A Direct-Measurement Framework for Enhanced Rock Weathering

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Abstract

Enhanced mineralization (EM) offers a robust pathway for permanent carbon dioxide (CO_2) sequestration as dissolved inorganic carbon (DIC) through enhanced rock weathering (ERW), a process accelerated on farmland where CO_2 levels in soil pores exceed atmospheric concentrations. By mimicking natural weathering, ERW transforms rocks into secondary minerals, facilitating the stable storage of carbon in marine environments for up to 500,000 years. With mineral inventories estimated to sequester 35,000 Gt of CO_2 globally, ERW has significant scalability potential, with the U.S., China, and India each projected to capture about 0.5 Gt of CO_2 annually through farmland applications. ERW involves seven stages: quarrying, mineral transport, milling to enhance CO_2 reactivity, field application, and carbon capture, utilization, and sequestration (CCUS) through mineral weathering. While the initial stages emit CO_2—measurable by lifecycle analyses—the CCUS stage is complex to account for on individual fields, limiting ERW's inclusion in current carbon accounting frameworks. This methodology targets this critical step, drawing on U.S. farmland and federal data to quantify field-scale carbon removal and assess potential CO_2 losses, akin to monitoring hydrologic losses in subsurface carbon reservoirs. By providing a detailed approach for ERW deployment and monitoring, this methodology aims to overcome data and scale limitations, paving the way for large-scale, sustainable carbon sequestration on U.S. farmland.

A Direct-Measurement Framework for Enhanced Rock Weathering

Methodology for Carbon Dioxide Removal by Enhanced Rock

Weathering on United States Farmland

ISO 14064-2:2019

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This methodology in its current version 1.0 state was developed by Eion.
The document was validated by DNV to meet all relevant requirements in ISO 14064-2:2019 (https://www.iso.org/standard/66454.html).

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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, 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.

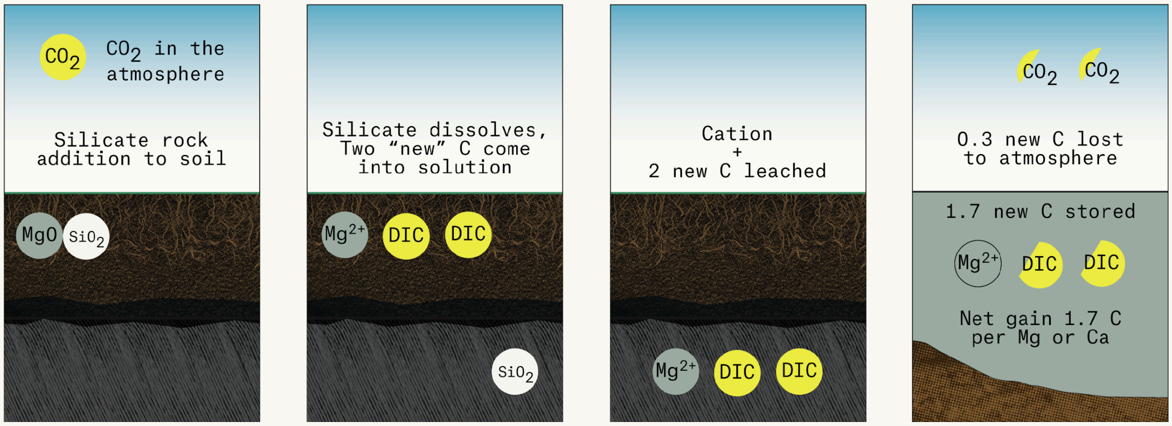

Figure 1: Chemical transformations in carbon capture by enhanced mineralization on croplands.

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, 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.

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 mildly acidic to circumneutral pH (5.0 - 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:

1. 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.
2. The silicate mineral used for this project must have sufficient concentration of alkaline elements (Ca, and Mg) to exceed potential plant uptake, and result in capture of dissolved CO_2.
3. The soil type of the system must be considered. Only soils where the field-average of pre-project pH is within the range of 5.0 - 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.
4. The land use must be farmland: all cropland, farmstead land, government program land, idle land, orchards, pasture, wasteland, and woodland.
5. 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.
6. 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.
7. 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.

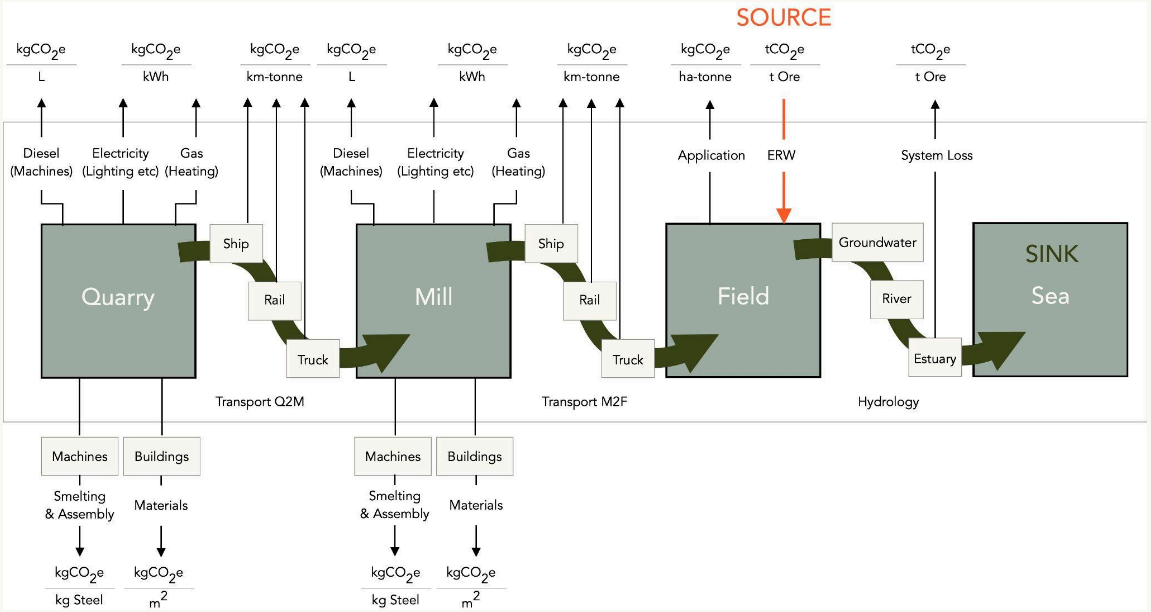

Figure 2: Project Boundary for Enhanced Rock Weathering Life Cycle.

