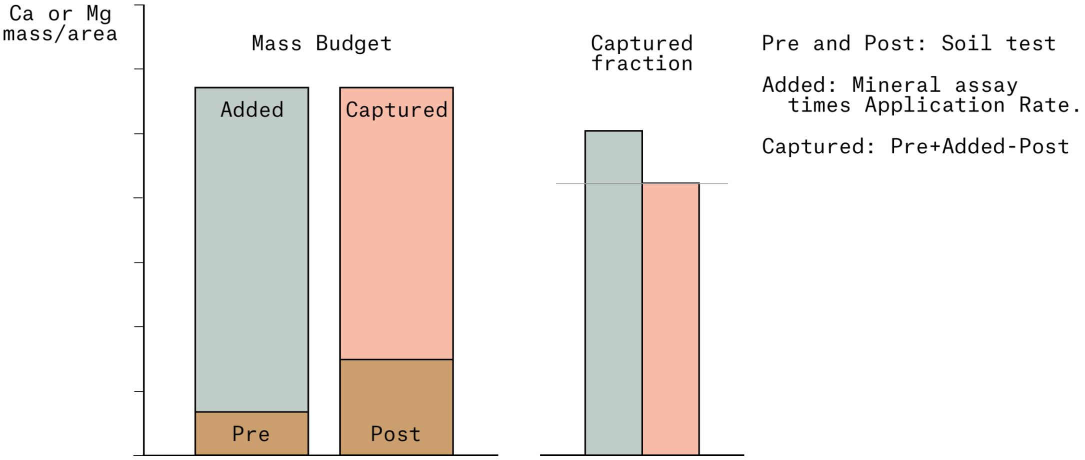


Figure 4: Simplified budget equation of divalent cations that remove CO_2.

Determining $DivAlk_{pre}$ **and** $DivAlk_{post,t}$: The elemental abundance of Mg and Ca in soils shall be determined from a soil test through analysis via total fusion-inductively coupled plasma mass spectrometry. The difference between $DivAlk_{pre}$ and $DivAlk_{post,t}$ quantifies the leached base cations that have in fact left the topsoil control volume. More specifically, $DivAlk_{post,t}$ allows for a direct measurement of persistent base cations; this accounts for various subsurface soil processes, including but not limited to adsorption to minerals, secondary mineral formation, and carbonate-based precipitation inefficiencies.

$$DivAlk_{pre/post} = \left(\frac{Mg\%}{MW_{Mg}} + \frac{Ca\%}{MW_{Ca}}\right)_{soil} \cdot V \tag{21}$$

where:

$DivAlk_{pre/post}$ = Divalent alkalinity in the pre- or post-application baseline soil (eq/g)
Mg% or Ca% = Mg or Ca content of the soil (g Mg/g soil or g Ca/g soil)
MW_{Mg} or MW_{Ca} = Molecular weights of Mg or Ca (g/mol)
V = Valence of Mg or Ca (eq/mol)

This expression has units $\frac{eq}{g_{soil}}$:

$$\frac{equivalents}{mass\ soil} = \frac{mass\ cation}{mass\ soil} \cdot \frac{mol\ cation}{mass\ oxide} \cdot \frac{equivalents}{mol\ cation} \tag{22}$$

Option 2: $DivAlk_{captured}$ is estimated using a lysimeter or other device that is used to capture the soil water. $DivAlk_{captured}$ is either measured episodically with sampling or continuously with a sensor.

Lossy Cation Budget:

$$DivAlk_{captured,t} = DivAlk_{pre} + \left(DivAlk_{rock} \cdot AR_{rock}\right) - DivAlk_{losses} - DivAlk_{post,t} \quad (23)$$

Determining DivAlk$_{losses}$: Divalent alkalinity losses is calculated as follows:

$$DivAlk_{losses} = DivAlk_{uptake} + DivAlk_{other} \quad (24)$$

where:

DivAlk$_{uptake}$ = Divalent alkalinity losses from plant uptake (eq/g)

DivAlk$_{other}$ = Divalent alkalinity charge-balance with non-DIC anions (e.g. NO_3^-, SO_3^- or Cl^-) (eq/g)

Determining DivAlk$_{uptake}$: DivAlk$_{uptake}$ assumes that plant uptake of Mg and Ca does not distinguish between rock vs. soil nutrients; therefore, the plant uptake fraction of divalent uptake is calculated as the total plant uptake times the fraction of Mg from the rock.

$$DivAlk_{uptake} = DivAlk_{uptake,Mg} + DivAlk_{uptake,Ca} \quad (25)$$

where:

DivAlk$_{uptake,Mg}$ = rockMg/(rockMg + soilMg) * plantuptakeMg

DivAlk$_{uptake,Ca}$ = rockCa/(rockCa + soilCa) * plantuptakeCa

rock(Mg,Ca) = the Mg or Ca content of the rock (g/m^2)

soil(Mg,Ca) = the Mg or Ca content of the soil (g/m^2)

plantuptake(Mg, Ca) = mass of Mg or Ca content taken up by the plant (g/m^2)

Determining plantuptake(Mg, Ca): When CDR is being calculated for a field with rock application before planting of an annual crop,

$$plantuptake(Mg, Ca) = plant(Mg, Ca) \quad (26)$$

where:

plant(Mg,Ca) = the mass of Mg or Ca in the plant (g Mg or g Ca)

When CDR is being calculated in other conditions, such as when rock has been applied after a plant has already been established, or when CDR is being calculated from a later time point than application

$$plantuptake(Mg, Ca) = plant(Mg, Ca)_{t2} - plant(Mg, Ca)_{t1} \quad (27)$$

Determining plant(Mg, Ca): The mass of Mg or Ca in the plant may be determined using one of the following options:

Option 1: Plant samples of leaves shall be collected at peak biomass and root samples should be collected at peak biomass or pre-harvest, and analyzed for C, N, Mg and Ca content. Total mass of shoots should be quantified, and the root:shoot ratio can be estimated by root N : grain N, root N : shoot N, and/or C:N ratio following Ordonez et al. 2020 (10). From the root:shoot ratio, total mass of shoots, and the Mg and Ca content of the roots and the shoots, the total plant Mg and Ca can be calculated.

Option 2: Use maximum literature values of the fraction of soil Mg and Ca that is taken up by the plant over a growing season.

Determining $DivAlk_{other}$: The divalent cations in the soil solution do not necessarily bind with bicarbonate, and can in fact leach out of the system with other anions that may weather the silicate rock, such as through nitrate ion-pair leaching.

$$DivAlk_{others} = DivAlk_{captured,t} \cdot f_{other} \tag{28}$$

where:

f_{other} = Fraction of divalent alkalinity charge-balanced with non-DIC cations (unitless)

Determining f_{other}:

Option 1: Using a lysimeter, capture the volume of soil water leachate from a small portion of the field. This collection should be performed on both applied- and control- fields. The lysimeter should be installed below soil at the same depth of the soil sampling conducted in this project region; this maintains transferability of knowledge between the calculations conducted in the solid soil matrix and analyses from the lysimeter measurements below the aforementioned collected soil. The resultant difference in measured inorganic nitrate (concentration of ammonia + concentration of nitrate) between applied- and control- fields allows for the quantification of additional nitrate leaching induced by the enhanced rock weathering process. The resultant difference value of inorganic nitrate concentration is converted from ppm (mg/L) to a molar quantity (mol/L) through division of N molar mass (14 g/mol) and a factor of 1000. The final molar quantity of inorganic nitrate difference is multiplied by 2 as a conservative estimate; this follows the assumption that all nitrogen is ultimately transformed into the form of NO_3^-, which requires 2 molecules to charge-balance a Mg^{2+} or Ca^{2+} cation.

Option 2: Use data from a lysimeter in a field trial in a similar ecosystem, crop and climate to estimate the fraction of divalent cations (equivalents/L) that are bonded to other anions than DIC in the water, making sure that the lysimeter is installed to capture leachate from the same depth as the soil samples.

8.4 System Loss

In the context of enhanced mineral weathering on land, physical hydrologic loss via equilibration of the carbonate system Loss takes place when the *DUI* in Equation 10 (depicted in Figure 3) drops below its nominal value of ~ 1, owing to shifts in the carbonate system equilibrium. This system loss is the reversal of CO_2 captured. It is widely known that the value of *DUI* in the ocean is below ~ 0.9, meaning that 10% of $CDR_{potential}$ will ultimately be returned back to the atmosphere as a natural and predictable phenomenon. This hydrologic loss fraction (HLF) is appreciated as simply the difference between the the initial and final $\frac{dDIC}{dAlk}$, which are referred to as initial *DUI* and the DUI retention index (*DRI*):

$$HLF = DUI - DRI_{waters} \tag{29}$$

where:

HLF = Hydrological Loss Fraction (unitless)

DUI = DIC uptake index in soils where weathering takes place, equivalent to $\frac{dDIC}{dAlk}$, the moles of DIC taken up by soil solution per marginal unit of added alkalinity

DRI_{waters} = DIC retention index in fresh and marine waters, also equivalent to $\frac{dDIC}{dAlk}$, where dissolved cations and inorganic carbonates added from EW are present.

