

**Eion Corp Whitepaper**

**Life Cycle Analysis and  
Full Carbon Accounting of  
Enhanced Rock Weathering**

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# Abstract

Enhanced rock weathering offers a promising pathway for scalable carbon dioxide removal while simultaneously improving soil health and agricultural productivity. This study presents a Life Cycle Assessment of Eion Corp's CarbonLock™ a carbon-negative alternative to agricultural lime (aglime) for soil amendment. Using one tonne Calcite Carbonate Equivalents (tCCE) as the functional unit, the analysis compares CarbonLock™ to aglime across extraction, transport, processing, application, and sequestration stages. Results demonstrate CarbonLock™'s significant carbon removal potential, achieving a net Carbon Dioxide Removal of -952 kgCO<sub>2</sub>/tCCE in a commercial supply chain scenario, sequestering over ten times more CO<sub>2</sub> than it emits. Sensitivity analyses confirm resilience to increased transport distances, maintaining strong carbon negativity (-867 kgCO<sub>2</sub>/tCCE). By contrast, aglime is often a net carbon emitter, even with minimal transport. These findings highlight CarbonLock™ as a scalable and resilient Carbon Capture, Utilization, and Storage solution capable of replacing aglime and removing millions of tons of CO<sub>2</sub> from the atmosphere annually.

# Executive summary

The objective of this document is to develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for the extraction, processing, transport, and application of Eion Corp's CarbonLock™ to agricultural fields as a replacement for the carbon-emitting soil amendment agricultural lime (aglime). The United States currently uses an estimated 27 million metric tons of aglime each year to manage the pH of agricultural fields [1]. Both aglime and CarbonLock™ effectively moderate soil acidity. However, once applied to the field the natural weathering of CarbonLock™ removes carbon dioxide (CO<sub>2</sub>) from the atmosphere and sequesters it at geological timescales whereas aglime can emit CO<sub>2</sub>. Thus, CarbonLock™ is a Carbon Capture Utilization and Sequestration (CCUS) technology that removes CO<sub>2</sub> through a process known as enhanced rock weathering (ERW). CarbonLock™ is a silicate product that can be composed of naturally occurring minerals or industrial byproducts and in principle could be a soil amendment applied to any acidic farmland, including croplands, pastures, and managed forests. In this study, we focus on CarbonLock™ composed of high cation-content silicate rock that is engineered to directly replace aglime for managing acidic soils in the Midwestern United States with the additional benefit of sequestering CO<sub>2</sub>. This LCA is required by the U.S. Internal Revenue Service to satisfy the requirements of 26 CFR Part 1, Section 1.45Q-4. This LCA report has been prepared in accordance with ISO 14040/14044 requirements and with the NETL CO<sub>2</sub>U LCA Guidance Document as modified by the 45Q addendum.

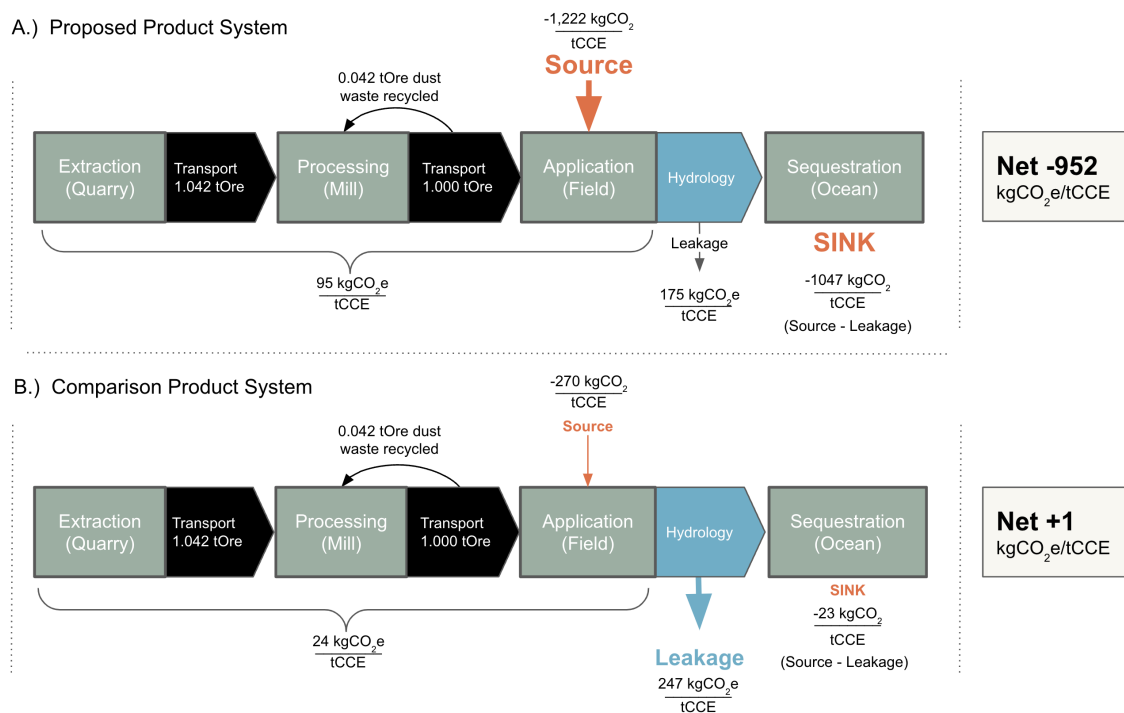
CarbonLock™ is carbon negative because the chemical dissolution of silicate rocks balances the positive charge of released cations that are released by retaining negatively charged bicarbonate anions in solution. The bicarbonate chemical compound originates as CO<sub>2</sub> that is present in the ambient air. The dissolved inorganic carbon (DIC) associated with CarbonLock™ is "locked" in solution to maintain charge balance with the reaction products of the dissolved silicate mineral. The bicarbonate is utilized in commercial agriculture as a buffer that brings the soil solution to a pH that reduces aluminum toxicity and increases the availability of essential nutrients. The captured DIC in solution is subsequently sequestered as it passes below the root zone and the cations are no longer subject to removal by crops. The DIC-enriched solution passes into groundwater and river systems, until it ultimately reaches the ocean, where the carbon is stored on the order of hundreds of thousands of years. Aglime follows a similar process but is made of carbonate rocks that contain "ancient" carbon. These minerals meet the charge balance of cation released partly by their own bicarbonate that is released as these carbonates weather. Some of this dissolved carbon is also released to the atmosphere, which together render makes aglime a slight emitter. Thus, CarbonLock™ is an effective form of CCUS because it captures carbon from the atmosphere, utilizes this transformed carbon to condition soil acidity, and sequesters this carbon in terrestrial waters and the ultimately the ocean.

Silicate minerals can be extracted, processed into CarbonLock™, applied to acidic soils, and help meet emissions goals particularly in the food and agriculture sector. Nevertheless, the emissions associated with the extraction, processing, transport, and application of CarbonLock™ must be considered to rigorously quantify the net carbon dioxide removal (CDR) from this CCUS approach. Silicates are not widely used as an aglime substitute in part because of their greater mineral hardness, which requires greater energy to engineer a product with comparable weathering rates as aglime. In addition, silicates may not be in proximity to fields that are currently amended with

aglime. Additionally, there are some well-known loss pathways of DIC that has been captured, particularly as freshwater mixes into alkaline ocean waters. The key components of this LCA are intended to address these core phenomena in estimating the net CDR relative to a carbonate aglime baseline.

In this LCA we analyzed the cradle-to-grave global warming potential (GWP as  $\text{kgCO}_2\text{e}$ ) of CarbonLock™ as a replacement for aglime). We used one tonne Calcium Carbonate Equivalents (tCCE) as the functional unit. Calcium Carbonate Equivalent (CCE) is a common metric in the aglime industry for assessing the neutralizing value of a liming material compared to pure calcium carbonate ( $\text{CaCO}_3$ ). A CCE of 100% indicates that a material will neutralize the same amount of acidity per unit mass as pure calcium carbonate. Using tCCE as the functional unit allows for a direct comparison between our Proposed Product System (CarbonLock™) and the Comparison Product System (aglime). The system boundaries included five process stages: extraction, transport, processing, application, and sequestration. The system boundary and process stages for CarbonLock™ are the same as aglime, which enables a direct comparison between the different products, as shown in the simplified system boundary in Fig.1. In our life cycle impact assessment (LCIA), we analyzed five scenarios. Scenarios 1 and 2 examined the life cycle emissions of CarbonLock™ under different transport modes and processing locations. Scenarios 3 and 4 examined chemically pure calcite and dolomite, the primary minerals in aglime, and scenario 5 used the chemical composition of commercially available aglime from a local quarry. We omit in this report patent-pending information related to the specific formulation of CarbonLock™ and some proprietary aspects of the monitoring and verification of its capture and sequestration.

The results of this LCA show that CarbonLock™ is very effective at removing carbon from the atmosphere and is highly resilient to variations in the supply chain impacting its net carbon negativity. In Scenario 2, which closely represents a commercial supply chain for CarbonLock™, CarbonLock™ sequesters  $-1047 \text{ kgCO}_2/\text{tCCE}$  and only emits  $95 \text{ kgCO}_2/\text{tCCE}$ , for a net CDR of  $-952 \text{ kgCO}_2/\text{tCCE}$ . In other words, CarbonLock™ removes more than ten times as much  $\text{CO}_2$  as it emits. In Scenario 2, transporting CarbonLock™ comprises 88% of its life cycle emissions. Even after doubling the transportation distances in our sensitivity analysis, CarbonLock™ in Scenario 2 still had a net CDR of  $-867 \text{ kgCO}_2/\text{tCCE}$ . Our analysis highlights that CarbonLock™ could be transported from virtually any continent by ship and then trucked inland over a thousand kilometers and still be carbon negative. Carbonate based aglime, on the other hand, is oftentimes a slight carbon emitter, even when transported from a quarry only a few kilometers away. Thus, this LCA shows that CarbonLock™ is an effective carbon negative replacement for aglime and is a resilient means of CCUS that can remove millions of tons of  $\text{CO}_2$  from the atmosphere each year.