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 (3).

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 CO2 sink or source, so a baseline scenario whereby all applied CaCO3 dissolves and liquid-gas exchange occurs between the soil-air interface should be addressed. This may include aqueous speciation modeling of the soil pore water and an equilibration with a gas phase, e.g. (4,5). The output should be the CO2 sink or source expressed as g CO2/m2.

For instances where a CO2 source is observed (positive values of g CO2/m2 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 CO2 sink is observed (negative values of g CO2/m2 emitted upon full dissolution of lime), the magnitude of the sink should be compared with the suggested project scope. If the calculated CO2 sink is estimated as at least 3 orders of magnitude (1000-fold) lower than the CDR project scope (i.e. the CO2 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 CO2 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 CO2 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 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

The net Carbon Dioxide removal (CDR_{net}) per metric tonne is calculated as the actual CO_2 removed ($CDR_{actual,t,x\text{-}confidence}$) at a given time, t, and confidence interval of X%, minus project emissions (*PE*) minus the system loss (*SL*), according to the following equation:

$$CDR_{net} = CDR_{actual,t,x-confidence} - PE \ - SL \tag{1}$$

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 energy in the extraction, transport, processing, and field application in Stages 1-5 of the process flow.

Project emissions per metric tonne of the project crediting period will be expressed as follows:

$$PE \ = f_Q \cdot PE_Q + PE_{TQ2M} + PE_M + PE_{TM2F} + PE_{FA} \tag{2}$$

where:

PE = Project emissions per metric tonne ($tCO_2e/tOre$)
PE_Q = Total quarry emissions per metric tonne ($tCO_2e/tOre$)
f_Q = Fraction of quarry activities involved in project (unitless)
PE_{TQ2M} = Transport emissions from the quarry to mill per metric tonne ($tCO_2e/tOre$)
PE_M = Mill emissions per metric tonne ($tCO_2e/tOre$)
PE_{TM2F} = Transport emissions from the mill to field per metric tonne ($tCO_2e/tOre$)
PE_{FA} = Field application emissions per metric tonne ($tCO_2e/tOre$)

8.2.1 Stage 1: Quarry

Determining PE_Q: 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:

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

where:

PE_Q	= Project emissions from the quarry per metric tonne ($tCO_2e/tOre$)
$V_{grid,Q}$	= Quantity of electricity from the grid used by the quarry per metric tonne (MWh/tOre)
$EF_{grid,Q}$	= Emissions factor of the electricity used to power the quarry (tCO_2e/MWh)
$V_{fuel,i,Q}$	= Quantity of fossil fuel of type i used by the equipment in the quarry per metric tonne (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 $V_{grid,Q}$: The quantity of electricity from the grid used by the quarry per metric tonne 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, UNFCC, Carbon Footprint or similar tools. For countries, such as the United States, Canada, and Australia, the eGrid emissions factor for the sub-region (state or province) where the facility is located shall be used (latest available information). If no country specific grid emissions factors are available, use option 2. 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 $V_{fuel,i,Q}$: The quantity of fossil fuel of type *i* used by the quarry per metric tonne 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 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:

$$PE_{TQ2M} = \sum_{i} PE_{TQ2M,j} \quad (4)$$

where:

PE_{TQ2M} = Total transport emissions from the quarry to mill per metric tonne (tCO_2e/tOre)
$\sum_{i,j}$ = Summation over all transport legs *j*.
$PE_{TQ2M,j}$ = Transport emissions from leg *j* from the quarry to mill per metric tonne (tCO_2e/tOre)

Determining $PE_{TQ2M,j}$: Transport emission from quarry to mill for each transport leg *j* per metric tonne *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.

$$PE_{TQ2M,j} = \sum_{i} V_{i,j} \cdot EF_{i,j} \tag{5}$$

where:

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

Option 2: Cargo transport measure.

$$PE_{TQ2M,j} = D_{j} \cdot EF_{tonne-km,j} \tag{6}$$

where:

$PE_{TQ2M,j}$ = Transport emissions from leg *j* from the quarry to mill per metric tonne (tCO_2e/tOre)
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 or a combination thereof:

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. Marine Traffic API or similar tools shall be used for ocean transport.

8.2.3 Stage 3: Mill

Mill emissions are calculated as follows:

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

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

8.2.4 Stage 4: Transport Mill to Field

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

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

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.

$$PE_{FA} = \frac{FPT}{APT} \cdot TA \cdot EF_{i} \tag{9}$$

where:

PE_{FA} = Field application emissions per metric tonne (tCO$_2$e/tOre)
FPT = Fuel usage per unit time (L/h)
APT = Area applied per unit time (ha/h)
TA = Total area applied (ha)

EF_i = Emissions factor of the fossil fuel *i* used for field application (tCO_2e/L)

FPT can be determined by conventional engineering calculations or retrieved from an officially designated OECD tractor test laboratories, namely the Nebraska Tractor Test Laboratory, or from the Association of Equipment Manufacturers. If available, an actual fuel survey is preferred, which shall be a direct measurement of the fuel consumption using e.g. a fuel flow meter.

APT can be determined by conventional engineering calculations, else an as-applied map can be used.