The System Loss (*SL*, in tCO_2e) can be computed as:

$$SL = CDR_{actual} \cdot HFL \tag{30}$$

The timing of the actual hydrologic loss is subject to large variation; it could be in months, if a field empties directly into surface waters, or 30 or more years if the depth to groundwater is large enough.

Given that *DUI* is defined to be equivalent to 1, by applying mineral at a rate sufficient to bring the soil pH into the range 6.5 - 7.2, the challenge in hydrologic loss estimation is to determine (a) the ultimate value of DRI in the final storage repository and (b) determine if any transient conditions exist in transport to the final storage repository that would result in DRI being lower than DRI in the final storage locale.

Two trivial cases where DRI is much lower than the oceanic value are readily identified: arid inland basins that don't drain to the ocean, where dissolved carbonates are precipitated as they evaporate (final DRI value ~ 0.5) and high latitude inland basins where lake waters are extremely acidic (final DRI value ~ 0.0). Such application locales are not recommended for EW because of the significant opportunity for hydrologic loss.

The remaining cases require consideration of the carbonate system within the fresh and marine waters as DIC and alkalinity are transported ultimately to the ocean.

8.4.1 River DRI

River DRI may be calculated in the following ways:

Option 1: A sensor network is set up to monitor the downstream river chemistry for pH, Alkalinity and partial pressure of CO_2 (pCO_2). Records should be monitored monthly until more information has been collected, at which point less frequent monitoring may take place.

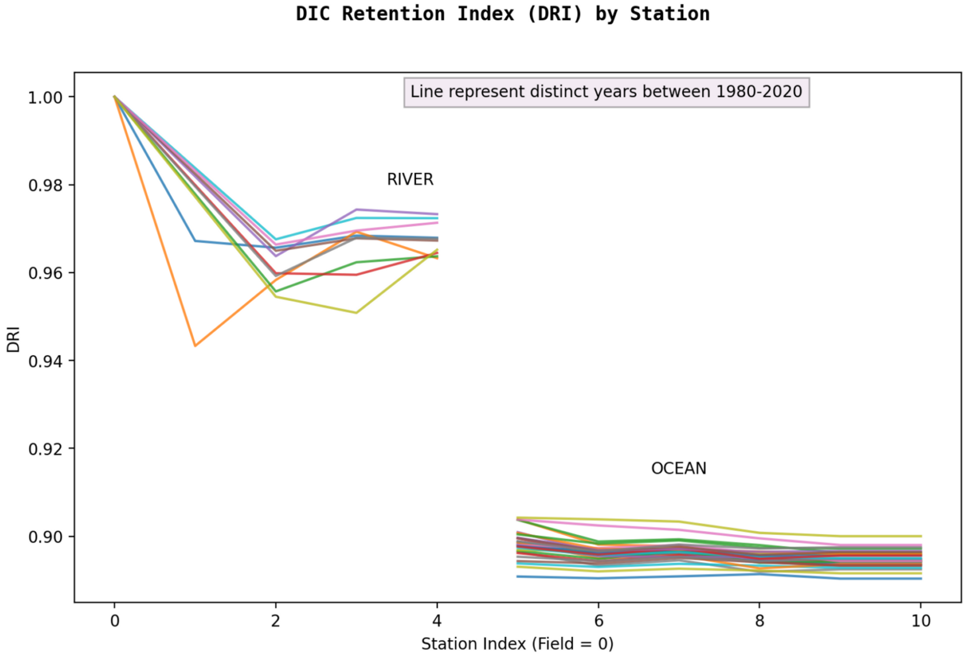
Option 2: For calculating river DRI in the United States, data may be used from the Global River Chemistry Database (GLORICH) (11) for rivers in the US between 1980-2007. This dataset includes all the sampling stations for rivers in the US, and hence all those within the Mississippi basin. The core parameters used are Alkalinity and pCO_2. Auxiliary parameters: water temperature, salinity of freshwater, and pressure. Sources of data for each parameter are given in Table 2.

Table 2: River DRI Input Sources. Pressure is calculated from the altitude of the sample.

Variable	Source
TA	USGS
pCO_2	NOAA (12)
Temperature	USGS
Salinity	N/A
Pressure	USGS

River DRI for all river water samples logged within the GLORICH database show that greater than 99.9% of samples have DRI > 0.85, as seen in Figure 5.

Figure 5: US River DRI estimates for water samples



Option 3: Use a conservative estimate of 20% hydrologic loss (i.e. 1.6 mol CO_2 per mol Mg or Ca).

8.4.2 Oceanic DRI

For oceanic DRI calculate two versions:

- A global oceanic baseline DRI
- A localized oceanic annual DRI, at 1 x 1 degree spatial resolution

Global oceanic baseline DRI

The global oceanic baseline is calculated using the following summary values and comes out to 0.85.

Table 4: Global Ocean DRI Parameter Values

Ocean Parameters	Value Used	Range	Source
Ocean pH	8.08	7.9-8.25	(13)
Ocean Salinity	35	34-35	(14)
Ocean Temperature (℃)	16.1	16-19	(15)
pCO^2	400	390-410	(12)

Localized annual oceanic DRI

For the localized annual DRI, the two system variables used to calculate the carbonate states are TA and pH. Auxiliary variables are seawater temperature and salinity and we take pressure = 0 at the ocean surface. We use data from the OceanSODA-ETHZ (16) dataset, which provides chosen variables at high spatial resolution, and for the years 1985-2018. Data is first processed by taking the weighted temporal average for each variable of interest to create an annual mean before DRI is calculated again using PyCO2SYS. Visualization of the mean of the annual means can be seen in Figure 6.

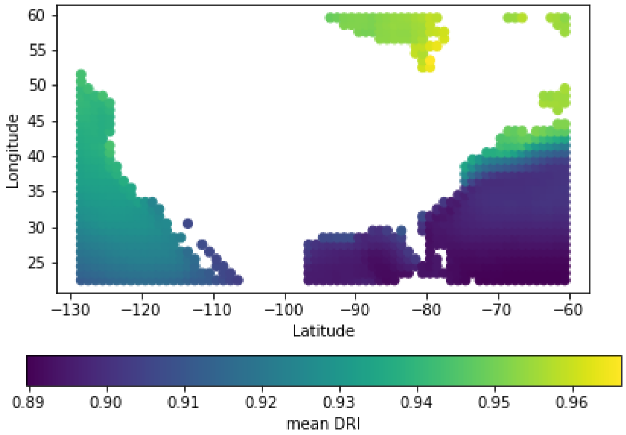


Figure 6: Localized mean oceanic DRI for years 1958 - 2018, at 1 x 1 degree resolution

8.4.3 Soil DRI

For agricultural soils with a pH between 6.5-7.2, DRI is calculated using the parameters land pH, land temperature, and net valence, and comes out at ~0.999. Parameters are given in Table 5 for silicate rocks.

Table 5: Soil DRI Parameters

Land Parameters	Value
Land pH	6.5 - 7.2
Land Temperature (°C)	25
Net Valence	2

9 Monitoring

9.1 Data and Parameters Available at Validation

9.1.1 Project Emissions

Parameter	$EF_{\text{grid,Q}}$ and $EF_{\text{grid,M}}$
Unit	tCO_2e/MWh
Source	Government agencies or UNFCCC data (CDM)
Value applied	Will vary, depending on location of project. For example, see: https://www.epa.gov/egrid/summary-data
Explanation/Comments	Emissions factor of grid to determine CO_2 impact of electricity use required by the project (quarrying, milling, etc.).

Parameter	$EF_{fuel,i,Q}$ and $EF_{fuel,i,M}$
Unit	tCO_2e/unit of fuel
Source	EPA or DEFRA defaults
Value applied	Will vary depending on fuel. See: https://www.epa.gov/climateleadership/ghg-emission-factors-hub or https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
Explanation/Comments	Emissions factor of each type of fossil fuel required to implement the project (quarrying, milling, etc.).

Parameter	$EF_{i,j}$ *and* EF_i
Unit	tCO_2e/unit of fuel
Source	EPA or DEFRA defaults
Value applied	Will vary depending on fuel. See: https://www.epa.gov/climateleadership/ghg-emission-factors-hub or

	https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
Explanation/Comments	Emissions factor of each type of fossil fuel (e.g. gasoline or diesel) required to transport materials across transport leg *j*. This parameter can also be used for fossil fuel required for field application.