**Fig. 1.** The system boundaries and process stages of the Proposed Product System and the Comparison Product System. The primary differences between the Proposed Product System of CarbonLock™ and the Comparison Product System of aglime are that the chemical weathering of aglime removes less CO<sub>2</sub> from the atmosphere, the source, and it releases more CO<sub>2</sub> through leakage. The figure shows the mass transfer, emissions, and net CDR for Scenarios 2 and 3.

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# 1. Introduction

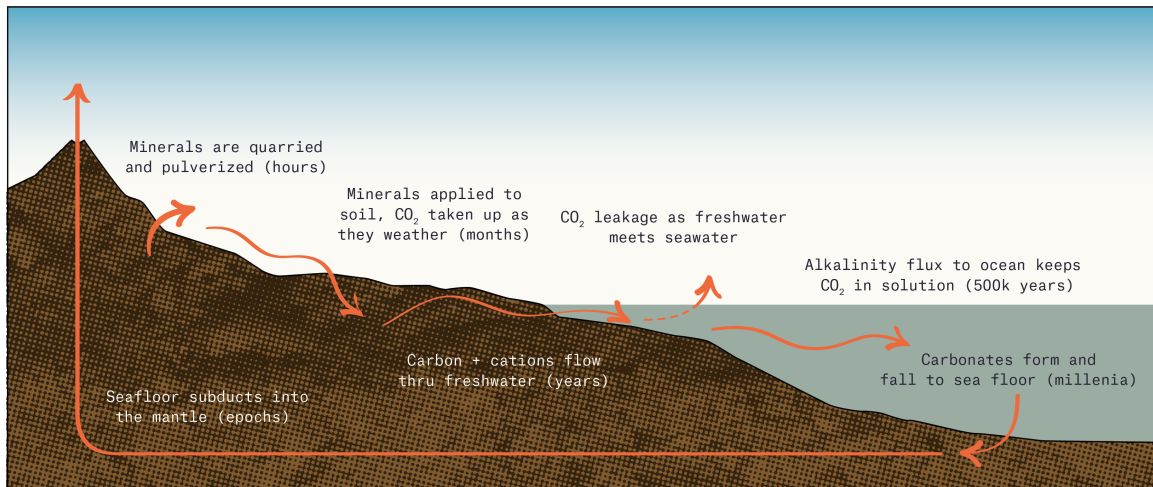
## 1.1 Project Background

The long-term strategy of the United States to reach net zero carbon emissions includes a significant volume of carbon dioxide (CO<sub>2</sub>) removal, both through enhancing the land sink, as well as the development of technological solutions that remove carbon dioxide from the ambient air [13]. There are a variety of Carbon Capture Utilization and Sequestration (CCUS) technologies that have been proposed to meet this carbon dioxide removal (CDR) requirement, which reaches approximately 1 Gt of CO<sub>2</sub> per year in 2050 [14]. Naturally, reaching this scale is an immense societal undertaking, with significant costs for research and development, infrastructure, and opportunity costs of competing approaches. As a consequence, there is considerable discussion around the relative merits of different CCUS approaches along a number of dimensions, including permanence, verifiability, additionality, leakage, life cycle emissions, social and environmental co-benefits, capital equipment requirements, competition for land area, current cost and anticipated learning curve. In short, CCUS technologies need to store CO<sub>2</sub> safely for thousands of years in a verifiable manner while also avoiding excess supply chain emissions and competing with existing land use [15].

Eion Corp is a vertically integrated company that originates and verifies CDR using the CCUS approach of enhanced rock weathering (ERW) on farmland (Fig. 2). Rock weathering is a foundational Earth system process that constitutes a natural control system for atmospheric CO<sub>2</sub>: When CO<sub>2</sub> increases, the rock weathering process accelerates to remove CO<sub>2</sub> through reactions on land and transport it to the ocean. Conversely, when atmospheric CO<sub>2</sub> decreases, the process slows and CO<sub>2</sub> accumulates [16]. Ordinarily, these processes take place over thousands to millions of years, not unlike hydrocarbon accumulation. Just as accumulated fossil carbon was rapidly deployed to address society's energy needs, enhanced rock weathering (ERW) can be leveraged to address our current carbon predicament, by increasing the rate of the carbon removal reactions, which are thermodynamically favored but slow. This approach is not strictly a nature-based solution as it is conventionally understood, because the minerals must be engineered to function properly as a CDR mechanism, nor is it strictly a technological solution, because the underlying chemistry is not fundamentally different from that which takes place in natural systems. Eion Corp was founded as a first-in-category company to implement ERW as a scalable solution for CDR within a broad portfolio of carbon management options to address the challenge of global climate change.

Eion Corp's proprietary ERW technology, CarbonLock™, is specially formulated to rapidly sequester CO<sub>2</sub> when applied to agricultural fields while simultaneously improving soils and crop yields in a manner analogous to aglime. CarbonLock™ technology also allows for rigorous verification that origin-preserved minerals have been applied, carbon removal reactions have taken place, and sequestration has occurred. The purpose of this report is to assess the life cycle emissions of Eion Corp's CarbonLock™ technology (the Proposed Product System) in comparison to the current standard practice of applying agricultural lime (aglime) to moderate soil acidity (the Comparison Product System). Our analysis demonstrates that aglime is at best a slight carbon emitter while the sequestered carbon from CarbonLock™ greatly exceeds that of its cradle-to-grave life cycle emissions. Therefore, CarbonLock™ is a suitable CCUS technology that qualifies to participate in the

U.S. Treasury's 45Q carbon credits program.



**Fig. 2.** Enhanced Rock Weathering is a geological process that typically takes thousands of years. With Eion Corp's processes and technology, ERW can be accelerated to remove carbon dioxide from the atmosphere and safely sequester it on an annual basis.

## 1.2 Life Cycle Assessment

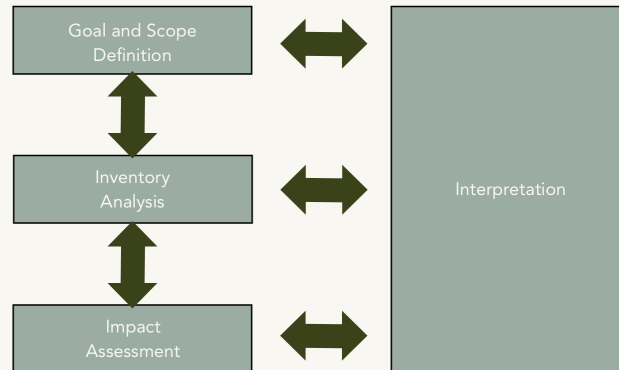
Life Cycle Assessment is an objective analysis used to evaluate environmental impacts of a product that is manufactured and/or consumed. The assessment takes stock of the entire life cycle of a product from inception to disposal (cradle-to-grave) and how the various processes impact a variety of environmental systems, such as pollution and resource depletion. The assessment includes four phases (Fig. 3):

1. Define the goal and scope of the study
2. Provide a complete inventory analysis
3. Conduct the impact assessment
4. Interpret the results, typically including a sensitivity analysis

A Life Cycle Assessment provides detailed insights to evaluate environmental performance across the manufacturing process, inform decision-makers, and identify key indicators for measuring environmental impacts. This project relies on the DOE's National Energy Technology Laboratory's (NETL) guidance documents for completing an LCA for the 45Q tax credit program [17] and [18]. The NETL's guidance applies the Life Cycle Assessment standards and requirements established by the International Organization for Standardization (ISO) specifically to carbon capture utilization and sequestration (CCUS) projects. The key references are listed here:

- ISO 14040:2006 Environmental management. Life cycle assessment. Principles and framework. [19]
- ISO 14044:2006(E) Environmental management. Life cycle assessment. Requirements and guidelines. [20]

- T. J. Skone et al., “Carbon Dioxide Utilization Life Cycle Analysis Guidance for the U.S. DOE Office of Fossil Energy,” National Energy Technology Laboratory, Pittsburgh, March 22, 2019. [18]
- M. Jamieson, M. Krynock, S. Moni, M. Mutchek, T. Skone, ”NETL 45Q Addendum to the CO2U LCA Guidance Toolkit,” National Energy Technology Laboratory, Pittsburgh, November 9, 2021. [17]



**Fig. 3.** The ISO 14040 LCA Framework includes defining the goal and scope, conducting an inventory analysis, impact assessment, and iteratively interpreting the results.

### 1.3 Historical Context

The role that silicate rocks play in Earth’s carbon cycle has been a foundational understanding since work by Harold Urey in 1952 [21]. Harold Urey won the Nobel Prize in 1934 for the discovery of deuterium, made significant contributions to the development of atomic weapons, and in his later career made key insights into the origins of life on Earth and its biogeochemical cycles. Wally Broecker [16] developed this understanding of the rock cycle as a kind of thermostat for the Earth—as CO<sub>2</sub> builds up in the atmosphere and warms the climate, the weathering rate is faster, bringing down the level of atmospheric CO<sub>2</sub>. As CO<sub>2</sub> levels decline, the process slows, letting CO<sub>2</sub> build up again (largely from volcanism). Over the 4.5 billion year history of the Earth, silicate weathering has played a fundamental role in keeping our planet “habitable”.

In the 1990’s Fraser Goff and Klaus Lackner of the Los Alamos National Lab identified the potential for certain types of silicate rocks to play a role in removing CO<sub>2</sub> from the atmosphere as a means to manage the emissions from fossil fuels [22]. Goff, a geologist, led an effort to identify the resources in the United States that could be deployed towards this goal [23]. Lackner, in turn, lobbied the Department of Energy to fund an effort led by the Albany Research Lab in Oregon (formerly a Bureau of Mines lab) to work through the process studies essential to establish the feasibility of such an effort [24, 25]. Although the DOE support for this program ended in 2005, it was a key catalyst to a significant amount of research around the world to explore the potential of mineral-based carbon removal [26], which has helped to earn recognition as a key Negative

Emissions Technology by the National Academy of Sciences [14].