TA can be retrieved from as-applied maps or computed based on field boundary coordinates.

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:

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

where:

$CDR_{potential}$ = Maximum potential CO_2 removal ($tCO_2/tOre$)
A = Area of mineral application (ha)

AR = Application rate of mineral (kg/m^2)
$tOre$ = Total metric tons of mineral applied over area A (tOre)
MP = Mineral potential of the applied silicate (tCO_2/tOre)
DUI = 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. Within the range of pH allowable by this methodology, this value will be 1.

At first glance, A, AR (converted to tOre/ha), 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 field boundaries, i.e. geometric borders of the field.

Determining *AR*: The application rate AR shall be determined by a rate prescription using a standard lime requirement calculation adjusted by the Calcium Carbonate Equivalent (*CCE)* of the silicate material.

$$AR = \frac{LR}{CCE} \tag{11}$$

where:

LR = Lime requirement (kg/ha)
CCE = Calcium Carbonate Equivalent (CCE) (unitless)

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

$$LR = 1250 + (((L - 0.3) - H) \cdot 1820) + ((6.95 - B) \cdot 5260) \tag{12}$$

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.

Determining CCE: Calcium Carbonate Equivalent shall be determined using one of the following options:

Option 1: CCE is computed as followed:

$$CCE = \frac{NE_m}{NE_c} \tag{13}$$

where:

NE_m = Neutralizing equivalent of any mineral m (eq/g)
NE_c = Neutralizing equivalent of $CaCO_3$ (eq/g)

The neutralizing equivalent of calcite is calculated as:

$$NE_c = \frac{CaO_c}{MW_{CaO}} \cdot V \tag{14}$$

where:

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

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

$$NE_m = \left(\frac{CaO\%}{MW_{CaO}} + \frac{MgO\%}{MW_{MgO}}\right) \cdot V \tag{15}$$

where *CaO%* and *MgO%* are mass fractions and are derived from an elemental analysis of the mineral to be used.

Option 2: Alternatively, it can be directly measured using a modified method for determining neutralizing value for liming material that ensures maximal dissolution of the silicate material.

Determining *tOre*: The total amount of mineral applied to the field (reported as dry weight) 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 16.

$$MP \equiv \frac{tCO_2e}{tOre} = \frac{MW_{CO2}}{100\%} \cdot \left(\frac{MgO\%}{MW_{MgO}} + \frac{CaO\%}{MW_{CaO}}\right) \cdot V \tag{16}$$

where:

$MgO\%$ = Mass fraction of magnesium oxide in the mineral
MW_{MgO} = Molecular weight of magnesium oxide (40 g/mol)
$CaO\%$ = Mass fraction of calcium oxide in the mineral
MW_{CaO} = Molecular weight of calcium oxide (56 g/mol)
MW_{CO2} = Molecular weight of CO_2 (44 g/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 because the soil will be at a pH where $\frac{dDIC}{dAlk}$ is within an appropriate range (that is, between 6.2 and 7.5, Figure 3). The above determined application rate *AR* will bring acidic soils into this pH range.

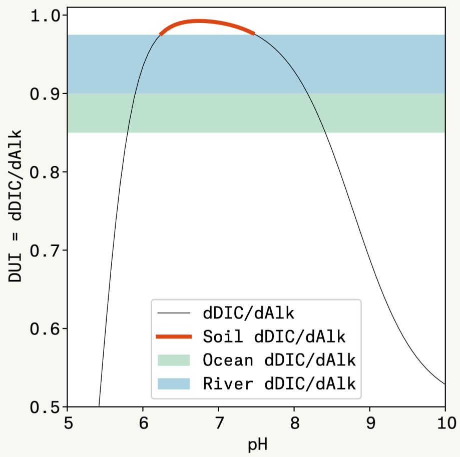

Figure 3: DIC Uptake Index (DUI) showing ideal range for soil uptake

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 (Fig. 1).

Actual CDR shall be computed as:

$$CDR_{actual,t,x-confidence} = CDR_{potential} \cdot f_{captured,t} \tag{17}$$

where:

$CDR_{actual,t,x\text{-}confidence}$ = Actual CO_2 removal at time t under X% confidence interval ($tCO_2/tOre$)
$CDR_{potential}$ = 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 $CDR_{potential}$:

$$f_{captured,t} = \frac{DivAlk_{captured,t}}{DivAlk_{added}} \tag{18}$$

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

$$DivAlk_{added} = \left(\frac{MgO\%}{MW_{MgO}} + \frac{CaO\%}{MW_{CaO}}\right)_{added} \cdot V \cdot AR_{rock} \cdot \frac{1}{d \cdot \rho} \tag{19}$$

where:

$MgO\%$ = Mass fraction of magnesium oxide in the mineral
MW_{MgO} = Molecular weight of magnesium oxide (40 g/mol)
$CaO\%$ = Mass fraction of calcium oxide in the mineral
MW_{CaO} = Molecular weight of calcium oxide (56 g/mol)
MW_{CO2} = Molecular weight of CO_2 (44 g/mol)
V = Valence of the cations (2 for Mg and Ca)
AR_{rock} = Estimated application rate based on presence of immobile trace element derived from the applied silicate material (kg/m^2)
d = Soil depth (m)
ρ = Soil bulk density (g/cm^3)

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*). For fields with multiple applications at different times, a new baseline soil sample must be collected before application. $\text{DivAlk}_{\text{added}}$ will therefore be specific to a single application. Equation 19 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 $\text{DivAlk}_{post,t}$, 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, such as predetermined project-specific tracers. This may include 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 (i.e. mineral amendment budget):

$$\left[Z_{post}\right]\cdot Mass_{soil} = \left[Z_{pre}\right]\cdot Mass_{soil} + \left[Z_{rock}\right]\cdot Mass_{rock} \tag{20}$$

where

$[Z_{post}]$ = Immobile trace element after treatment (ppm)
$Mass_{soil}$ = Soil mass (kg)
$Mass_{rock}$ = Added rock mass (kg)
$[Z_{pre}]$ = Immobile trace element before treatment (ppm)
$[Z_{rock}]$ = Immobile trace element in rock (ppm)

Immobile trace element [Z] may include rare earth elements such as scandium (Sc), yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) or a combination thereof, rare metals such as beryllium (Be), cesium (Cs), gallium (Ga), germanium (Ge), hafnium (Hf), niobium (Nb), rubidium (Rb), tantalum (Ta), zirconium (Zr), or a combination thereof, transition metals such as nickel (Ni), chromium (Cr), and zinc (Zn) among others and may include a combination of transition metals.