Parameter	$EF_{tonne-km,j}$
Unit	tCO_2e/tonne-km
Source	EPA or DEFRA defaults
Value applied	Will vary depending on vehicle type. See: https://www.epa.gov/climateleadership/ghg-emission-factors-hub or https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting
Explanation/Comments	Emissions factor to transport a tonne of minerals one kilometer for transport leg *j*. This option can be used as an alternative to calculate transport emissions based on the distance traveled by each ton of ore.

Parameter	*FTP*
Unit	Liters per hour
Source	Project owner (Appendix F)
Value applied	28.6 L/h
Explanation/Comments	Fuel usage per unit time (e.g. liters/hour) based on a 100-150HP motor. Other motor sizes will be different.

Parameter	*TPMPA*
Unit	hours/tOre/hectare
Source	Conventional engineering calculations

Value applied	Based on two tons per acre in 5 minutes, this figure would be 5 tons per hectare in 12.5 minutes
Explanation/Comments	Application time per mass of mineral applied per area, based on a 100-150HP motor. Other motor sizes will be different.

9.1.2 Carbon Dioxide Removal

Parameter	MW_{MgO}
Unit	g/mol
Source	N/A
Value applied	40
Explanation/Comments	Used to determine MP, mineral potential of the applied silicate, which is a key part of assessing the overall CDR potential.

Parameter	MW_{CaO}
Unit	g/mol
Source	N/A
Value applied	56
Explanation/Comments	Used to determine MP, mineral potential of the applied silicate.

Parameter	MW_{CO2}
Unit	g/mol
Source	N/A
Value applied	44
Explanation/Comments	Used to determine MP, mineral potential of the applied silicate.

Parameter	V

Unit	number
Source	N/A
Value applied	2 for Mg and Ca
Explanation/Comments	Valence of cations, used to determine *MP*.

Parameter	*L*, *B* and *H*
Unit	pH
Source	Agronomic standard soil test
Value applied	Will vary
Explanation/Comments	pH goal, pH buffer and pH of the soil, used to determine lime requirement (*LR*). This can be determined by soil testing by an agronomic soil testing laboratory certified by a national or state body. The pH goal is calculated via hands.eioncarbon.com. The buffer pH is calculated after the application of a buffer pH and the soil pH is calculated by using a 1:1 mixture of soil and water.

Parameter	CCE
Unit	number
Source	Mineral elemental analysis
Value applied	Will vary
Explanation/Comments	Calcium Carbonate Equivalent of silicates in references to common aglimes (Table A4). Calculation is provided in Appendix D. Alternatively, it can be directly measured using modified AOAC 955.01 method: use 1.0N HCl and 0.5N NaOH; titrate to pH of 8.2.

9.2 Data and Parameters Monitored

9.2.1 Project Emissions

Parameter	f_Q
Unit	unitless
Source	Project owner
Explanation/Comments and Measurement Techniques	Fraction of quarry activities involved in project

Parameter	$PE_{Q,y}$
Unit	tCO_2e
Source	Zero (option 1) or value according to LCA (option 2)
Explanation/Comments and Measurement Techniques	Not applicable if option 3 for determining $PE_{Q,y}$ is selected. Total quarry emissions from the extraction of minerals, including primary crushing activities, are zero if, for example, the emissions have been accounted for in other products coming from the quarry (option 1). Alternatively, a life cycle analysis may be available for the quarry as a whole, or each product coming from the quarry, which assigns a summary emission factor for the feedstock (tCO2e/tOre) (option 2).

$PE_{Q,y}$ = Project emissions from the quarry in year *y* (tCO_2e)

Parameter	TPY_Q and tOre,j
Unit	Tons of Ore
Source	Project owner/scale readings
Explanation/Comments and Measurement Techniques	Annual production of all minerals processed and used by the project as determined by scales (at the quarry) that are calibrated in accordance with manufacturer recommendations. This information is separated by different transport legs *j* so the end destination of all tons of ore are compiled into a spreadsheet that can be reviewed by a verifier. This will also provide the tons of ore used per project unit (farm), which can determine if any ore has been lost between the quarry, mill and farm. Knowing the quantity of minerals per farm is

	also required for *AR* (application rate in tons of ore per hectare). Project developer will create a data management system to track every ton of mineral from the quarry to the milling facility to the farm.

Parameter	$V_{grid,Q}$ and $V_{grid,M}$
Unit	MWH
Source	Electricity usage records or output of bottom-up engineering model
Explanation/Comments and Measurement Techniques	The primary source for calculating MWH includes metered electricity readings or bills for the given hours of operation (option 1). Alternatively (option 2), it can be estimated using MW requirements for all equipment used, the number of shifts and hours per shift to calculate MWH. This information is available in product specs, energy labels, technical documents, and databases. These estimates are considered conservative because we assume the equipment is running for the entire shift, which does not include equipment downtime and/or worker breaks.

Parameter	$V_{fuel,Q}$ and $V_{fuel,M}$
Unit	Dependent on fuel type (literes, MMBTU, etc.)
Source	Fuel receipts or utility gas bills; or conservative estimates if not calculated separately
Explanation/Comments and Measurement Techniques	The primary source for calculating fuel type includes metered fuel/gas readings, or fuel receipts for the given hours of operation. In lieu of primary source data, we estimate the fuel requirements for all equipment used and the number of hours to calculate total fuel consumption. This information is available in equipment specs, technical documents, and databases. These estimates are considered conservative because we assume the equipment is running for the entire shift, which does not include equipment downtime and/or worker breaks.

Parameter	D_j
Unit	km
Source	Project owner
Explanation/Comments and Measurement Techniques	Distance of transport leg *j* as calculated by GPS tracking of vehicle or using appropriate app, such as Google Maps. All end destinations of the ore and (if different transport modes are used) the distance from one leg to another – quarry to mill to farm – should be entered into a data management system and archived for verification purposes.

Parameter	$V_{i,j}$
Unit	Liters
Source	Project owner
Explanation/Comments and Measurement Techniques	Quantity of gasoline or diesel (or kWhs if electric vehicles) needed to transport materials across transport leg *j*. Fuel receipts will provide the quantity used for each leg. To calculate kWhs for electricity vehicles, we log the amount of electricity used for each leg from the onboard system. In lieu of receipts or logs, we can estimate fuel usage in miles-per-gallon or miles-per-kwh and the total miles for each vehicle's leg.

9.2.2 Carbon Dioxide Removal

Parameter	A
Unit	Hectares
Source	Project owner
Explanation/Comments and Measurement Techniques	Area of mineral application during the project. Additional lands can be added throughout the project, but the project owner should keep .kml files, satellite image or similar visuals, along with GPS coordinates or physical address, to denote the area of land coverage per farm and across the entire project boundary. These files should be made available to a verifier.

Parameter	*AR* and thus *tOre*
Unit	Tons of ore per hectare and total metric tons of mineral applied over area A
Source	Farmer and project owner
Explanation/Comments and Measurement Techniques	Application rate of mineral as measured by farmer records of an as-applied map, applicator measurements or similar approach and validated by project owner in a similar manner to how farmers determine fertilizer application rates per ha. To corroborate these measurements, the project shall measure immobile trace elements (ITEs) or isotope tracers, through soil testing of pre- and post-application of material. The specific measurements depend on the specific implementation of the methodology as defined in the "Determining $DivAlk_{added}$" section. This information should be crossed-checked with sales and shipping.

Parameter	Soil testing
Unit	Various units including pH, Mg and Ca content, soil depth and density. Used to determine divalent alkalinity pre- and post-project
Source	Project owner/laboratory results
Explanation/Comments and Measurement Techniques	In addition to pH, soil testing will measure Mg and Ca content of the soil (to determine rockMg and soilMg) as well as depth of area where sequestration takes place (d) and the bulk density of the soil in g/cm^3. Soil testing should be done prior to the project start date (baseline testing) as well as annually. Project proponents should develop a testing protocol in terms of how many tests should be required per farm based on the level of homogeneity of each field and across different fields within the project boundary. Guidance around such protocols can be developed following guidance in VM0042, as well as the sources below. Soil sampling should follow established best practices, such as: 1) Cline, M.G. 1944. Principles of soil sampling. Soil Science. 58: 275 – 288. 2) Petersen, R.G., and Calvin, L.D. Sampling. In A. Klute, editor, 1986. Methods of Soil Analysis: Part 1—Physical and Mineralogical Methods. SSSA Book Ser. 5.1. SSSA, ASA, Madison, WI.

	3) Bulk density may be determined using empirical or model-based methods, e.g. Saxton and Rawls 2006. Lab results should be made available to the verifier upon request and all test results should be archived.