In the last decade, a group of British and U.S. scientists, based at the University of Sheffield and the University of Illinois respectively, have explored the potential for Enhanced Rock Weathering (ERW) to be a solution leveraged in agriculture, which was a sharp turn from the initial work above focused on CO<sub>2</sub> injection into ore bodies, and carbonation of mine tailings. Certainly, the use of high calcium and magnesium silicates, particularly industrial byproducts, had been recognized as fulfilling a function analogous to aglime in agriculture [27], and aglime itself had been identified as a carbon emitter [1], but the potential for deploying silicates in agricultural settings as a carbon solution had not been quantified and in fact remained outside of key decarbonization pathway analyses [13, 28, 29].

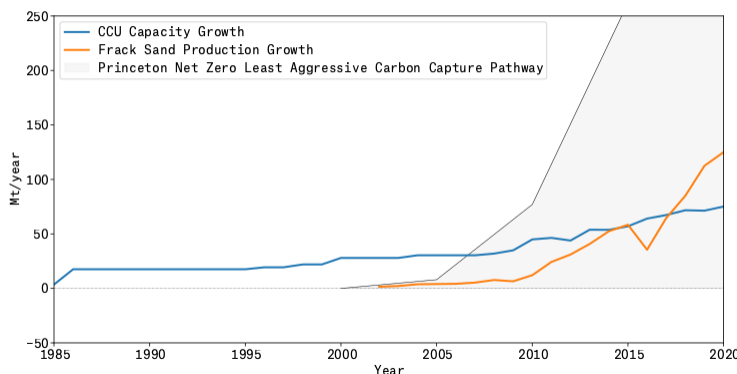
The first efforts on land-applied ERW focused on critical techno-economic factors including energy demands in processing and transportation, and of course the cost of deployment [30]. Subsequent work [6, 31–38] examined the potential role and scale that ERW could play in the “hard to decarbonize” sectors such as agriculture and transportation, while also refining the understanding of the chemistry and agronomy involved. Specifically, scientists identified acidic soils, with high crop productivity and rainfall, to be the ideal locales for deployment of ERW [6].

Agricultural soils are an ideal environment for ERW because all direct air capture techniques are challenged by the fact that CO<sub>2</sub>, while a potent greenhouse gas, is actually quite dilute in the ambient air, just 0.04%. By contrast, soils supporting intense plant growth can have CO<sub>2</sub> concentrations that are 10x to 100x higher. This is because plants and microbes are producing an abundance of CO<sub>2</sub> as respiration, which only diffuses out of the soil relatively slowly. Relevant to the positioning we are advancing in this document, the preamble of the Final Regulations for 45Q stipulates that respiration is commonly understood to be a natural constituent of ambient air. The high concentration of CO<sub>2</sub> dissolves into the soil pore water where it becomes carbonic acid, the source of acidity that Urey first identified as weathering the silicate rocks. Agricultural lands are also acidic owing to plant uptake (plants produce acidity in order to take up key nutrients), and from fertilizer itself (e.g., urea). Of course some soils, chiefly older weathered soils in the southeast, are naturally quite acidic and unbuffered.

Agriculture is a natural fit for ERW as well, because there are clear agronomic benefits to the application of fresh silicate minerals to soils. The weathering of the fresh silicate produces alkalinity that raises the pH of soils, which reduces aluminum toxicity and increases the bioavailability of essential nutrients. Recently, researchers at the University of Illinois also found evidence that ERW can also reduce N<sub>2</sub>O emissions through a combination of increased nitrogen use efficiency and reduced N<sub>2</sub>O reductase activity by soil microbes (itself driven by increased pH) [33]. Perhaps most importantly to farmers, these same trials showed that applications of silicate minerals in conventional corn/soy rotations have resulted in yield improvements of 11-16% ([35]).

As a benchmark of the speed and scale that ERW can and must be deployed, consider the development of sand used in hydraulic fracking, relative to the rate of development of CCUS technology deployed in the fossil energy industry [39] (Fig. 4). In approximately half the span of time, twice the capacity for fracking sand production came online, compared to CCUS technology for injecting CO<sub>2</sub> into saline aquifers and depleted fossil energy reservoirs. The extraction of fracking sand is a

good analogy for the pace that ERW can be scaled to capture CO<sub>2</sub>. Quarrying and transporting ore is an activity society undertakes today cost effectively at scale, with technology, infrastructure, and human capital already in place. Nonetheless, it is sobering to consider the rapid growth of the fracking sand industry against the cadence of carbon dioxide removal that will be required to actually meet net zero emissions by 2050 [29]. Under even the least aggressive scenarios, in which electrification and renewable energy are rapidly deployed, the required pace of CDR dwarfs the rapid growth of of fracking sand production. Our interpretation is that the straightforward technological pathway of ERW, combined with the large deployment area of 900M acres of farmland in the United States, is an approach that appears to be one of the only viable pathways to meet our net-zero objectives.



**Fig. 4.** U.S. Carbon Capture and Storage and U.S. Fracking Sand Production Growth compared to the modeled pathway for the development of CCUS technology required to meet emission goals.

## 1.4 Geochemistry

Atmospheric carbon dioxide is naturally removed from the atmosphere when CO<sub>2</sub> dissolved in rain water interacts with exposed silicate rocks. The mild acidity of the water dissolves the mineral, which brings its reaction products into solution. Among these reaction products are calcium and magnesium, which raise the charge, and the alkalinity, of the water solution. This charge is balanced by the dissolved CO<sub>2</sub>, which effectively keeps this dissolved inorganic carbon in solution in the rainwater runoff. The water with its raised alkalinity carries the stored CO<sub>2</sub> through the terrestrial waterways and groundwater and eventually to the ocean [40]. In the ocean, this carbon is retained for thousands to hundreds of thousands of years as it participates in the oceanic carbonate and silicate cycles [41, 42]. Natural weathering is a thermodynamically favorable process that is nonetheless very slow, limited by the mildness of rainwater’s acidity and the slow rate of exposure of fresh mineral surfaces. This process can be accelerated by increasing the surface area of the minerals, increasing the acidity, raising the temperature, and removing the reaction products [5].

Looking more closely at the chemistry of ERW: When CO<sub>2</sub> dissolves in water it forms carbonic acid (H<sub>2</sub>CO<sub>3</sub>), which then dissociates into H<sup>+</sup> and HCO<sub>3</sub><sup>-</sup>, thus increasing the acidity of the water. Soils with high-yielding crops respire CO<sub>2</sub> directly into the root zone which greatly increases CO<sub>2</sub> concentration in the root zone. The atmospheric carbon, now dissolved in water in the form of an



$\text{HCO}_3^-$  ion (bicarbonate) is abundant at the pH present in acidic soils (pH~5-6). At higher pH, such as in the ocean (pH~8), it dissociates again into  $\text{H}^+$  and  $\text{CO}_3^{2-}$ . Together,  $\text{H}_2\text{CO}_3$ ,  $\text{HCO}_3^-$ , and  $\text{HCO}_3^{2-}$  are called dissolved inorganic carbon (DIC).

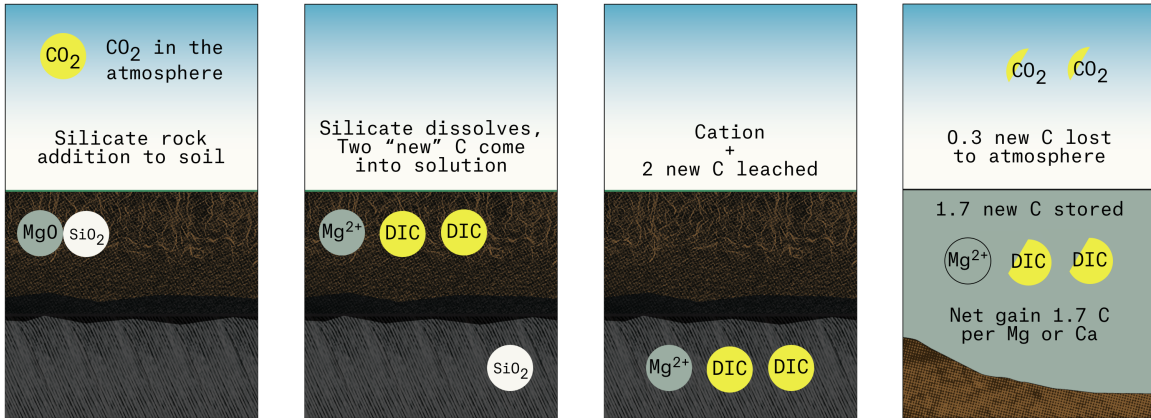
In the absence of other ions (pure water), the concentration of DIC is determined by the ambient levels of  $\text{CO}_2$  in the air surrounding the solution. Increased concentrations of  $\text{CO}_2$  increases all species of DIC. If this water were to be exposed to lower  $\text{CO}_2$  concentrations, the DIC would return back to a lower level. With silicate weathering however, the acidity from carbonic acid is consumed, which releases conserved cations such as magnesium and calcium. These cations introduce a conserved positive charge that is balanced by the negative charge of  $\text{HCO}_3^-$ . So long as these cations remain in solution, the DIC is effectively "locked" in solution, even if the water is brought into equilibrium with a lower ambient  $\text{CO}_2$  concentration. This phenomenon is important, because the root zone has very high concentrations of  $\text{CO}_2$ , but the water passes through the root zone into groundwater and eventually rivers and streams the surrounding  $\text{CO}_2$  concentrations return to ambient levels. The presence of dissolved cations prevents the escape of  $\text{CO}_2$  from solution and is a key to achieving permanent sequestration.

Many aspects of the source mineral affect its performance as a carbon removal technology, including chemistry (how much calcium and magnesium) and mineralogy (the crystal structure and its resistance to weathering). In general the chemistry determines the total amount of carbon that may be removed, and the mineralogy shapes the rate at which it may be removed. An important principle going back to Goff and Lackner [22] is that the mineral potential of a particular rock (tonnes of  $\text{CO}_2$  removed per tonne of rock) is defined by its magnesium (Mg) and calcium (Ca) composition. For each atom of Mg or Ca, two carbon atoms (in the form of  $\text{HCO}_3^-$ ) are captured.