The mass of soil is calculated as followed:

$$Mass_{soil} = A \cdot d \cdot \rho \tag{21}$$

The mass of silicate material applied is calculated as follows using the quantification of immobile trace elements present in the added rock:

$$Mass_{rock} = \frac{([Z_{post}]-[Z_{pre}])\cdot Mass_{soil}}{Z_{rock}} \quad (22)$$

The estimated application rate based on presence of immobile trace element derived from the applied silicate material is calculated as followed:

$$AR_{rock} = \frac{Mass_{rock}}{A}. \quad (23)$$

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 21, where *d* 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 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$_{added}$. The total application of mineral shall be calculated using statistical analysis utilizing each individual soil-based data of AR$_{rock.}$ Additionally, the same statistical analysis method will be used to compute a confidence interval for $DivAlk_{captured,t}$ as followed:

To conduct the statistical analysis, a normality test will first be conducted on the dataset. If the test yields a normally distributed dataset, traditional statistical methods will be used to compute a confidence interval of X%. To calculate the confidence intervals, the appropriate percentiles will be determined. It is encouraged to evaluate confidence at a value of at least X = 90% interval. To be 90% confident, a 10th percentile should be computed.

If the dataset is not normally distributed, a best-practice bootstrapping method will be used instead. Random populations of size *n* from a set of *n* values (of $DivAlk_{captured,t}$ or AR$_{rock}$) with replacement will be used to compute the mean of each generated population. A minimum value of 10,000 bootstrap samples are encouraged to minimize artifacts of insufficient random sampling.

Using the bootstrapped sample means of $DivAlk_{captured,t}$, the overall estimated CDR can be computed using Equation 17, where $DivAlk_{captured,t}$ includes the uncertainty quantification of X% confidence. This ensures that the reported $CDR_{actual,t,x-confidence}$

has included the uncertainty induced by the natural variability present in the soil-based datasets.

Option 2: DivAlk$_{added}$ is estimated using the application rate *AR* 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. Option 2 shall be selected only for individual fields where option 1 results in inaccurate results. Explanation for selecting option 2 shall be provided at the monitoring stage.

Determining 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: *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.

Option 2: DivAlk$_{captured,t}$ is calculated as (Figure 4):

$$DivAlk_{captured,t} = DivAlk_{pre} + DivAlk_{added} - DivAlk_{losses} - DivAlk_{post,t} \tag{24}$$

where:

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, charge-balance with non-DIC cations (e.g. NO_3^-, SO_3^- or Cl^-), and background soil mineral weathering (eq/g)
DivAlk$_{post,t}$ = Divalent alkalinity in the post-application soil at time *t* (eq/g)

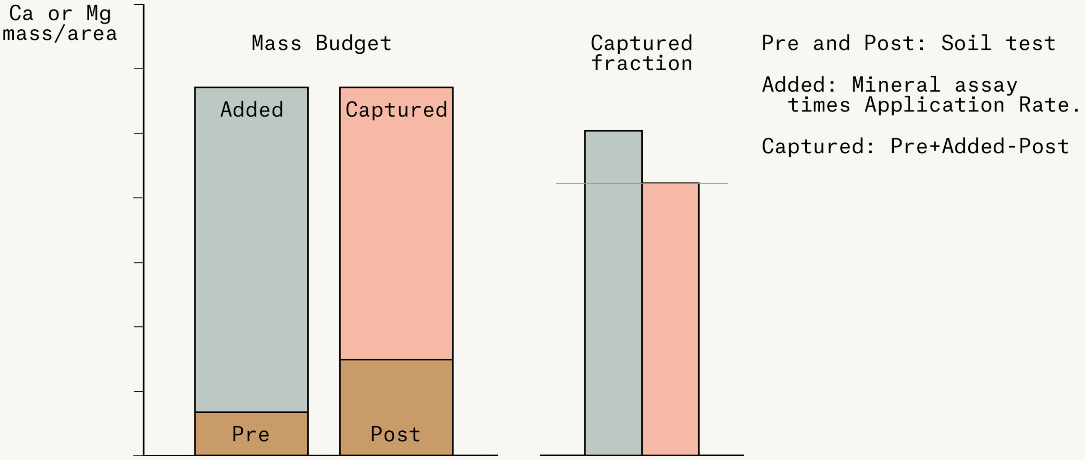

Figure 4: Simplified budget equation of divalent cations that remove CO_2.