Parameter	Testing of tracers
Unit	N/A
Source	Project owner/laboratory results
Explanation/Comments and Measurement Techniques	Used for measurements of $DivAlk_{post,t}$ and the elemental composition of the mineral amendment. This same elemental analysis can be used to determine *MP* as well (mineral potential of the applied silicate (tCO_2/tOre) in the case of elemental tracers; isotopic analysis is required for isotopic tracers.

Parameter	plant(Mg,Ca)
Unit	g/m^2
Source	Project Owner
Explanation/Comments and Measurement Techniques	Mass of Mg or Ca in the plant to determine plant uptake. Samples of leaves and roots should be taken as articulated in Option 1 and 2 of plantuptake(Mg,Ca). Maximum literature values of the fraction of soil Mg and Ca may also be used (Option 3) – sources shall be provided to the verifier.

Parameter	f_{other}
Unit	Fraction
Source	Project Owner
Explanation/Comments and Measurement Techniques	Using a lysimeter, capture the volume of soil water from a small portion of the field to quantify the ratio of cations:DIC in the soil water. This ratio should be close to but not exceeding 2. Option 2 is to use a default of 10%.

10 References

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11 Appendices

A. Electricity Grid Emissions Factors

Table A1: US Emissions Factors in kgCO$_2$e/kWh.
Source: United States EPA eGrid Database (Published: Jan 2020. Revised: Mar 2020)
URL: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

Area	Region	Value	Area	Region	Value
US: Average		0.453	US: Mississippi (MS)	SERC - South	0.438
			US: Missouri (MO)	SERC - South	0.817
US: Alabama (AL)	SERC - South	0.414	US: Montana (MT)	WECC - Rockies	0.556
US: Alaska (AK)	ASCC - Alaska Grid	0.436	US: Nebraska (NE)	MRO-West	0.676
US: Arizona (AZ)	WECC - Southwest	0.463	US: Nevada (NV)	WECC - Rockies	0.356
US: Alabama (AL)	SERC - South	0.414	US: New Hampshire (NH)	NPCC - New England	0.146
US: Alaska (AK)	ASCC - Alaska Grid	0.436	US: New Jersey (NJ)	RFC - East	0.239
US: Arizona (AZ)	WECC - Southwest	0.463	US: New Mexico (NM)	WECC - Southwest	0.639
US: Arkansas (AR)	SERC - South	0.581	US: New York (NY)	NPCC - LI NYC/Upstate NY	0.200
US: California (CA)	WECC- California	0.201	US: North Carolina (NC)	SERC - Virginia/Carolinas	0.383
US: Colorado (CO)	WECC - Rockies	0.653	US: North Dakota (ND)	MRO-West	0.723
US: Connecticut (CT)	NPCC - New England	0.243	US: Ohio (OH)	RFC - West	0.634
US: Delaware (DE)	RFC - East	0.429	US: Oklahoma (OK)	SPP- South	0.426
US: Florida (FL)	FRCC - All	0.452	US: Oregon (OR)	WECC - Northwest	0.150
US: Georgia (GA)	SERC - South	0.444	US: Pennsylvania (PA)	RFC - West	0.376
US: Hawaii (HI)	HICC - Oahu	0.729	US: Rhode Island (RI)	NPCC - New England	0.414
US: Idaho (ID)	WECC - Rockies	0.077	US: South Carolina (SC)	SERC - Virginia/Carolinas	0.303
US: Illinois (IL)	MRO- East	0.390	US: South Dakota (SD)	MRO-West	0.248
US: Indiana (IN)	RFC - West	0.834	US: Tennessee (TN)	SERC - Tennessee Valley	0.357
US: Iowa (IA)	MRO - East	0.514	US: Texas (TX)	ERCOT - All	0.469
US: Kansas (KS)	SPP- North	0.475	US: Utah (UT)	WECC - Rockies	0.767
US: Kentucky (KY)	SERC - Tennessee Valley	0.875	US: Vermont (VT)	NPCC - New England	0.027
US: Louisiana (LA)	SERC - South	0.400	US: Virginia (VA)	SERC - Virginia/Carolinas	0.354
US: Maine (ME)	NPCC - New England	0.128	US: Washington (WA)	WECC - Northwest	0.095
US: Maryland (MD)	RFC - East	0.401	US: Washington DC (DC)	RFC - East	0.210
US: Massachusetts (MA)	NPCC - New England	0.350	US: West Virginia (WV)	SERC - Virginia/Carolinas	0.935
US: Michigan (MI)	RFC - Michigan	0.532	US: Wisconsin (WI)	MRO - East	0.666
US: Minnesota (MN)	MRO - East	0.478	US: Wyoming (WY)	WECC - Rockies	0.983

B. Transportation Emissions Factors

Table A2: Transport Emissions Factors in $kgCO_2e$/tonne-km
Source: DEFRA (Published: June 2021)
URL:
https://www.gov.uk/government/publications/greenhousegas-reporting-conversion-factors-2021

Transport Type	Size	$kgCO_2e$	$kgCO_2$	$kgCH_4$	kgN_2O
Cargo Ship/Bulk	200,000+ dwt	0.00254	0.00250	0.00000	0.00003
	100,000–199,999 dwt	0.00304	0.00300	0.00000	0.00004
	60,000–99,999 dwt	0.00416	0.00410	0.00000	0.00006
	35,000–59,999 dwt	0.00578	0.00570	0.00000	0.00008
	10,000–34,999 dwt	0.00801	0.00790	0.00000	0.00011
	0–9999 dwt	0.02961	0.02920	0.00001	0.00040
	Average	0.00354	0.00349	0.00000	0.00005
Cargo Ship/Handy	10,000+ dwt	0.01207	0.01190	0.00000	0.00016
	5000–9999 dwt	0.01602	0.01580	0.00001	0.00022
	0–4999 dwt	0.01409	0.01390	0.00000	0.00019
	10,000+ dwt 100+ TEU	0.01115	0.01100	0.00000	0.00015
	5000–9999 dwt 100+ TEU	0.01774	0.01750	0.00001	0.00024
	0–4999 dwt 100+ TEU	0.02008	0.01980	0.00001	0.00027
	Average	0.01323	0.01305	0.00000	0.00018
Cargo Ship/Container	8000+ TEU	0.01267	0.01250	0.00000	0.00017
	5000–7999 TEU	0.01683	0.01660	0.00001	0.00023
	3000–4999 TEU	0.01683	0.01660	0.00001	0.00023
	2000–2999 TEU	0.02028	0.02000	0.00001	0.00027
	1000–1999 TEU	0.03255	0.03210	0.00001	0.00044
	0–999 TEU	0.03681	0.03630	0.00001	0.00050
	Average	0.01614	0.01592	0.00001	0.00022
Heavy Goods Vehicle	Rigid (>3.5 - 7.5 tonnes)	0.52043	0.51410	0.00010	0.00623
	Rigid (>7.5 tonnes-17 tonnes)	0.36835	0.36388	0.00007	0.00440
	Rigid (>17 tonnes)	0.18306	0.18084	0.00004	0.00219
	All rigids	0.21275	0.21017	0.00004	0.00254
	Articulated (>3.5 - 33t)	0.14179	0.13932	0.00002	0.00245
	Articulated (>33t)	0.07773	0.07638	0.00001	0.00134
	All artics	0.07936	0.07798	0.00001	0.00137
	All HGVs	0.10650	0.10487	0.00002	0.00161
Rail	Freight train	0.02556	0.02531	0.00002	0.00023

C. Fuel Emissions Factors

Table A3: Fuel Emissions Factors in kgCO_2e/tonne and kgCO_2e/liters
Source: DEFRA (Published: June 2022)
URL:
https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022

Fuel	Unit	kgCO2e	kgCO2	kgCH4	kgN2O
Diesel (average biofuel blend)	tonnes	3032.89	2988.85	0.31	43.73
	liters	2.56	2.52	0.00	0.04
Diesel (100% mineral diesel)	tonnes	3208.76	3164.33	0.31	44.12
	liters	2.70	2.66	0.00	0.04
Petro (average biofueld blend)	tonnes	2903.08	2884.53	9.68	8.87
	liters	2.16	2.15	0.01	0.01
Petro (100% mineral petrol)	tonnes	3153.90	3135.00	9.86	9.04
	liters	2.34	2.33	0.01	0.01
Marine gas oil	tonnes	3249.99	3205.99	0.81	43.19
	liters	2.78	2.74	0.00	0.04
Marine fuel oil	tonnes	3159.50	3113.99	1.27	44.24
	liters	3.11	3.06	0.00	0.04
Average	tonnes	1560.31	1542.35	1.85	16.11
	liters	1437.60	1421.80	1.98	13.81

D. Determination of crop lime requirement

The need for conditioning the pH of soils is widespread, and consequently there are many resources for guiding applications of limestone to raise pH and gypsum to lower pH. Examples can be found through cooperative extension in nearly every state. Illinois (link) and Delaware (link) have particularly good resources.