If the ultimate sink of carbon is in the ocean, it may not be immediately apparent why to conduct ERW on land, least of all to distribute materials across a wide swath of agricultural land. The pH dependence of mineral dissolution is important, as well that soil water is high in DIC. At levels of acidity found in the ocean (pH~8), mineral dissolution is exceptionally slow. In agricultural soils by contrast, moderate acidity (pH~5-6) drives mineral dissolution orders of magnitude more quickly. If the mineral were to be carbonated in situ (e.g., a tailings pile), then the reaction products would accumulate and bring the solution into the alkaline range (pH > 7), effectively self-limiting the reaction, and moreover the process would be limited by the small amount of  $\text{CO}_2$  that was able to diffuse into the tailings pile. Finally, the utility of adding alkalinity to agricultural soils has a well understood utility that has an economic value.

Although the carbon capture in farmlands is at a pH in which  $\text{HCO}_3^-$  predominates (>99.99%), the fate of the solution is in the ocean where the higher pH shows a greater abundance of  $\text{CO}_3^{2-}$  (~10%). This is relevant, because in terrestrial water systems, one Ca or Mg is matched by two carbon atoms, whereas in the ocean, some small proportion are balanced by just one carbon atom, again under the principle of charge balance. This process could be considered as a type of leakage, induced by pH changes as freshwater meets the oceans in estuaries. The carbonate system is well enough studied (e.g., [12]) that this leakage may be estimated using known mathematical expressions with well-studied coefficients for the carbonate system. The key result in this analysis is that the net carbon dioxide removal can be computed from the mineral potential of the feedstock and an estimate of the pH-driven losses in estuaries en route to the ocean. See Appendix A for further

details.



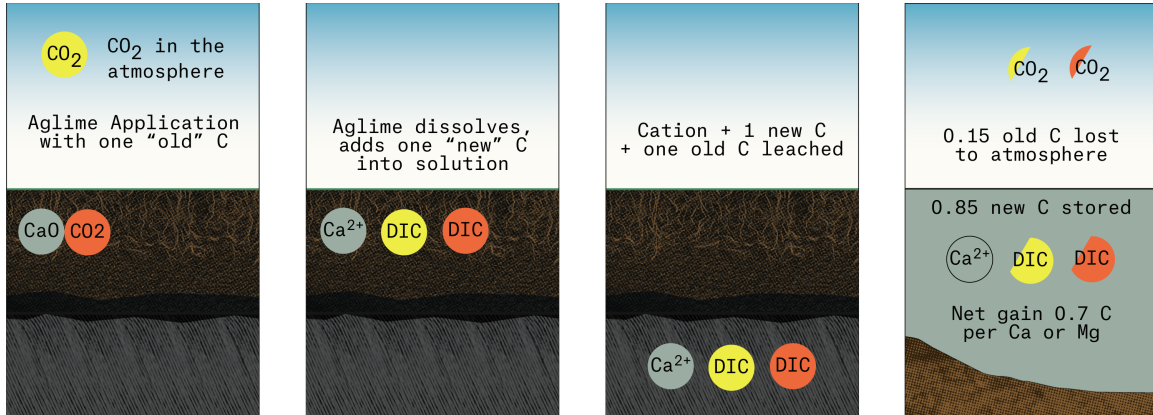
**Fig. 5.** Silicate weathering where atmospheric  $\text{CO}_2$  is dissolved in acidic water along with silicate rock and sequestered in the terrestrial water systems and eventually the ocean for hundreds of thousands of years.

Silicate rocks are not the only minerals that undergo weathering. Carbonate rocks also dissolve in acidic conditions, which is why they are used commonly as soil conditioners (e.g., aglime). Consider the chemical formula of a silicate rock, such as  $\text{Mg}_2\text{SiO}_4$  or  $\text{CaSiO}_3$ . Compare this with carbonates such as calcite (limestone) ( $\text{CaCO}_3$ ) or dolomite ( $\text{CaCO}_3 \cdot \text{MgCO}_3$ ), the common minerals in aglime. Both categories have calcium oxide ( $\text{CaO}$ ) and magnesium oxide ( $\text{MgO}$ ). But silicates have a silicon dioxide ( $\text{SiO}_2$ ) in place of a carbon dioxide ( $\text{CO}_2$ ). Because our goal is both to stop adding new  $\text{CO}_2$  to the atmosphere, and to remove existing  $\text{CO}_2$  from the atmosphere, this distinction is important.

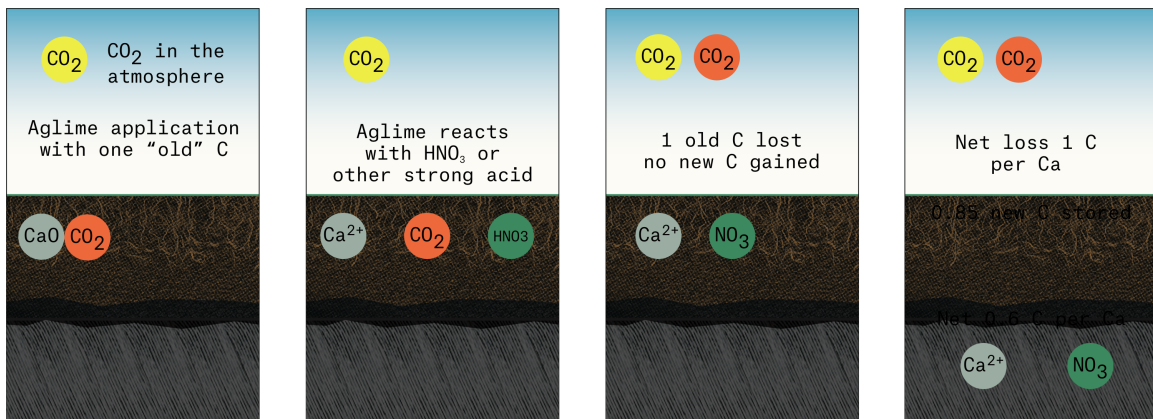
Looking more closely at how carbonate weathering works, we see that the calcite ( $\text{CaCO}_3$ ) comes with one  $\text{CO}_2$  already, so only one new  $\text{CO}_2$  dissolves into solution, which is half as effective as a silicate in its mineral potential. Once these two DIC ions reach the ocean, 85% is retained like with silicate, but some of the loss to the atmosphere is “old” carbon from the  $\text{CaCO}_3$ . Together, the net gain is only 1/3rd of silicate.

In agricultural settings though, the situation is slightly worse for carbonates like limestone. Fertilizer applications and natural biotic activity produce nitric acid ( $\text{HNO}_3$ ), which is very strongly acidic. It is this strong acid that dissolves the limestone, which results in the immediate loss of “old” carbon directly to the atmosphere, meaning the limestone is a source of  $\text{CO}_2$ .

For many years, IPCC guidelines on greenhouse gas inventories [43] assumed that all carbon in agricultural lime (calcite and dolomite) applications was immediately lost to the atmosphere. Careful analyses by researchers at DOE and Michigan State University [1, 44] concluded that only 40-50% of the limestone weathered in the strong acid reaction, resulting in a chemical balance that was near zero. Combined with the process emissions in extraction and transportation, the consensus remains that aglime is a slight  $\text{CO}_2$  emitter.



**Fig. 6.** Limestone weathering under ideal conditions results in only a net sequestration of 0.7 kg new C/kg old C from  $\text{CaCO}_3$ .

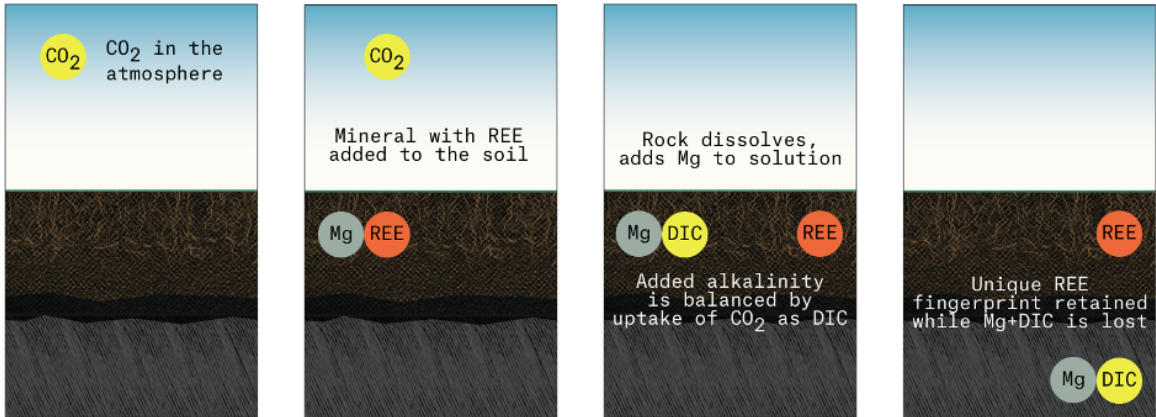


**Fig. 7.** Limestone weathering in the presence of strong acid results in a net emission of 1 kg new C/kg old C from  $\text{CaCO}_3$ . Experimental studies indicate emissions of 0.5 kg new C/kg old C from  $\text{CaCO}_3$  under real world conditions.

## 1.5 Monitoring and Verification

We have shown that ERW removes  $\text{CO}_2$  permanently and irreversibly, and that CarbonLock™, a silicate-based product, is a substantial  $\text{CO}_2$  sink that is able to replace carbon-emitting carbonate-based agricultural lime. ERW is also distinct from efforts to increase carbon storage in soil organic pools (SOC) and live timber [14], which for all their merits are both temporary and reversible as a national carbon management solution. SOC in particular also suffers from a lack of tools for monitoring and verification. ERW by contrast can be traced from the source to the sink, much like any physical supply chain, but the chemistry of ERW also allows for proof of origin, as well as proof of application and proof of performance.