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.

$$DivAlk_{pre/post} = \left(\frac{Mg\%}{MW_{Mg}} + \frac{Ca\%}{MW_{Ca}}\right)_{soil} \cdot V \tag{25}$$

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)

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

$$DivAlk_{losses} = f_{total\ losses} \cdot (DivAlk_{pre} + DivAlk_{added} - DivAlk_{post,t}) \tag{26}$$

where:

$$f_{total\ losses} = 1 - [(1 - \frac{DivAlk_{uptake}}{DivAlk_{captured,t}}) \cdot (1 - \frac{DivAlk_{other}}{DivAlk_{captured,t}}) \cdot (1 - \frac{DivAlk_{background}}{DivAlk_{captured,t}})] \quad (27)$$

$DivAlk_{uptake}$ = Divalent alkalinity losses from plant uptake (eq/g)
$DivAlk_{other}$ = Divalent alkalinity charge-balance with non-DIC anions (e.g. NO_3^-) (eq/g)
$DivAlk_{background}$ = Divalent alkalinity losses from natural mineral weathering (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.

$$DivAlk_{uptake} = DivAlk_{uptake,Mg} + DivAlk_{uptake,Ca} \quad (28)$$

where $DivAlk_{uptake,Mg}$ and $DivAlk_{uptake,Ca}$ is calculated as follows:

$$DivAlk_{uptake,Mg} = \frac{Rock_{Mg}}{(Rock_{Mg} + Soil_{Mg})} \cdot plantuptake(Mg) \quad (29)$$

$$DivAlk_{uptake,Ca} = \frac{Rock_{Ca}}{(Rock_{Ca} + Soil_{Ca})} \cdot plantuptake(Ca) \quad (30)$$

where:

$Rock_{Mg,Ca}$ = 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,

$$plantuptake(Mg, Ca) = plant(Mg, Ca) \quad (31)$$

where:

plant(Mg,Ca) = the mass of Mg or Ca in the plant (g Mg/m^2 or g Ca/m^2)

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.

$$plantuptake(Mg, Ca) = plant(Mg, Ca)_{t2} - plant(Mg, Ca)_{t1} \quad (32)$$

Determining plant(Mg, Ca): The mass of Mg or Ca in the plant per area 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 in field trials in a similar ecosystem, crop and climate. The samples should be 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 (8). 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.

$$DivAlk_{other} = 2 \cdot [Flushed\ Nitrate]_{eq/L} \cdot \text{Volume collected / Mass of soil} \tag{33}$$

where:

$[Flushed\ Nitrate]_{eq/L}$ = Measured nitrate concentration (eq/L)
Volume collected = Amount of leachate collected (L)
Mass of soil = Amount of representative soil in control volume (kg)

Determining *DivAlk*$_{other}$: Divalent alkalinity charge-balanced with non-DIC cations shall be determined using one of the following options:

Option 1: Using a lysimeter, capture the volume of soil water leachate from a small portion of the deployment field. 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 measured inorganic nitrate (dominant nitrate species) concentration allows for the conservative quantification of nitric acid weathering on the applied silicate. The 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 molar quantity of inorganic nitrate concentration 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. The resultant equivalent amount of nitric acid weathering (eq/L) can be converted to a mass-normalized unit (eq/kg soil) by multiplying by the ratio of Volume of fluid collected : Mass of representative soil.

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.

Determining $DivAlk_{background}$: The divalent cations in the soil solution do not necessarily all come from the additional amendment and weathering of silicates. Naturally occurring, background weathering of pre-existing minerals may lead to an elevated, non-zero baseline of divalent element flushing.

Option 1: As background weathering may vary according to the local soil biogeochemistry, a co-located field trial dataset is important to constrain this parameter. Using data of flushed divalent cations (eq/L) from a lysimeter in a field trial in a similar ecosystem, crop and climate, estimate the fraction of divalent cations (equivalents/L) that are generated from non-amended, control plots. Make sure that the lysimeter is installed to capture leachate from the same control volume size between amended- and non-amended sites. This option is similar to option 2 for determining $DivAlk_{other}$ with a focus on cationic aqueous species.

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*):

$$HLF = 1 - [DRI_{water} \cdot (1 - DPL_{river})] \tag{34}$$

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 and is equivalent to 1.
DRI_{water}	= 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.
DPL_{river}	= DIC Precipitation Likelihood in riverine transport to the ocean, equivalent to $\frac{number\ of\ points\ of\ calcite\ precipitation\ SI > 1}{total\ number\ of\ river\ chemistry\ points\ evaluated}$,where dissolved inorganic carbon may precipitate as a calcium carbonate mineral, leading to reversal of CO_2 captured.

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

$$SL = CDR_{actual,t,x-confidence} \cdot HFL \tag{35}$$

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 post-amended 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 do not 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.

Determining DRI_{water}: DRI_{water} is the lower value between the DRI of the river (DRI_{river}) or DRI of the ocean (DRI_{ocean}). A lower DRI indicates a higher loss. DRI shall be computed using the marine carbonate system calculations developed by NOAA (PyCO2SYS) (9,10).

Determining DRI_{river}: The input parameters shall be determined using one of the following options:

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). Monitoring frequency must be specified and justified by either published academic research for the specific parameters monitored or by statistical analysis demonstrating optimized monitoring frequency. Sensors should be installed and maintained according to the manufacturer's instructions. Number and locations of monitoring stations shall correspond to the readily available data extracted from the Global River Chemistry Database (GLORICH) (see Option 2 below).

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 or the most recent version available. This dataset includes all the sampling stations for rivers in the US. 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 determined from altitude of the sample.

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

Determining DRI_{ocean}: The localized annual oceanic DRI shall be calculated. The two system variables used to calculate the carbonate states are TA and pH. Auxiliary variables are seawater temperature and salinity and a pressure = 0 at the ocean surface. Data from the OceanSODA-ETHZ (13) dataset shall be used, which provides chosen variables at high spatial resolution, and for the years 1985-2018 (or most recent version available). 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 5.