Our focus is in determining lime requirements in acidic soils. Lime requirements make use of soil tests that combine the soil pH, the buffer pH, and the target pH for the crop under consideration.

One such method is the widely used Shoemaker-McLean-Pratt (SMP) soil analysis method. *LR* is calculated as:

$$LR = 1250 + (((L - 0.3) - H) \cdot 1820) + ((6.95 - B) \cdot 5260) \quad (31)$$

where:

L = pH goal (dependent on the crop)
H = actual pH of the soil (1:1 in water)
B = buffer pH (method dependent; a measure of exchangeable cations)

Note that the *LR* is based on application of a material with a Calcium Carbonate Equivalence (CCE) of 1, based on the neutralizing potential of pure calcite (units eq/g). The neutralizing potential of any particular silicate mineral may be considerably less, depending on its cation concentration.

In general, the neutralizing equivalent of calcite is calculated as:

$$NE_c = \frac{CaO_c}{MW_{CaO}} \cdot V \quad (32)$$

where:

NE_c = Neutralizing equivalent of $CaCO_3$ (eq/g)
CaO_c = Mass fraction of calcium oxide in $CaCO_3$ (56.03%)
MW_{CaO} = Molecular weight of calcium oxide (56g/mol)
V = Valence of the cations (2 for Mg and Ca)

The neutralizing equivalent of any mineral *m* can then be calculated as:

$$NE_m = \left(\frac{CaO_m}{MW_{CaO}} + \frac{MgO_m}{MW_{MgO}}\right) \cdot V \quad (33)$$

where CaO_m and MgO_m are derived from an elemental analysis of the mineral to be used. The CCE is then calculated by computing the ratio $\frac{NE_m}{NE_c}$. The neutralizing value of common carbonates used as aglime is provided below, alongside the neutralizing value for common silicates used for ERW.

Table A4: Calcium Carbonate Equivalent of silicates in references to common aglimes.

		C	H	O	Si	Ca	Mg	CaO	MgO	CCE
Compound	MW	12	1	16	28	40	24	56	40	
	g/mol	# of atoms						mass %		
$CaCO_3$	100	1		3		1		56		1
$MgCO_3$	84	1		3			1		47	1.19
CaO	56			1		1		1		1.79
$Ca(OH)_2$	74		2	2		1		75		1.35
$(CaxMg)CO_3$	92	1		3		0.5	0.5	30	22	1.09
$CaSiO_3$	116			3	1	1		48		0.86
Mg_2SiO_4	140			4	1		2		46	1.14
Basalt								10	8	0.38

E. Derivation of DRI

CO2 in the atmosphere is dissolved into the ocean, where it can speciate into other forms including carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-). The dissolution of gaseous, atmospheric CO_2 into dissolved CO_2 is based on a solubilization coefficient that is inversely related to the temperature of the surface ocean and is proportional to the partial pressure of CO_2 in the surface ocean. The equation follows Henry's law, which is that the dissolved gas in solution is proportional to its partial pressure. Thus, Kh , the solubility of CO_2 in water is defined as:

$$\left[CO_2\right] = K_0(T, S) \cdot pCO_2 \tag{34}$$

Computed as:

$$\begin{aligned} \ln K_h = {} & 9345.17/T - 60.2409 + 23.3585 \ln(T/100) \\ & + S\left[0.023517 - 0.00023656T + 0.00047036(T/100)^2\right] \end{aligned} \tag{35}$$

where T is temperature in °K, S is salinity in UNITS, and units are mol/kg. The partial pressure, pCO_2 can be closely approximated by the fugacity of $[CO_2]$, $f[CO_2]$ [?].

Once dissolved, CO_2 speciates into the other forms of DIC (including carbonate $CO^2{}_3{}^-$ and bicarbonate HCO_3^-) based on equilibrium kinetics. K_1* is the stoichiometric equilibrium constant of the first dissociation of carbonic acid, between carbon dioxide and bicarbonate, defined as:

$$K_1 = \frac{\left[H^+\right]\left[HCO_3^-\right]}{\left[CO_2\right]} \tag{36}$$

and K_2* is the stoichiometric equilibrium constant of the first dissociation of carbonic acid, between bicarbonate and carbonate, defined as:

$$K_2 = \frac{[H^+][CO_3^{2-}]}{[HCO_3^-]} \tag{37}$$

These constants can be computed as:

$$\begin{aligned} ln\, K_1 = {} & 2.83655 - 2307.1266/T - 1.5529413\, ln\, T \\ & - (0.207608410 + 4.0484/T)\sqrt{S} \\ & + 0.0846834\, S - 0.00654208\, S^{3/2} + ln\,(1 - 0.001005\, S) \end{aligned} \tag{38}$$

and

$$\begin{aligned} ln\, K_2 = {} & - 9.226508 - 3351.6106/T - 0.2005743\, ln\, T \\ & - (0.106901771 + 23.9722/T)\sqrt{S} \\ & + 0.1130822\, S - 0.00846934\, S^{3/2} + ln\,(1 - 0.001005\, S) \end{aligned} \tag{39}$$

where T is in °K and units are mol/kg. [?]

Dissolved organic carbon (DIC) is the sum of all dissolved forms, including CO_2, HCO_3^-, and CO_3^{2-}, and is notated as DIC or $\sum CO_2$, as defined in the following equation:

$$DIC = [CO_2] + [HCO_3^-] + [CO_3^{2-}] \tag{40}$$

The relative proportion of these three species of DIC is driven by temperature and salinity. The speciation of DIC in turns impacts the concentration of $[H^+]$ in the water, and therefore impacts the pH. These relationships are shown in Figure 7 below.

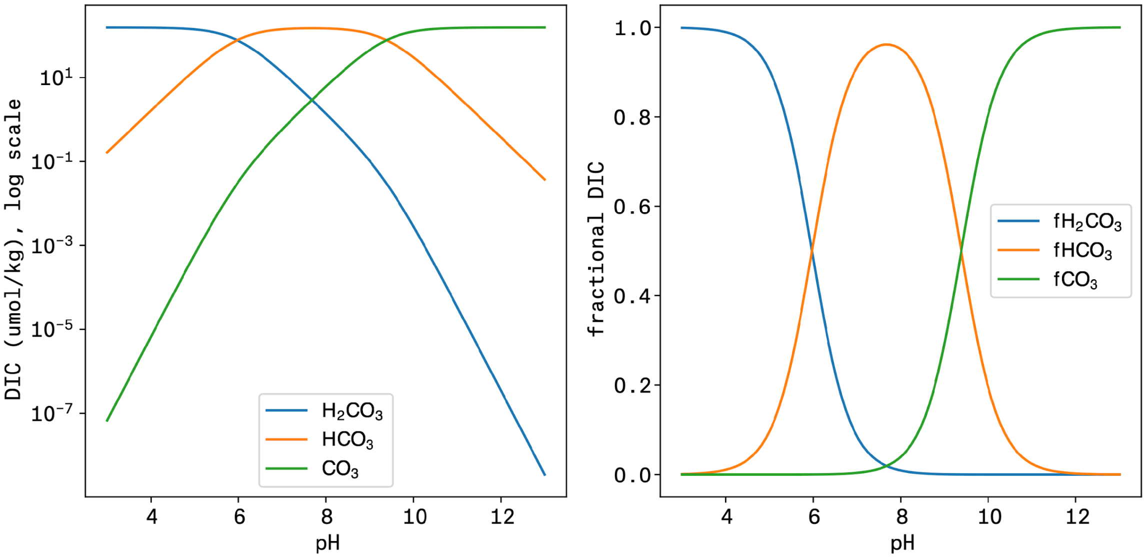

Figure 7: DIC speciation vs. pH, showing CO_2, HCO_3^-, and CO_3^{2-}, on a log scale (left) and as a fraction of total DIC (right)

Carbonate alkalinity (CA) is the sum of the total charges on the carbon forms, which is:

$$CA = \left[HCO_3^-\right] + 2 \cdot \left[CO_3^{2-}\right] \tag{41}$$

CO_3^{2-} has twice the influence on *CA* as HCO_3^- because it has two negative charges, while HCO_3^- only has one.

The equivalence point is defined as the point at which carbonate alkalinity is 0, so

$$\left[H^+\right] = \left[HCO_3^-\right] + 2 \cdot \left[CO_3^{2-}\right] + \left[OH^-\right] \tag{42}$$

The equivalence point is also known as the proton condition, which can be experimentally determined via titration.