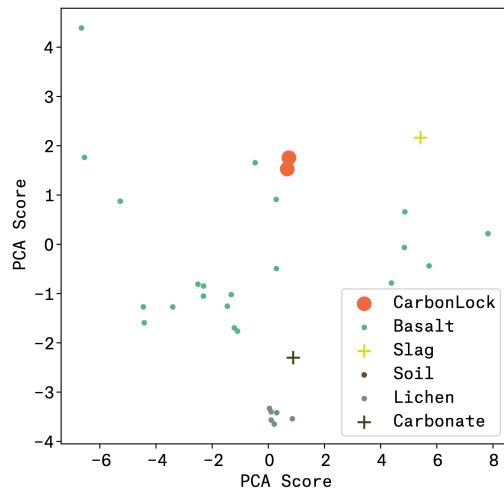
Silicate rocks themselves have an elemental signature that can readily distinguish many different ore bodies (see Fig.9). This means both that the proof of authenticity can be established, preventing the injection of unknown materials into the supply chain, but also that the mineral potential can be



**Fig. 8.** As mineral is added to the soil trace amounts of rare earth elements are left behind creating a unique fingerprint that allows for easy verification and monitoring of the sequestered CO<sub>2</sub>.

traced back to the original material. Next, consider that the rocks are not pure. They have trace elements present that in part provide the fingerprint. Certain trace elements, known as immobile trace elements (ITEs), have high valence charge which makes them adhere strongly to soil mineral and organic matter exchange surfaces. An example of a class of ITEs that can be exploited for enhanced rock weathering monitoring include rare earth elements (REEs) that are trivalent (3+) and immobile in the reactive top soil [45]. While cations (Mg<sup>2+</sup> and Ca<sup>2+</sup>) and HCO<sub>3</sub><sup>-</sup> pass below the root zone, ITEs remain in the topsoil, providing proof of which material was applied, and how much of it was truly measured from soil-based artifacts [46]. Proof of application is an important checkpoint in verifying that the carbon may be captured from a field, but it is not sufficient to demonstrate that carbon was sequestered from the field.

Pre-application and post-application soil samples of ITEs and cations (Mg<sup>2+</sup> and Ca<sup>2+</sup>) can establish that the carbon removal potential was met by the reaction and removal HCO<sub>3</sub><sup>-</sup> alongside the cations. This phenomenon has strong theoretical and empirical proof under carefully controlled conditions. It is in essence the same way that we measure CO<sub>2</sub> emissions in transportation. We do not actually have CO<sub>2</sub> sensors in the tailpipes of vehicles (such work is not only expensive but requires a high level of expertise to conduct). Instead, it is sufficient only to know how much fuel was put into the tank. Although it is possible to imagine loss pathways other than combustion (volatilization, leaking, siphoning), a first approximation of a vehicle's CO<sub>2</sub> budget can be



**Fig. 9.** Rare earth elements can be used to create mineral fingerprints to allow CarbonLock™ to be traced from source to sink.

computed from totaling its fuel use at the pump. The approach outlined here expands on this by having rigorous controls on the exact composition of the fuel itself (the silicate), as well as a chemical record of the cumulative amount of fuel used (the ITE retained in the soil), and finally a complete inspectable supply chain from the source material and its transportation to the field. In total, it is a level of auditable carbon removal unmatched anywhere in the industry.

## 1.6 Previous LCA studies

Life-cycle analysis (LCA) is a tool used to detail the environmental impacts of a product from initial conception to production to distribution, and finally disposal of the product as waste that degrades through time. The analysis provides a detailed approach to understanding the environmental impacts of each component that might be missed by simply looking at production and distribution impacts, such as the types of machinery used, with explicit energy consumption and associated CO<sub>2</sub> emissions. Such analyses have been conducted for the aggregates industry [47, 48], chiefly focusing on their energy demand and emissions profile. The latter work relies on well-established engineering formulae to estimate the size and number of equipment used, and fuel and electricity needed to power such equipment [49]. The present work expands that consideration by contextualizing silicate weathering within the ecosystem of carbon dioxide removal and soil amendment technologies. Carbon dioxide removal (CDR) technologies have an ever-growing body of LCA literature for each technology, especially as the technology becomes more mainstream [50, 51].

While natural rock weathering is a known process, engineering methods to accelerate this process for enhanced carbon sequestration are still developing. One of the initial LCA analyses estimated a potential net CO<sub>2</sub> reduction of approximately 858 tCO<sub>2</sub> per day [52]; however, this study did not focus solely on CO<sub>2</sub> sequestration through ERW but rather discussed the potential under certain environmental conditions and chemical reactions. Additionally, several studies have explored the techno-economic aspects and possible scale of ERW ([6, 8, 30, 34]) without adhering to the ISO LCA framework.

The most relevant LCA study assesses carbon dioxide removal (CDR) potential and emissions from ERW in the Midwest (Chicago and Duluth), with net carbon removal ranging from 128 to 1055 kg CO<sub>2</sub>e/t mineral depending on the CDR yield (0.2–1.1 t CO<sub>2</sub>/t mineral) [34]. Transportation emissions, primarily from barge and truck routes, constitute the bulk of embodied GHGs, underscoring the importance of local operations to decrease carbon footprint. These results show that ERW’s environmental impact is on par with other CDR methods such as biochar and direct air capture, heavily influenced by CDR yields and transportation logistics. Another LCA from Sao Paulo, Brazil, provides baseline data for various stages impacting total CO<sub>2</sub> emissions [53], identifying transportation as the main detractor from sequestration efficiency. This analysis also recorded that 0.110 kg CO<sub>2</sub> is emitted for each kg of CO<sub>2</sub> removed, equating to a net removal of 890 t CO<sub>2</sub> per tonne of mineral. Future research could expand on these frameworks to include additional regions, more efficient energy sources, and improved transportation methods. These areas indicate opportunities for enhancement through Life-cycle Optimization (LCO) and Life-cycle Sustainabil-

ity Analysis (LCSA) in ERW [54]. LCO uses mathematical models to maximize LCA results within constraints [55], while LCSA considers the environmental, economic, and social dimensions [56]. As ERW evolves as a carbon management strategy to achieve net zero targets, these analytical tools will become critical in evaluating the feasibility of achieving negative CO<sub>2</sub> emissions.

Previous studies have typically integrated their modeling and data into standard LCA frameworks. For example, Lefebvre et al. [53] used the SimaPro 8.3 software, drawing on databases like EcoInvent 3 and USLCI to perform the Life Cycle Inventory and Assessment. Their main modification to the typical LCA approach was the adjustment of CO<sub>2</sub> emission factors to yield accurate measurements across different stages of the LCA.

While tools like SimaPro are commonly used, alternative LCA software like openLCA also offers extensive capabilities for integrating various databases and conducting detailed environmental impact analyses. These software solutions provide robust platforms for standard LCA but might lack flexibility in certain specific applications.

In our project, we have chosen to primarily use spreadsheet modeling due to its flexibility and potential for customization. This approach allows us to integrate our own collected data and case-specific details more seamlessly. By using spreadsheets, we can tailor the analysis to our particular needs and update it readily as new data becomes available, providing a comprehensive and customizable overview of the LCA for our study.

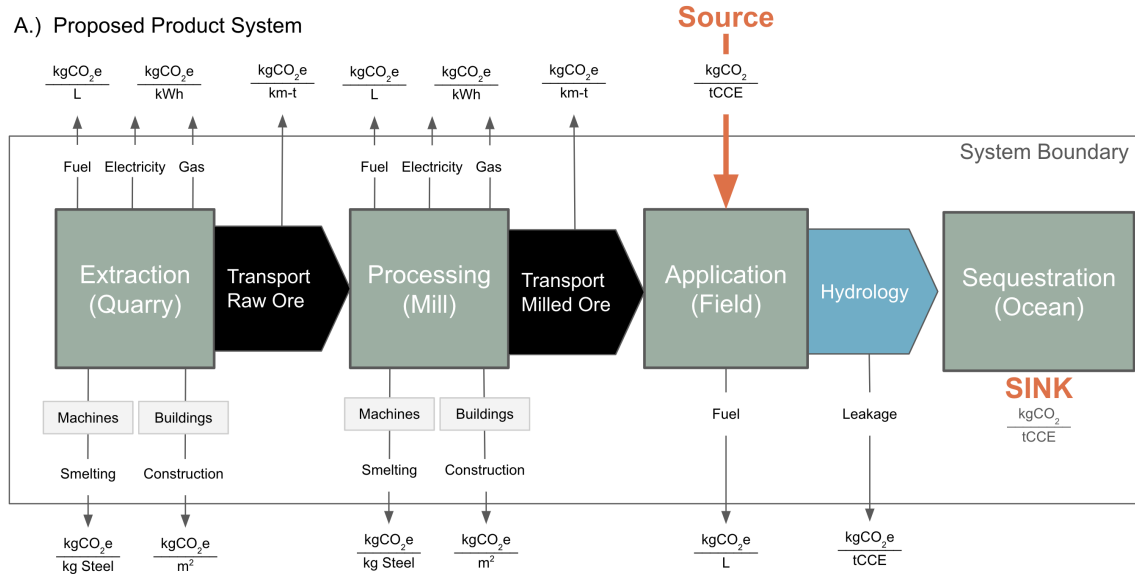
## **2. Goal and Scope**

### **2.1 Study Goal**

The goal of this life cycle assessment of CarbonLock™ is to demonstrate that the carbon dioxide removed and sequestered by CarbonLock™ exceeds that of the cradle-to-grave life cycle emissions of creating CarbonLock™, and to provide a comparison to the current industry standard for managing the pH of agricultural soils using carbonate minerals. The reason for carrying out this study is to determine the amount of qualified carbon oxide utilized by Eion Corp through the ERW of CarbonLock™ under paragraph (2)(B)(ii) or (4)(B)(ii) of subsection (a) of 26 CFR Part 1, Section 1.45Q-4. The intended audience for this report are the U.S. Internal Revenue Service (IRS) and Department of Energy (DOE). We believe CarbonLock™ is an excellent fit for the 45Q program because it captures CO<sub>2</sub> directly from the ambient air, sequesters the CO<sub>2</sub> for hundreds of thousands of years; the sequestration of the CO<sub>2</sub> can be measured and verified from source to sink, and CarbonLock™ fully displaces a product that is currently a carbon emitter. Eion Corp does not plan to make this report public at this time.

## 2.2 Scope

The purpose of this section of the report is to define what was modeled, what the data quality/representative goals are, what the basis of comparison is in terms of the functional unit, and how the results are to be compared. This section also defines the level of completeness required to make a comparison between the Proposed Product System and Comparison Product System.