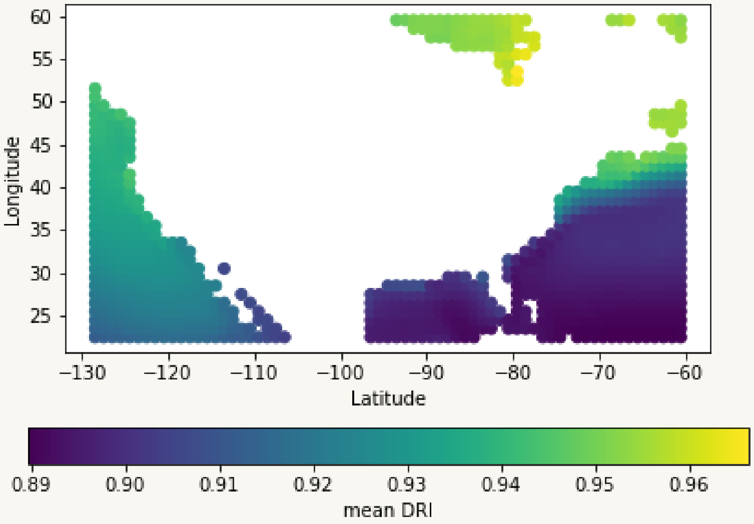

Figure 5: Localized mean oceanic DRI for years 1958 - 2018, at 1 x 1 degree resolution

Determining DPL_{river}: DIC Precipitation Likelihood in riverine transport to the ocean shall be computed using the aqueous chemistry data provided by the GLORICH or USGS database of monitored river chemistry data. An aqueous speciation calculation will evaluate the saturation indices of calcium carbonate phases. Programs such as the USGS-developed PHREEQC (14) or similar shall be used. Data points that show saturation indices > 1.0 will be flagged and counted. The DPL_{river} will be reported as the percentage of flagged SI>1 data points normalized by the total number of data points evaluated using PHREEQC. Figure 6 shows an example calculation.

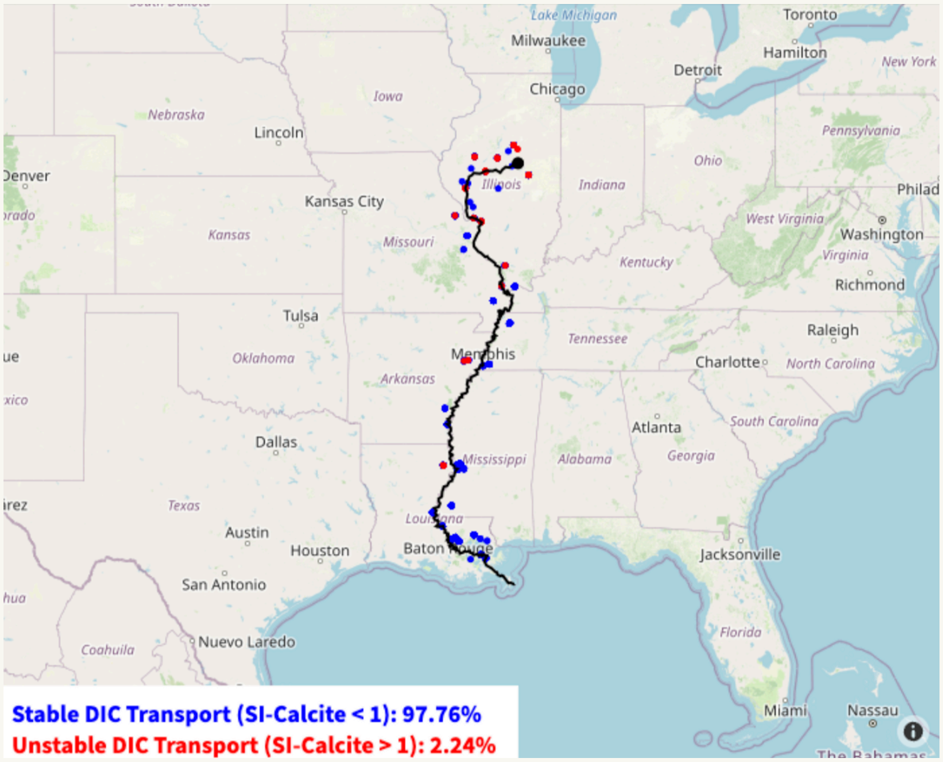

Figure 6: Stable riverine transport of DIC and determination of calcium carbonate precipitation leading to captured CO$_2$ reversal. This example calculation was evaluated from Illinois to the Gulf of Mexico along the Mississippi River.

9 Monitoring

9.1 Data and Parameters Available at Validation

9.1.1 Project Emissions

Parameter	$EF_{grid,Q}$
Unit	tCO_2e/MWh
Description	Emissions factor of the electricity used to power the quarry
Equations	Equation 3
Source of Data	Option 1: Country specific grid emission factors published by a government agency (for US: https://www.epa.gov/egrid/summary-data) or by UNFCC based on IFI methodology (https://unfccc.int/documents/198197) or from Carbon Footprint (https://www.carbonfootprint.com/) or similar tools. Option 2: UNFCCC data (CDM);
Value applied	See source of data
Additional Comments	Not applicable if option 1 or 2 for determining PE_Q is selected.

Parameter	$EF_{fuel,i,Q}$
Unit	tCO_2e/unit of fuel
Description	Emissions factor of the fossil fuel of type *i* used by the equipment in the quarry
Equations	Equation 3
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data

Additional Comments	Not applicable if option 1 or 2 for determining PE_Q is selected.

Parameter	$EF_{i,j}$ (quarry to mill)
Unit	tCO_2e/unit of fuel
Description	Emissions factor of each type of fossil fuel (e.g. gasoline or diesel) required to transport materials across transport leg *j* (quarry to mill)
Equations	Equation 5
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	Not applicable if option 2 for determining $PE_{TQ2M,j}$ is selected.

Parameter	$EF_{tonne\text{-}km,j}$ (quarry to mill)
Unit	tCO_2e/tonne-km
Description	Transport emissions factor of conveyance used for transport leg *j* (from quarry to mill)
Equations	Equation 6
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	Not applicable if option 1 for determining $PE_{TQ2M,j}$ is selected.