Total alkalinity is similar but includes the influence of other ions, including Boron. Define total alkalinity (TA) as the sum of proton acceptors minus proton donors (for now ignoring minor species), and is interpreted as a charge imbalance:

$$TA = \left[HCO_3^-\right] + 2 \cdot \left[CO_3^{2-}\right] + \left[OH^-\right] - \left[H^+\right] \tag{43}$$

This definition of TA is has units of meq/kg, where meq is the charge weighted molar concentration of the species under consideration:

$$TA = \sum_j z_j \left[c_j\right] \tag{44}$$

where c_j is an ion of interest, *c* is the concentration of that ion (units mol/kg) and *z* is the valence of that ion (1, 2, or 3, positive or negative), hence 2 for $[CO_3^{2-}]$ and -1 for $[H^+]$.

We interpret alkalinity as the charge imbalance of conservative cations over conservative anions, and therefore that alkalinity is a conserved quantity. The charge imbalance between the cations and the anions in the ocean is responsible for the total alkalinity of the ocean. The chemical reactions in the ocean include photosynthesis and respiration, which remove or add CO_2, respectively. The charges remain constant even though the forms of carbon change.

Alkalinity defined by the conservative ion budget equals the alkalinity defined by the proton acceptor/donor budget. The proton acceptor/donor budget definition of the total alkalinity is the number of moles of H+ ions equivalent to the excess of proton acceptors over proton donors in one kg of sample. Bases formed from acids with pK>=4.5 are proton acceptors, while acids with pK<4.5 are considered proton donors.

Electroneutrality is the property where the sum of the positive charges of the cations equals the sum of the negative charges of the anions. The mass budget of conservative cations and conservative anions can be computed as a charge. To maintain electroneutrality, the sum of the positive charges must equal the sum of the negative charges.

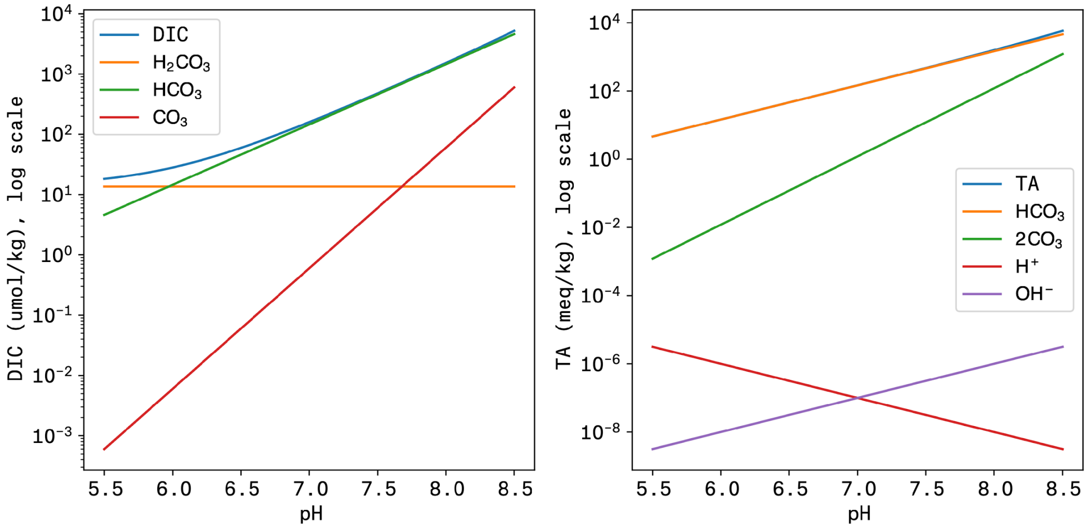

Figure 8: Carbonate species as they comprise DIC (left) and total alkalinity (right) across a range of pH.

$$\left[Na^{+}\right] + 2 \cdot \left[Mg^{2+}\right] + 2 \cdot \left[Ca^{2+}\right] + \left[K^{+}\right] + \left[H^{+}\right]$$

$$-\left[Cl^{-}\right]-2\cdot\left[SO_4^{2-}\right]-\left[NO_3^{-}\right]-\left[HCO_3^{-}\right]+2\cdot\left[CO_3^{2-}\right]+\left[B(OH)_4^{-}\right]+\left[OH^{-}\right]=0 \tag{45}$$

This equation can also be expressed as $z_j[c_j]=0$ where $[c_j]$ is concentration of a compound, z_j is the charge of the compound, and *j* is the compound.

An important principle arises here, namely that the charge balance of water itself is zero, whereas *TA* is positive. What accounts for the charge imbalance? It turns out that *TA* is also the charge imbalance of conserved cations (positive charges) over conserved anions (negative charges). Conserved in this context means that they do not vary with temperature or pressure, nor are they proton donors or acceptors at the pH threshold of 4.5 used in the definition of *TA* above. Thus, an alternative expression for total alkalinity is by way of these conserved species:

$$TA=\left[Na^{+}\right]+2\cdot\left[Mg^{2+}\right]+2\cdot\left[Ca^{2+}\right]+\left[K^{+}\right]+\ldots-\left[Cl^{-}\right]-2\cdot\left[SO_4^{2-}\right]-\left[NO_3^{-}\right] \tag{46}$$

The importance of this expression is that it relates a change in *TA* by way of a conserved cation, such as $[Mg^{2+}]$ or $[Ca^{2+}]$ originating from mineral dissolution, to a change in *TA* that includes carbonate terms, i.e. $[HCO_3^{-}]$ and $[CO_3^{2-}]$. The sum of total charges remains constant even while the forms of DIC change. Below, we will develop an expression for this change, $\frac{dDIC}{dTA}$, which quantifies a "stoichiometry" between cations and carbonate species, based on the fundamental equations provided above.

The complexity of the stoichiometry is due to the presence of both monovalent $[HCO_3^{-}]$ and divalent $[CO_3^{2-}]$, which causes the stoichiometric ratio to value between 1:2 (two $[HCO_3^{-}]$ per $[Mg^{2+}]$ or $[Ca^{2+}]$) at lower pH down to 1:1 (one $[CO_3^{2-}]$ per divalent cation) at higher pH. Moreover, the original dissolution event will likely take place in an environment (i.e. soil) that is more acidic, not saline, and at a different temperature, than the ultimate sink for cations and carbonates (i.e. the ocean), which is less acidic, very saline, and differs by temperature. Because the dissolution constants of carbonic acid vary with temperature and salinity, and the distribution of carbonates between $[HCO_3^{-}]$ and $[CO_3^{2-}]$ varies with acidity, the answer is not straightforward. Nonetheless, we will arrive at an analytical expression for $\frac{dDIC}{dTA}$ that can be used in terrestrial, riverine, and marine environments. We will show that the stoichiometry at the source is what can be measured and verified as the site of sequestration; that the stoichiometry at the ocean sink is what will be stored on millennial timescales; and the difference between these two can be interpreted as system loss of $[CO_2]$ back into the atmosphere.

First, simplify the expressions for *DIC* and *TA* to be functions of $[CO_2]$ and $[H^+]$ alone. For convenience (and consistency with Zeebe [?]), we will use notation where s = $[CO_2]$ and h = $[H^+]$.

From (3.1) express $[OH^{-}]$ as:

$$\left[OH^{-}\right]=\frac{K_w}{h} \tag{47}$$

From (3.5) express $[HCO_3^{-}]$ as:

$$\left[HCO_3^-\right] = s \cdot \frac{K_1}{h} \tag{48}$$

From (3.5) and (3.6) express $[CO_3^{2-}]$ as:

$$\left[CO_3^{2-}\right] = s \cdot \frac{K_1K_2}{h^2} \tag{49}$$

These allow us to express *DIC* and *TA* as:

$$DIC = s \cdot \left[1 + \frac{K_1}{h} + \frac{K_1K_2}{h^2}\right] \tag{50}$$

$$TA = s \cdot \frac{K_1}{h} + s \cdot 2 \cdot \frac{K_1K_2}{h^2} + \frac{K_w}{h} - h \tag{51}$$

With these definitions in place, we can develop an estimate of $\frac{dDIC}{dTA}$. First, compute the derivative $\frac{dTA}{dh}$:

$$\frac{dTA}{dh} =- s \cdot \left(\frac{K_1}{h^2} + 4 \cdot \frac{K_1K_2}{h^3}\right) - \frac{K_w}{h^2} - 1 \tag{52}$$

Next compute the derivative $\frac{dDIC}{dh}$:

$$\frac{dDIC}{dh} =- s \cdot \left(\frac{K_1}{h^2} + 2 \cdot \frac{K_1K_2}{h^3}\right) \tag{53}$$

Finally multiply $\frac{dDIC}{dh}$ by the inverse of $\frac{dh}{dTA}$ to calculate $\frac{dDIC}{dTA}$:

$$\frac{dDIC}{dTA} = \frac{dDIC}{dh} \cdot \frac{dh}{dTA} \tag{54}$$

What these calculations show is that (at constant temperature and salinity) at lower pH values, the carbon storage per cation introduced is higher than the carbon storage per cation at higher pH. At pH 5.5, the change in *DIC* per change in *TA* is nearly 1:1, though at higher pH such as 8.3 the balance is lower because some of the charge is balanced by CO_3^{2-}, not just HCO_3^- (Figure 9a). At lower pH, the change in pH is also more significant per unit TA than at higher pH (Figure 9b).