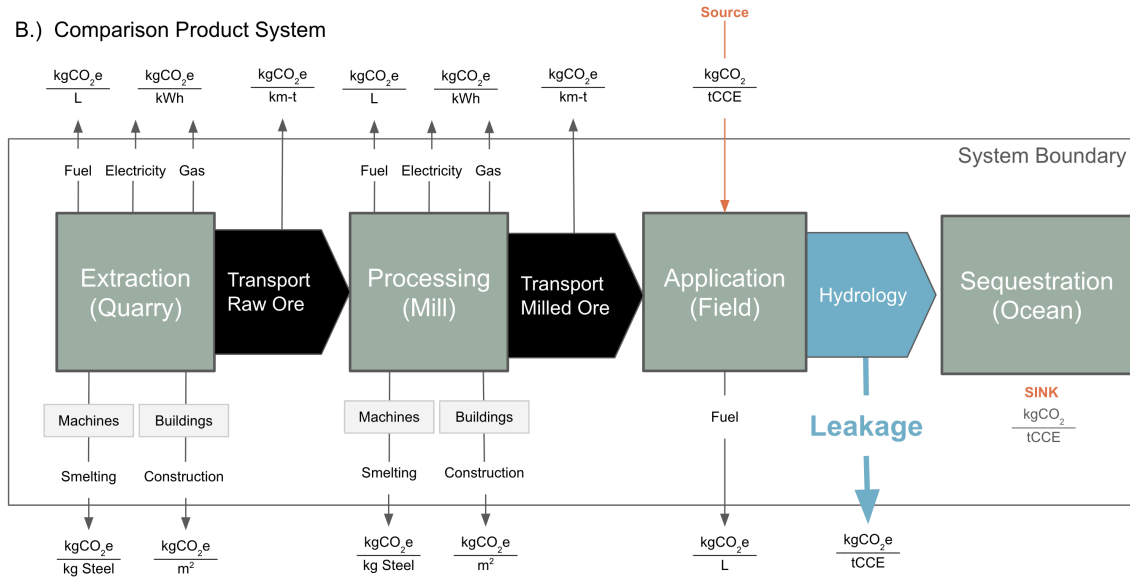
**Fig. 10.** The system boundaries and process stages of the Proposed Product System. The system boundaries include: extraction, transport, processing, application, and sequestration.

### 2.2.1 Functional Unit

The functional unit for this study is one tonne of Calcium Carbonate Equivalents (tCCE). Calcium Carbonate Equivalent (CCE) is a common metric in the aglime industry for determining the neutralizing value of a liming material compared to pure calcium carbonate  $\text{CaCO}_3$ . A CCE of 100% indicates that a material will neutralize the same amount of acidity per unit mass as pure calcium carbonate. The Proposed Product System (CarbonLock™) and the Comparison Product System (aglime) both have the functionality of neutralizing soil acidity and as a result we are able to compare both systems based on their ability to neutralize one tonne of pure calcium carbonate (tCCE).

In our LCA model we analyzed the life cycle emissions per tCCE from three different aglime feedstocks in comparison to CarbonLock™. In Scenario 3, we analyzed was calcite, which is pure calcium carbonate  $\text{CaCO}_3$  and as a result one tonne of calcite is equal to one tCCE. Limestone is primarily made of calcite and is mined and crushed to form aglime. Real world limestone quarries, however, contain impurities that impact the overall CCE of the aglime product with different quarries producing aglime with vary levels of purity and CCE. To address this variability, in the Scenario 5 U.S. Aglime we used the chemical composition of aglime from an active aglime mine in Joslin,

Illinois that had a CCE of 0.936 tCCE. Thus, it takes 1.06 tonnes Joslin Aglime to have the same neutralizing potential of one tonne of pure calcium carbonate. Other minerals such as magnesium oxide (MgO) and calcium oxide (CaO) have a CCE greater than one. To account for this we also model dolomite in Scenario 4, a common alternative to limestone in making aglime that has high concentrations of magnesium oxide (MgO) in addition to calcium oxide (CaO). As a result, it takes slightly less dolomite to achieve the same changes in soil pH as pure calcite. Thus, the tonnes Calcium Carbonate Equivalents (tCCE) of dolomite is slightly lower than calcite (specifically, 0.923 tonnes of dolomite is equal to the neutralizing potential of 1 tonne of calcite). CarbonLock™, the Proposed Product System in this study analyzed in Scenarios 1 and 2, is made of dunite ore, which is a silicate rock comprised of high levels of MgO and low levels of CaO. Dunite ore is very effective at managing soil pH but requires slightly more ore, 1.13 tonnes dunite, to achieve the same neutralizing equivalents as a tonne of calcite. Thus, our functional unit of one tonne Calcium Carbonate Equivalents allows us to directly compare the carbon emissions and sequestration potential of the Proposed Product System (CarbonLock™) to the Comparison Product System (aglime).



**Fig. 11.** The system boundaries and process stages of the Comparison Product System. The primary differences between the Proposed Product System of CarbonLock™ and the Comparison Product System of aglime is that the chemical weathering of aglime removes less CO<sub>2</sub> from the Source and it releases more CO<sub>2</sub> through leakage.

## 2.2.2 System Boundary

This Life Cycle Inventory and Assessment is composed of five independent systems that connect together. Fig. 10 provides a detailed view of the system boundaries and process stages. First, in the extraction stage, the raw material is extracted from a surface quarry. Then the raw material is transported to a mill for processing. The mode of transport and distance can vary considerably depending on the location of the quarry and the mill, which we explore in our LCIA scenarios. Once



processed at the mill, the material (CarbonLock™ or aglime) is transported to the agricultural field where it is spread on the soil. The agricultural crops on the field pull carbon from the atmosphere and release it into the root zone creating a CO<sub>2</sub> rich environment, which is the Source of CO<sub>2</sub> in our Carbon Capture Utilization and Sequestration (CCUS) process. To this point our Proposed Product System is the same as our Comparison Product System; they only differ significantly in the amount of carbon removed from the Source and the amount of leakage that occurs downstream from the field, as shown in the difference between Fig. 10 and Fig. 11. In this LCA we calculate the capital and process emissions from the extraction and process stages, the process emissions from the transportation and application stages, and the leakage emissions from the hydrological transport of CO<sub>2</sub> to the sink. Thus, our LCA spans the full cradle-to-grave life cycle of CarbonLock™.

### 2.2.3 Process Stages

1. **Extraction:** Ore is mined from the quarry.
2. **Transport:** Ore is moved from quarry to mill and from the mill to the field.
3. **Processing:** Ore is ground and formulated at the mill.
4. **Application:** Processed ore is spread on the agricultural fields.
5. **Sequestration:** Dissolved CO<sub>2</sub> is sequestered in terrestrial and oceanic water systems at geological timescales with some loss due to leakage.

## 2.3 Carbon Oxide Source and Utilization

In our Proposed Product System, the Source of CO<sub>2</sub> is the ambient atmosphere, including CO<sub>2</sub> from animal (microbial) respiration originating in the soil. The concentrations of CO<sub>2</sub> in the root zone are much higher than the atmosphere and thus increase soil acidity and dissolved inorganic carbon (DIC) in the water that percolates through the soil. When CarbonLock™ is applied to soils, the minerals in CarbonLock™ also dissolve in the acidic water and the ionic association between the dissolved CarbonLock™ minerals and CO<sub>2</sub> ensure that the CO<sub>2</sub> is "locked" into solution. Natural hydrology then sequesters the carbon rich solution in terrestrial waterway systems and eventually ocean, the sink, where it is sequestered on geological time scales. Some leakage does occur in the hydrological transport of the DIC to the ocean as the pH and ionic concentrations change. We account for this leakage in our model and provide in-depth discussions of the geochemistry in Section 1.4 and in Appendix A. Based on these models and empirical research the CO<sub>2</sub> is considered sequestered once it moves beyond the top 10 cm of soil in the agricultural field.

## 2.4 Technology Representativeness

The life cycle inventory and assessment developed is based on current and emerging technologies. One of the main advantages of CarbonLock™ is that it can sequester carbon using well-established technologies and processes in the surface mining and agricultural lime industries. The extraction, processing, transportation, and application all use technologies that are used today, are well known

by experts, and well described in the LCA literature. To characterize the technology used in extraction and processing, we used the software program SHERPA, which is widely and actively used in the mining industry [57, 58]. With the SHERPA software we modeled the mining and milling of a quarry and mill able to process 1.35 million tons per year, which matches the active silicate quarry in Norway. For aglime we used the mineral properties from an active quarry in Illinois, USA that is located near Eion Corp's field site. After extracting the values from SHERPA, we had our quarry and mill models reviewed by mining experts Kevin Stansbury and Mark Erickson at Samuel Engineering who agreed they were reasonable. The emission factors from transportation, the stage that makes up 88% of the emissions in our CarbonLock™ scenarios, is well documented in the LCA literature [11]. The application of soil-buffering amendments, such as CarbonLock™ and aglime, is also a standard practice that is well-documented in the literature and Eion Corp has firsthand experience at our field site in Illinois. The primary difference in the Proposed Product System of CarbonLock™ and the Comparison Product System of aglime is in the weathering chemistry of the two products. We extensively discuss the chemistry in Section 1.4 and Appendix A. Eion Corp is actively running field studies to verify the geochemistry of CarbonLock™, and the geochemistry of aglime is well described by careful research by the DOE and Michigan State University [1, 44]. Eion Corp's innovation comes from the particular milling specifications for creating CarbonLock™, supply chain management, and the verification process, none of which require new or carbon-intensive technologies.

## **2.5 Geographic Representativeness**

The geographical boundary for this study is global. Specifically, the ore for CarbonLock™ is mined from the largest active olivine quarry in the world located in Norway. The ore is then shipped to the port in New Orleans, Louisiana, which is a major U.S. industrial and agricultural port. From New Orleans the ore is moved by inland ship or train to Peoria, Illinois, and finally to our field site approximately 50 km away. The supply chain of CarbonLock™, shown in Fig. 14, represents a very realistic supply chain for our product. In our model scenarios we explore the impact of locating the mill in Norway or in New Orleans, both of which are reasonable potential sites for the mill as confirmed by our industry experts. The CO<sub>2</sub> Source in our Proposed Product System is the CO<sub>2</sub> rich root zone ambient air at our field site in Illinois, USA. In the Comparison Product System, aglime is sourced from local quarries in Illinois, USA. Fig. 15 shows that there are numerous potential aglime quarries within 130 km of our field site, providing a realistic and conservative transport distance from the quarry/mill to the field site. In this study, we use the regional power grid emission factors depending on the location of the quarry and mill.