Parameter	$EF_{grid,M}$
Unit	tCO$_2$e/MWh
Description	Emissions factor of the electricity used to power the mill
Equations	Equation 7
Source of Data	Option 1: Country specific grid emission factors published by a government agency (for US: https://www.epa.gov/egrid/summary-data) or by UNFCC based on IFI methodology (https://unfccc.int/documents/198197) or from Carbon Footprint (https://www.carbonfootprint.com/) or similar tools. Option 2: UNFCCC data (CDM);
Value applied	See source of data
Additional Comments	Not applicable if option 1 or 2 for determining PE_M is selected.

Parameter	$EF_{fuel,i,M}$
Unit	tCO$_2$e/unit of fuel
Description	Emissions factor of the fossil fuel of type *i* used by the mill
Equations	Equation 7
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	Not applicable if option 1 or 2 for determining PE_M is selected.

Parameter	$EF_{i,j}$ (mill to field)
Unit	tCO$_2$e/unit of fuel

Description	Emissions factor of each type of fossil fuel (e.g. gasoline or diesel) required to transport materials across transport leg *j* (mill to field)
Equations	Analogous to Equation 5
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	Not applicable if option 2 for determining $PE_{TM2F,j}$ is selected.

Parameter	$EF_{tonne\text{-}km,j}$ (mill to field)
Unit	tCO_2e/tonne-km
Description	Transport emissions factor of conveyance used for transport leg *j* (mill to field)
Equations	Analogous to Equation 6
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	Not applicable if option 1 for determining $PE_{TM2F,j}$ is selected.

Parameter	EF_i
Unit	tCO_2e/L
Description	Emissions factor of the fossil fuel *i* used for field application

Equations	Equation 9
Source of Data	Emission factor published by a government agency, such as EPA (https://www.epa.gov/climateleadership/ghg-emission-factors-hub) or DEFRA (https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting).
Value applied	See source of data
Additional Comments	N/A

9.1.2 Carbon Dioxide Removal

Parameter	CCE
Unit	unitless
Description	Calcium Carbonate Equivalent
Equations	Equation 11 and 13
Source of Data	Project Proponent/laboratory results
Value applied	See source of data
Additional Comments	Calcium Carbonate Equivalent of the silicate material shall be calculated according to equation 13 (option 1) or alternatively, it can be directly measured using a modified method for determining neutralizing value for liming material that ensures full dissolution of the silicate material (option 2).

Parameter	MgO% and CaO%
Unit	Mass fraction in %
Description	Mass fraction of magnesium and calcium oxide in the mineral
Equations	Equation 15, 16, and 19
Source of Data	Project proponent/laboratory results

Value applied	See source of data
Additional Comments	N/A

Parameter	DRI_{water}
Unit	unitless
Description	DIC retention index in fresh and marine waters, where dissolved cations and inorganic carbonates added from EW are present
Equations	Equation 34
Source of Data	Project proponent
Value applied	See source of data
Additional Comments	DRI shall be computed using the marine carbonate system calculations developed by NOAA.

Parameter	DPL_{river}
Unit	unitless
Description	DIC precipitation likelihood in riverine transport towards the ocean. Calcium carbonate phases are evaluated for saturation indices > 1.0 to indicate river chemistry data points that are likely candidates for carbonate precipitation and subsequent de-gassing / reversal of CO_2 captured.
Equations	Equation 34
Source of Data	Project proponent
Value applied	See source of data
Additional Comments	DPL_{river} shall be computed using the aqueous chemistry data provided by the GLORICH or USGS database of monitored river chemistry data. An aqueous speciation calculation using programs such as the USGS-developed PHREEQC executable will evaluate the saturation indices of calcium carbonate phases. Data points that show saturation indices > 1.0 will be flagged and counted. The DPL_{river} will be reported as the percentage of

	flagged SI>1 data points normalized by the total number of data points evaluated using PHREEQC.

9.2 Data and Parameters Monitored

9.2.1 Project Emissions

Parameter	f_Q
Unit	unitless
Description	Fraction of quarry activities involved in project
Equations	Equation 2
Source of Data	Project proponent
Additional Comments	N/A

Parameter	PE_Q
Unit	tCO_2e
Description	Total quarry emissions from the extraction of minerals, including primary crushing activities
Equations	Equation 2
Source of Data	Zero (option 1) or value according to LCA provided by project proponent (option 2)
Additional Comments	Not applicable if option 3 for determining PE_Q 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 LCA 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 2).

Parameter	$V_{grid,Q}$

Unit	MWh
Description	Quantity of electricity from the grid used by the quarry per metric ton
Equations	Equation 3
Source of Data	Electricity usage records (option 1) or output of bottom-up engineering model (option 2)
Additional Comments	Not applicable if option 1 or 2 for determining PE_Q is selected. 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	$V_{fuel,i,Q}$
Unit	Dependent on fuel type (liters, MMBTU, etc.)
Description	Quantity of fossil fuel of type *i* used by the quarry per metric ton
Equations	Equation 3
Source of Data	Fuel receipts or utility gas bills (option 1) or output of bottom-up engineering model (option 2)
Additional Comments	Not applicable if option 1 or 2 for determining PE_Q is selected. 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, fuel requirements may be estimated 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 it is assumed the

	equipment is running for the entire shift, which does not include equipment downtime and/or worker breaks.

Parameter	$V_{i,j}$ (quarry to mill)
Unit	Dependent on fuel type (liters, MMBTU, etc.)
Description	Quantity of fossil fuel of type *i* used in leg *j* per metric ton (quarry to mill)
Equations	Equation 5
Source of Data	Project proponent
Additional Comments	Not applicable if option 2 for determining $PE_{TQ2M,j}$ is selected. 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, the amount of electricity used for each leg from the onboard system is logged. In lieu of receipts or logs, fuel usage in miles-per-gallon or miles-per-kwh and the total miles for each vehicle's leg can be estimated.