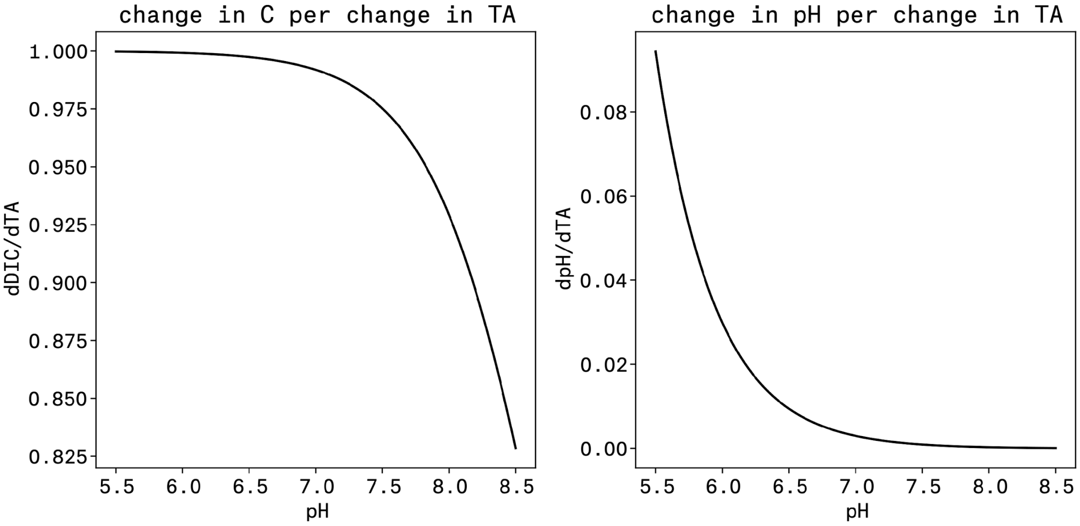

Figure 9: Change in derivatives of carbonate system with respect to changes induced by a change in alkalinity. Derivatives of DIC (left) and pH (right).

Additionally, these calculations can illustrate the impact of alkalinity on pH, which surfaces the counter-intuitive phenomenon that alkalinity is not simply the inverse of acidity.

$$\frac{dpH}{dTA} =- log_{10}(e) \cdot \frac{1}{h} \cdot \frac{dh}{dTA} \tag{55}$$

Figure 9 shows that across any value of pH, additions in alkalinity always result in positive increases in pH and thus reductions in acidity.

In the ocean, dissolved boric acid contributes to the alkalinity budget. Total boron, that is the sum of $B(OH)_3$ and $B(0\ H)_4^-$, is proportional to salinity, which itself varies with the freshwater budget, both influx of freshwater from rivers, and evaporation of pure water from the surface.

The constant for boric acid is defined as:

$$K_b = \frac{\left[H^+\right]\left[B(OH)_4^-\right]}{B(OH)_3} \tag{56}$$

Is is computed as:

$$\begin{aligned} ln\, K_B = {} & (-\ 8966.9\ -\ 2890.53\, S^{1/2}\ -\ 77.942\, S\ +\ 1.728\, S^{3/2}\ -\ 0.0996\, S^2)/T \\ & +\ 148.0248\ +\ 137.1942\, S^{1/2}\ +\ 1.62142\, S \\ & -\ (24.4344\ +\ 25.085\, S^{1/2}\ +\ 0.2474\, S)\ ln\, T\ +\ 0.053105\, S^{1/2} T \end{aligned} \tag{57}$$

In marine settings (where S is large and pH > 8), the boric acid term $\left(\frac{K_B B_T}{K_B + h}\right)$ is added to the equation for *TA*, and the derivative of *TA* with respect to *h* becomes:

$$\frac{dTA}{dh} = - s \cdot \left(\frac{K_1}{h^2} + 4 \cdot \frac{K_1 K_2}{h^3}\right) - \frac{K_B B_T}{K_B + h^2} - \frac{K_w}{h^2} - 1 \tag{58}$$

In the ocean, the alkalinity is more or less defined by the consistent cation/anion budget, proportional to salinity. Alkalinity measures the charge concentration of anions and cations in the solutions, and is equal to the number of moles of acid (e.g. HCl) to add to neutralize the anions of the weak acid equals the carbonate alkalinity. The carbonate system is one contributor to total alkalinity, though there are other contributors including boric acid ($B(OH)_4^-$), phosphoric acid, and water. Practical alkalinity (*pA*) is a simplified equation for alkalinity, which includes carbonate alkalinity, borate alkalinity, and water alkalinity, following the equation:

$$pA = \left[HCO_3^-\right] + 2 \cdot \left[CO_3^{2-}\right] + \left[B(OH)_4^-\right] + \left[OH^-\right] - \left[H^+\right] \tag{59}$$

The equilibrium constants in the carbonate equations depend on pressure and temperature, which vary throughout the water column. Thus, as carbon sinks from the surface to deeper waters, these values change. However, when only the temperature and pressure change (and not salinity), DIC and TA are constant.

Ocean alkalinity is roughly -2.5. As pH increases, with no other changes to the system, carbonate alkalinity will decrease (Figure 10).

D.a. Aqueous Carbonate System Chemistry

Dissolved inorganic carbon (DIC) in natural water is made up of three components: free CO_2 (a gas), the bicarbonate ion (HCO_3^-), and the carbonate ion (CO_3^{2-}). The relative abundance of these carbon compounds is a major driver of water pH. Free CO_2 is the dominant acid, while the two carbonates contribute to the alkalinity. The amount of exchange of water surface CO_2 with the atmosphere depends on the carbonate equilibrium state of the water, defined by water pH and alkalinity, along with temperature and salinity among others. Oceanic pH and alkalinity (*TA*) sit in a narrow range and hence so does oceanic DIC, sitting around 2400µM. River water has a greater variation in alkalinity, which leads to a greater range of DIC: from <20µM to 5000µM in acidic and alkaline waters respectively.

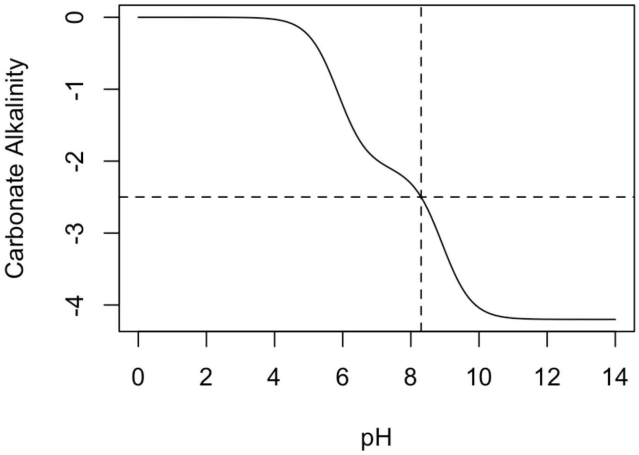

Figure 10: This figure shows carbonate alkalinity vs. pH. The dashed lines show where pH=8.3, and carbonate alkalinity = -2.5.

With fixed *pCO_2*, an increase in pH (decline in [H^+]) results in an increase of *DIC* and *TA* (Fig. 11). Soil pH can be as low as 5.5, and ocean pH is typically 8.3. As pH increases, total DIC and the fraction of DIC that is bicarbonate increases. Across these pHs, total TA is primarily due to bicarbonate (HCO_3^-), though as pH increases carbonate (CO_3^{2-}) accounts for a larger proportion. Aqueous CO_2 never changes, as it is set by the atmosphere and the solubility constant of CO_2. However, declines of [H^+] push the equation to the right, bringing especially more HCO_3^- into the solution.

Due to the chemical equilibrium relationship between water surface CO_2 and atmospheric CO_2, a variation in water alkalinity drives a change in the amount of DIC stored. We refer to the carbon storage potential of the water as the DRI, which is defined as $\frac{dDIC}{dTA}$, the variation in the DIC caused by a small change in alkalinity. At constant temperature and salinity, across that range of pH, all increases in *TA* (e.g. by the introduction of a conservative cation) must be balanced by an increase of DIC and must be balanced by an increase in pH. However, while the balance is initially 1:1 of conservative cation to DIC (e.g. Mg^{2+}:HCO_3^-), the balance drops to approx 0.85 at pH 8.3, because some of the charge is balanced by CO_3^{2-}.The amount of change in DIC and pH induced by a change in *TA* varies according to pH - as seen in Figure 12).