## **2.6 Temporal Representativeness**

Aglime is commonly applied to agricultural fields in one to three year rotations depending on the acidity and productivity of the soil, with roughly 60% weathered by year 1 and greater than 80% weathered by year 3 as shown in Fig. 19 in Section 3.3.3. If appropriate for the field, applications of soil amendment can be added without requiring 100% of the pH modifier to be reacted, and in many

cases overlapping applications will produce the optimal outcome for both weathering rates and soil pH. In formulating CarbonLock™ we target similar weathering rates. As discussed in more detail in Section 3.3.3, the rate that CarbonLock™ weathers is highly dependent on the size of the particle, with smaller particle sizes weathering faster but requiring more energy to produce. We chose the final particle size of the rocks to be 90 microns, which is small enough to have similar weathering rates compared to aglime with relatively low energy requirements. The weathering rate of CarbonLock™ will be monitored using the ITE fingerprinting discussed in Section 1.5, thus allowing for the application rate to be tailored to a specific field. Using the ITE fingerprint monitoring, Eion Corp will be able to count carbon credits based on the specific amount of carbon weathered from the field. In our LCIA model we model the full sequestration potential of CarbonLock™ but the specific rate of that will be dependent on the specific field and soil environment. Once CarbonLock™ and the absorbed atmospheric carbon moves beyond the top 10 cm of soil, it is sequestered in the terrestrial waterways and groundwater and eventually (from years to hundreds of years) it reaches the ocean where it resides for hundreds of thousands of years. Leakage in the carbonate system is well studied and can be modeled using known mathematical expressions and chemical coefficients and those models can be applied to the silicate system [12]. Additional discussion on the weathering chemistry is found in Section 1.4 and Appendix A. The energy and emissions from the quarry and mill equipment and buildings are levelized across the life of quarry or mill and the total ore produced or milled.

## **2.7 Life Cycle Impact Assessment Methods for Results Interpretation**

The goal and scope of this LCA is to assess the ability of CarbonLock™ to remove CO<sub>2</sub> from the atmosphere in excess of its life cycle emissions and to compare its net emissions to the current industry standard of aglime (limestone or dolomite). As a result, the impact category we consider in our LCIA is global warming potential (GWP100 kgCO<sub>2</sub>e) Table A-1 of 40 CFR Part 98 subpart A [59] and the IPCC GWP equivalents (AR5 version of IPCC GWP) [60]. Because we are only considering one impact category (GWP), we do not conduct a normalization step.

## **2.8 Completeness Requirements**

To meet the completeness requirements for this study we document the energy and mass inputs and outputs to Proposed Product System and the Comparison Product System. Fig. 12 shows the unit processes modeled in our system. The primary value chain includes the direct inputs required to produce a tonne of ore, which are primarily diesel fuel, electricity from the power grid, and gas for heating to run the equipment and facilities in the extraction, transport, processing, and application stages. During the application phase the amount of ore applied to the field is adjusted to produce the desired tonnes Calcium Carbonate Equivalents (tCCE), thus allowing direct comparison between all of the modeled scenarios. The final stages of hydrology and sequestration rely on natural systems and do not require additional energy inputs. In Fig. 12 under hydrology we list the mineral sequestration and leakage primary processes and leave off the sequestration box to save space for the figure. The secondary unit processes include the emission factors for transporting and processing

the fuel or electricity. The tertiary unit processes include the energy and emissions required to forge the steel for the capital equipment or to construct the buildings. In the case of the extraction and milling processes we model the amount of capital equipment needed using the SHERPA models as part of our model. For diesel fuel, however, the capital emissions are included in literature emission factors. We also decided to only model the diesel fuel consumption for applying the ore during the application phase and excluded any secondary or tertiary capital or equipment energy or emissions for the field site. CarbonLock™ or aglime both require standard farming equipment to apply, are part of normal farm activity, and when co-products are accounted for are expected to be even smaller than the capital emissions from the quarry or mill. Fig. 35 show the table results from our completeness analysis. When we calculate the percent of total emissions from each stage we find that the capital and equipment emissions are less than 1% of each scenario, except that the mill capital emissions under the aglime scenarios are 1.6%. To be conservative we include the capital emissions from the processing and mill stages for all scenarios.

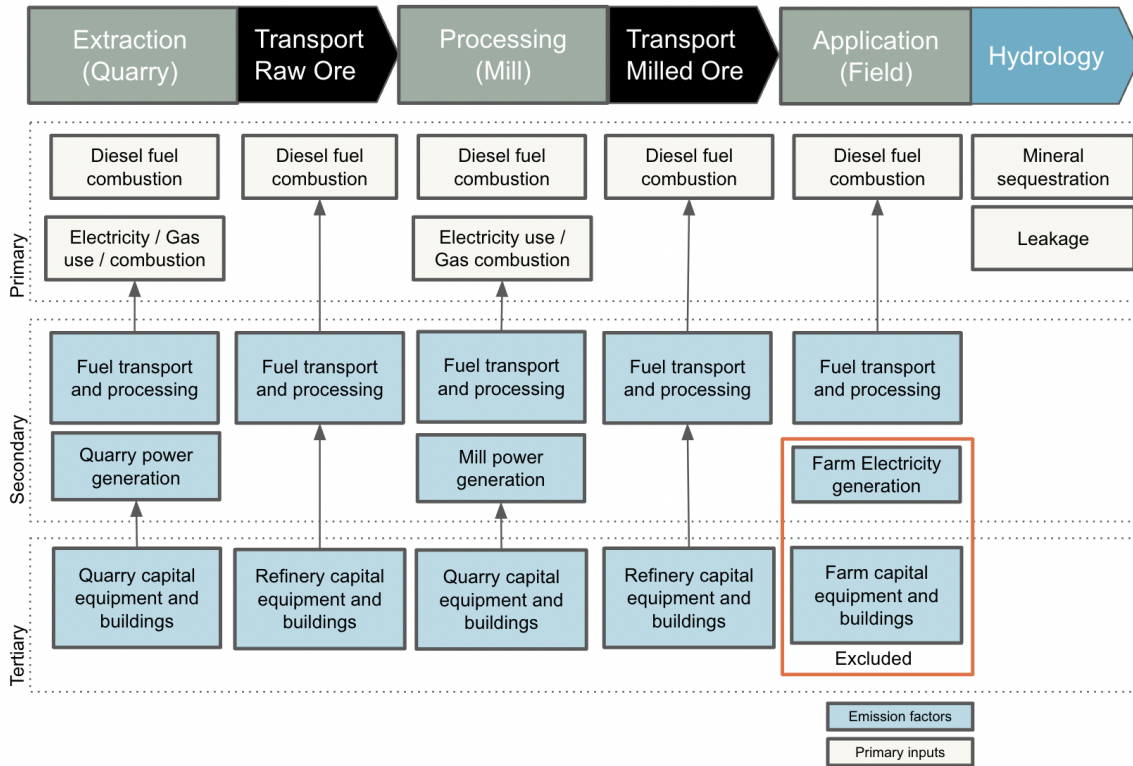
In Fig. 13 we show the mass flow of CarbonLock™ and atmospheric CO<sub>2</sub>. The Proposed Product System and Comparison Product System have the same mass efficiency upstream from the Application stage. Based on the SHERPA models and industry expert feedback we expect a 4% loss of ore during the milling process. The lost ore is captured as mill bag dust and recycled back into the mill. The primary differences between the mass flow of the Proposed Product System and the Comparison Product System is in the absorption of atmospheric CO<sub>2</sub> during the application stage and the leakage during the hydrology stage. Fig. 13 shows that CarbonLock™ captures more CO<sub>2</sub> at the field site and that there is less CO<sub>2</sub> leakage than aglime.

## **2.9 Sensitivity analysis**

A sensitivity analysis has been conducted to address how changes in inputs and methodological choices impact the main results. The LCA interpretation of each case study also includes a sensitivity analysis to estimate how changes in data and methodological assumptions will impact the results.