Parameter	D_j (quarry to mill)
Unit	km
Description	Distance of transport leg *j* (quarry to mill)
Equations	Equation 6
Source of Data	Project proponent
Additional Comments	Not applicable if option 1 for determining $PE_{TQ2M,j}$ is selected. Distance of transport leg *j* as calculated by GPS tracking of vehicle (option 1) or using appropriate app, such as Google Directions API, Bing Maps Directions API or Marine Traffic API (option 2). 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	PE_M
Unit	$tCO_2e/tOre$
Description	Total mill emissions
Equations	Equation 2
Source of Data	Zero (option 1) or value according to LCA provided by project proponent (option 2)
Additional Comments	Not applicable if option 3 for determining PE_M is selected. Total mill emissions are zero if, for example, the material does not need to be pulverized (option 1). Alternatively, a LCA may be available for the mill as a whole, or each product coming from the mill, which assigns a summary emission factor for the feedstock ($tCO_2e/tOre$) (option 2).

Parameter	$V_{grid,M}$
Unit	MWh
Description	Quantity of electricity from the grid used by the mill per metric ton
Equations	Equation 7
Source of Data	Electricity usage records (option 1) or output of bottom-up engineering model (option 2)
Additional Comments	Not applicable if option 1 or 2 for determining PE_M is selected. 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	$V_{fuel,i,M}$

Unit	Dependent on fuel type (liters, MMBTU, etc.)
Description	Quantity of fossil fuel of type *i* used by the mill per metric ton
Equations	Equation 7
Source of Data	Fuel receipts or utility gas bills (option 1) or output of bottom-up engineering model (option 2)
Additional Comments	Not applicable if option 1 or 2 for determining PE_M is selected. 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, fuel requirements may be estimated 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 it is assumed the equipment is running for the entire shift, which does not include equipment downtime and/or worker breaks.

Parameter	$V_{i,j,}$ *(mill to field)*
Unit	Dependent on fuel type (liters, MMBTU, etc.)
Description	Quantity of fossil fuel of type *i* used in leg *j* per metric ton (mill to field)
Equations	Analogous to Equation 5
Source of Data	Project proponent
Additional Comments	Not applicable if option 2 for determining $PE_{TM2F,j}$ is selected. 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, the amount of electricity used for each leg from the onboard system is logged. In lieu of receipts or logs, fuel usage in miles-per-gallon or miles-per-kwh and the total miles for each vehicle's leg can be estimated.

Parameter	D_j (mill to field)

Unit	km
Description	Distance of transport leg *j* (mill to field)
Equations	Analogous to Equation 6
Source of Data	Project proponent
Additional Comments	Not applicable if option 1 for determining $PE_{TM2F,j}$ is selected. Distance of transport leg *j* as calculated by GPS tracking of vehicle (option 1) or using appropriate app, such as Google Directions API, Bing Maps Directions API or Marine Traffic API (option 2). 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	*FPT*
Unit	L/h
Description	Fuel usage per unit time for field application
Equations	Equation 9
Source of Data	Project proponent
Additional Comments	FPT can be determined by conventional engineering calculations or retrieved from an officially designated OECD tractor test laboratories, namely the Nebraska Tractor Test Laboratory, or from the Association of Equipment Manufacturers. If available, an actual fuel survey is preferred, which shall be a direct measurement of the fuel consumption using e.g. a fuel flow meter.

Parameter	*APT*
Unit	ha/h
Description	Area applied per unit time
Equations	Equation 9

Source of Data	Project proponent
Additional Comments	APT can be determined by conventional engineering calculations, else an as-applied map can be used.

Parameter	*TA*
Unit	ha
Description	Total area applied
Equations	Equation 9
Source of Data	Project proponent
Additional Comments	TA can be retrieved from as-applied maps or computed based on field boundary coordinates.

9.2.2 Carbon Dioxide Removal

Parameter	*A*
Unit	ha
Description	Area of mineral application
Equations	Equation 10, 21, and 23
Source of Data	Project proponent
Additional Comments	The area of mineral application shall be determined by field boundaries, i.e. geometric borders of the field.

Parameter	*AR*
Unit	kg/m^2
Description	Application rate
Equations	Equation 10, 19, and 23
Source of Data	Project proponent

Additional Comments	The application rate *AR* shall be determined by a rate prescription using a standard lime requirement calculation adjusted by the Calcium Carbonate Equivalent *(CCE)* of the silicate material.

Parameter	*tOre*
Unit	tOre
Description	Total metric tons of mineral applied over area *A*
Equations	Equation 10 and 16
Source of Data	Project proponent
Additional Comments	N/A

Parameter	*d*
Unit	m
Description	Soil depth
Equations	Equation 19 and 21
Source of Data	Project proponent
Additional Comments	N/A

Parameter	ρ
Unit	g/cm^3
Description	Bulk density
Equations	Equation 19 and 21
Source of Data	Project proponent
Additional Comments	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.

Parameter	Z
Unit	ppm
Description	Immobile trace element
Equations	Equation 20 and 22
Source of Data	Project proponent/laboratory results
Additional Comments	Identity of immobile trace elements must be reported.

Parameter	$Mg\%$ and $Ca\%$
Unit	g Mg/g soil and g Ca/g soil
Description	Mg and Ca content of the soil
Equations	Equation 25
Source of Data	Project proponent/laboratory results
Additional Comments	N/A

Parameter	$DivAlk_{uptake}$
Unit	eq/g
Description	Divalent alkalinity losses from plant uptake
Equations	Equation 27, 28, 29, and 30
Source of Data	Project proponent
Additional Comments	N/A

Parameter	$DivAlk_{other}$
Unit	unitless
Description	Fraction of divalent alkalinity charge-balanced with non-DIC cations
Equations	Equation 27 and 33
Source of Data	Project proponent
Additional Comments	N/A

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