As pH increases from soil to the ocean, the change in DIC per unit of *TA* decreases from about 1 to 0.85. The change in pH per unit of *TA* also decreases, from 0.09 to nearly 0. These decreases occur because as pH increases, more of the alkalinity charge is balanced by carbonate (CO_3^{2-}) rather than bicarbonate (HCO_3^-).

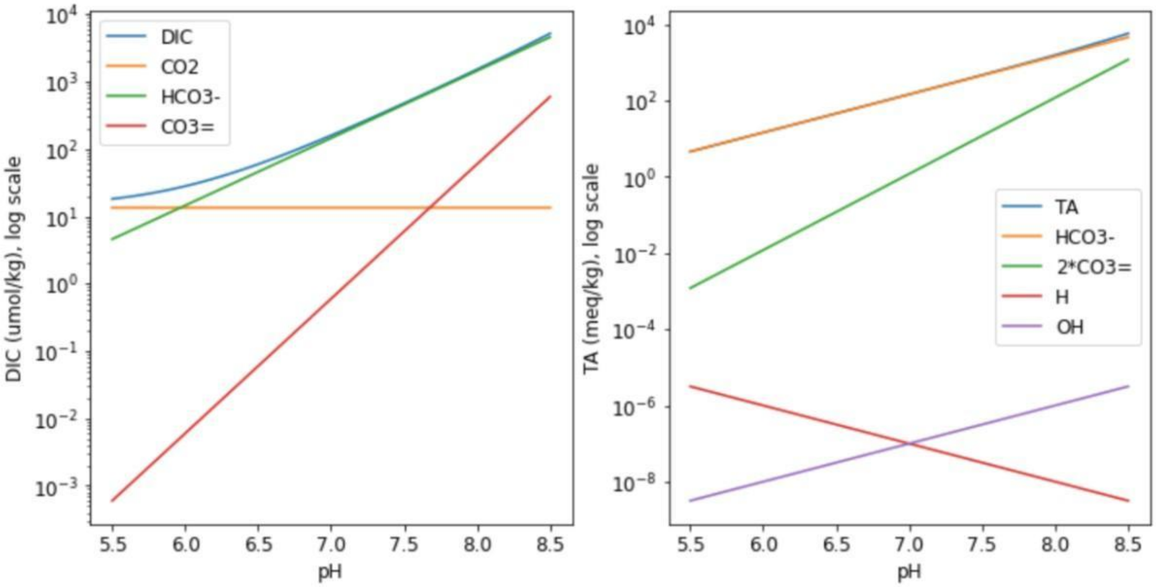

Figure 11: Changes in DIC and TA driven by pH.

When considering the long-term storage of CO_2 removed on the field through enhanced weathering, the oceanic DRI acts as a limiting factor on the amount of carbon that can be stored. In order to ensure we are not overestimating the amount of carbon removed through the application of silicate rocks, we need to validate that there is no leakage in the river, over and above the expected oceanic leakage. Additional leakage would occur if the river DRI dropped below oceanic DRI, which could potentially happen due to the greater variation in river alkalinity. DRI is conventionally defined between 0, when variation in alkalinity does not affect the DRI, and 1, when a change in alkalinity corresponds to an equal change in DRI.

Solving the marine carbonate system is done in python with PyCO2SYS [?]. Note that any two core parameters (including but not limited to DIC, *TA*, partial pressure of CO_2 (pCO_2), plus auxiliary data including temperature, pressure, and salinity), are enough to solve for the complete carbonate equilibrium [?].

DRI is defined as the change in DIC (*dDIC*) per change in TA (*dTA*), as in the equation:

$$DRI = \frac{dDIC}{dTA} = \frac{dDIC}{dh} \cdot \frac{dh}{dTA} \tag{60}$$

which are calculated as *dDIC*

$$\frac{dDIC}{dh} = - s \cdot \left(\frac{K_1}{h^2} + 2 \cdot \frac{K_1 K_2}{h^3} \right) \tag{61}$$

and *dTA*

$$\frac{dTA}{dh} =- s \cdot \left(\frac{K_1}{h^2} + 4 \cdot \frac{K_1 K_2}{h^3}\right) - \frac{K_w}{h^2} - 1 \tag{62}$$

where h are the protons and K_x are kinetic rate constants. The full derivation can be found in Appendix E.

We note that our derivation of DRI takes a different form but aligns with the alkalinization carbon-capture efficiency (ACCE) derived in [?].

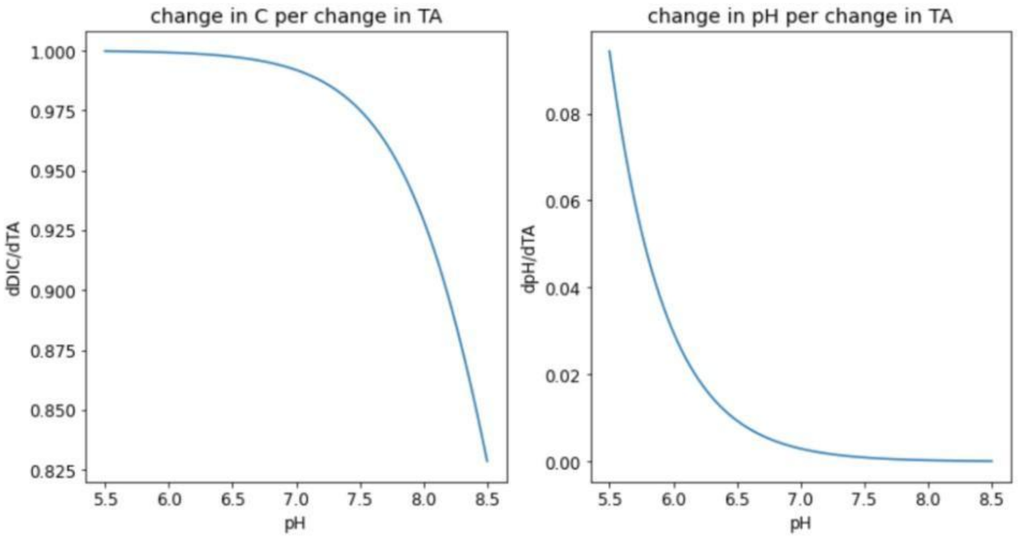

Figure 12: Changes in $\frac{dDIC}{dTA}$ and $\frac{dpH}{dTA}$ driven by pH.

F. Diesel consumption estimate for field application

We assume an average diesel consumption rate of 28.57 l/h for a 140-155 hp tractor. Consumption rates were retrieved for 9 common tractors sold in the U.S. from test reports by the Nebraska Tractor Testing Laboratory operated by the University of Nebraska in accordance with Nebraska law to test the performance of agricultural equipment. We use the fuel consumption rate for the rated engine speed at maximum power and fuel consumption and calculate an average diesel consumption across the 9 selected tractors.

About the Nebraska Tractor Testing Laboratory:

The Nebraska Tractor Testing Laboratory is a research center at the University of Nebraska-Lincoln that was established in 1919. The laboratory conducts standardized tests to evaluate the performance of tractors and other agricultural machinery, and publishes the results in a series of reports known as the Nebraska Tractor Tests. The Nebraska Tractor Tests have become widely recognized as a benchmark for tractor performance and are used by manufacturers, dealers, and farmers to make informed decisions about which tractors to purchase. The reports are available to the public and can be accessed online through the laboratory's website (https://tractortestlab.unl.edu/) or through the University of Nebraska-Lincoln's Digital Commons (https://digitalcommons.unl.edu/).

Tractor (Make & Model)	Engine HP (rated)	Test Report ID	Test result (pdf)	Fuel consumption	
				Gal/hr	**l/h**
Case IH Maxxum 150	150	3638	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4253&context=tractormuseumlit	7.20	27.26
Case IH Maxxum 145	145	3637	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4252&context=tractormuseumlit	7.46	28.42
John Deere 6155M	155	3472	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=3530&context=tractormuseumlit	6.29	23.83
John Deere 6155R	155	3675	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=3611&context=tractormuseumlit	8.32	31.49
New Holland T6.175	140	3642	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4257&context=tractormuseumlit	7.46	28.22
New Holland T6.180	145	3643	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4258&context=tractormuseumlit	7.20	27.26
Massey Ferguson 6715 S	140	3648	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4268&context=tractormuseumlit	8.03	30.41
Massey Ferguson 7715 S	140	3604	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4210&context=tractormuseumlit	8.20	31.02
Fendt 714 Vario	147	3827	https://digitalcommons.unl.edu/cgi/viewcontent.cgi?article=4388&context=tractormuseumlit	7.73	29.26
			Average	**7.54**	**28.57**