## **2.10 System expansion**

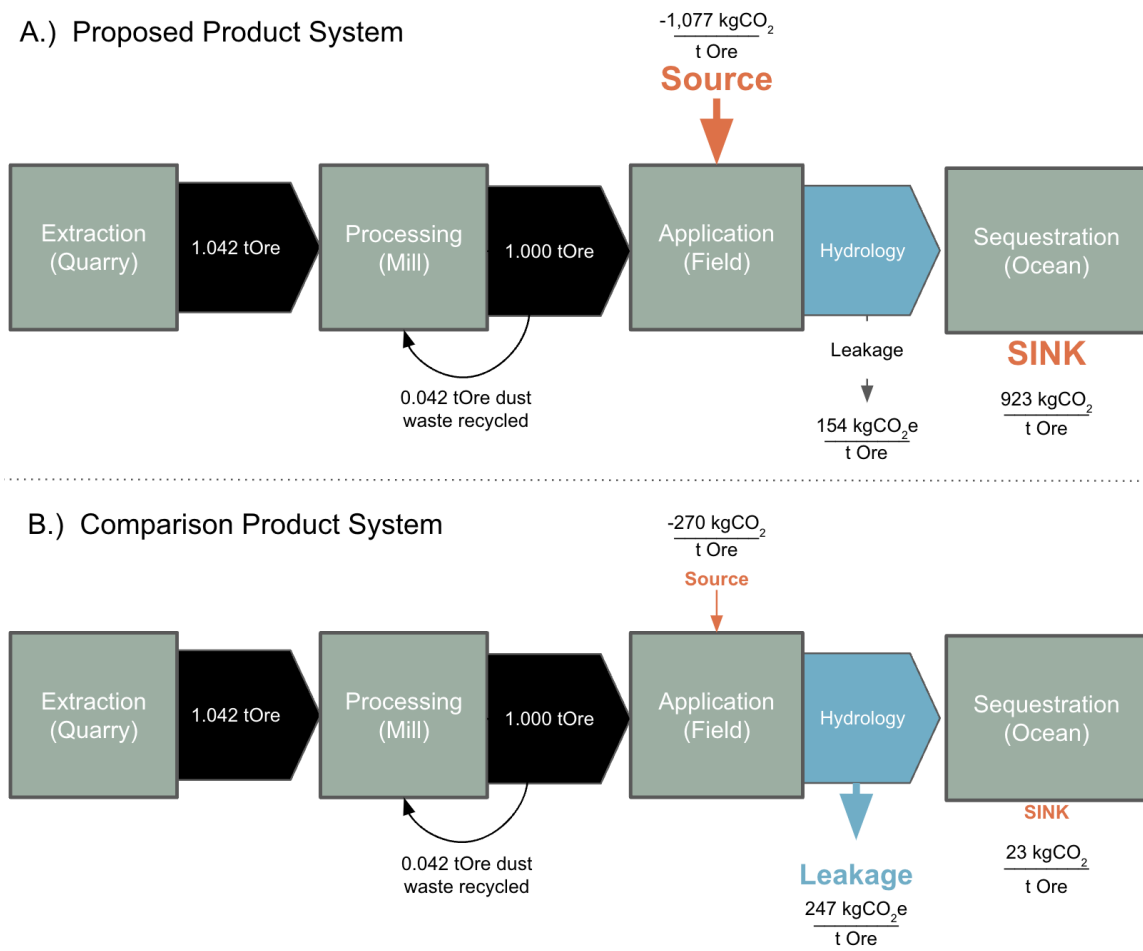
The system could be expanded to include quarry shutdown and the recycling/reuse of on-site resource materials. However, given the negligible capital emissions from creating the quarry and mill we do not believe this would change our analysis in any meaningful way. The system could also include return trips for transportation vehicles, but we feel we address this potential issue in our sensitivity analysis by doubling transportation distances. Finally, the system could be expanded to include other farm based emissions, but given that the farm processes will be identical between aglime and CarbonLock™ and that emissions will be exceedingly small after co-products are considered, we exclude farm based emissions.



**Fig. 12.** This diagram shows the unit processes of our completeness analysis. The top shows the primary LCA stages of extraction, transport, processing, and application. The secondary and tertiary unit processes are mostly comprised of emission factors chosen from the academic, government, and industry LCA sources.

## 2.11 Inclusions and exclusions

This project includes capital carbon expenses, including manufacturing and setup of the quarry as a one-time accumulation of emissions. We include the end state of the product because tracing the absorbed CO<sub>2</sub> to permanent sequestration is core to the goals of this LCA. The project excludes labor emissions due to the uncertainty and complexity around emission estimates. In lieu of labor, we allocate hourly (daily) shifts to each capital asset equipment and calculate the necessary emission costs. We also do not include the shutdown and recycling of the quarry and mill capital equipment or include return trips from transport vehicles. We model double the transportation distances in our sensitivity analysis. Finally, there are some preliminary data indicating that CarbonLock™ may reduce N<sub>2</sub>O emissions from the field, which could be a significant source of emission reductions, but empirical studies are currently ongoing so we refrained from included in it our model.



**Fig. 13.** This diagram shows the mass flow through the Proposed Product System (Scenario 2 is shown) compared to the Comparison Product System (Scenario 3 is shown). The overall mass flow of ore is the same between the two systems and the primary differences occur in the absorption of CO<sub>2</sub> from the atmosphere and leakage through the hydrological system. The mass values for all scenarios are shown in Fig. 35.

### 3. Life Cycle Inventory

The inventory analysis procedure includes gathering a comprehensive list of materials and equipment with their respective energy requirements and timeframe usage. The project uses the inventory list and requirements to implement a model to translate proposed real-world activities into mathematical relationships. The model refers to linking the various components in the life cycle inventory at each stage (extraction, processing, transport, application, and sequestration as shown in Fig. 10) within the boundaries described in the LCA. The project uses spreadsheet software to conduct the LCI modeling, calculations, scenario modeling, and sensitivity analyses.

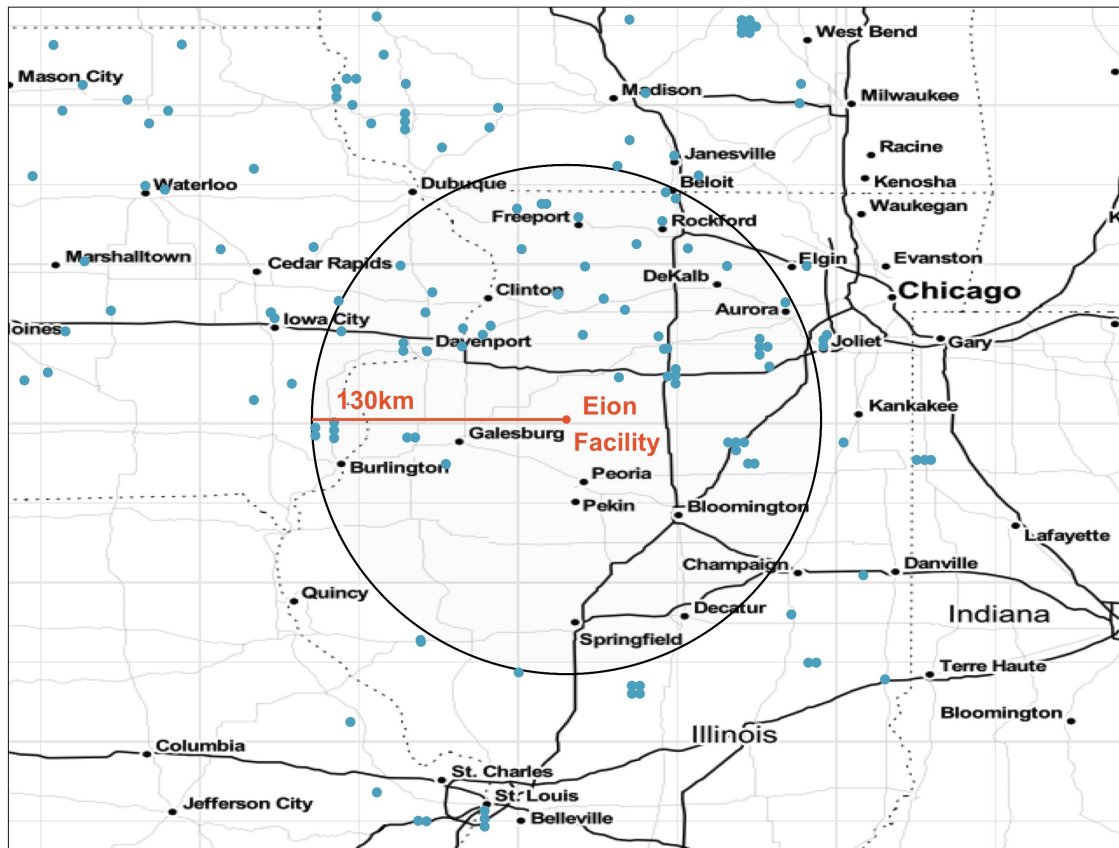
### 3.1 Scenarios

In this LCA study we examine the life cycle emissions in terms of GWP ( $\text{kgCO}_2\text{e}$ ) from CarbonLock™ (specially formulated silicate rock) and compare it to the life cycle emissions of traditional aglime (carbonate rocks). CarbonLock™ has the same process stages as aglime, allowing for a direct comparison between the technologies. The primary differences in these scenarios are the location of the quarry and mill and their associated power grid emissions, the transportation modes and distances, the Bond Work Index (energy needed to crush the rock), and most importantly the weathering chemistry, i.e., the sequestration potential of the rock. The weathering chemistry and transportation dominate the results of this study.



**Fig. 14.** The transportation route for Scenarios 1 and 2 goes from the Port of Aheim, Norway to the Port of New Orleans and then up to the Port of Peoria IL by inland ship or train. The last 50 km leg from Peoria to the Eion Corp field site is not shown.

- **Scenario 1: Quarry and Mill in Norway:** High olivine content dunite is quarried and milled in Norway and then transported to New Orleans by ship (8,815km), New Orleans to Peoria IL by inland barge (1,450 km), Peoria IL to a field site in IL (50 km) by truck, and includes capital emissions of quarry and mill. We define capital emissions as the emissions embodied in the steel manufacture for the equipment used as well as the embodied emissions of buildings made to house the stationary equipment. We examine this scenario because Norway is the site of largest active olivine quarry, producing approximately 80% of the world's supply of this industrial mineral. Norway is distinguished by its low-carbon hydro power grid, but this may be offset by the long transportation distances. We also use barge transport in the United States, which is the most carbon efficient method of transporting the material within the Mississippi River network.



**Fig. 15.** Aglime (calcite and dolomite) is typically sourced locally for application to agricultural fields. This figure shows that there are numerous aglime quarry sites within 130 km radius from the Eion Crop facility. For Scenarios 3, 4, and 5 the distance of 130 km was chosen as a representative distance for trucking aglime from the quarry to the field site.

- **Scenario 2: Quarry in Norway, Mill in USA:** This scenario is the same as Scenario 1 but locates the mill in New Orleans, which uses electricity from the regional U.S. grid with a different emissions factor. We replace the inland barge with more carbon intensive rail transport. This scenario allows us to understand the role of the power grid in the life cycle emissions from processing CarbonLock™ and examine the impacts of rail shipping. High olivine content dunite is quarried in Norway and then transported to New Orleans by ship (8,815 km) where it is milled, milled rock is then transported from New Orleans to Peoria IL by rail (1,450 km with DEFRA rail emission factor), Peoria IL to field site (50 km) by truck, and again incorporating capital emissions of the quarry and mill.
- **Scenario 3: Domestic idealized limestone:** In this scenario we model chemically pure calcium carbonate ( $\text{CaCO}_3$ , also called calcite or limestone). This represents an idealized case for locally available agricultural lime (aglime). The limestone is quarried in Illinois and is trucked 10 km to the mill. There are numerous aglime quarries within 130 km of the



Illinois field site so 130 km is used as the representative distance from the mill to the field site. We assume 39% of the CO<sub>2</sub> contained in aglime is emitted due to exposure to strong acid at the field site [1]. For consistency, capital emissions of quarry and mill are included here as well.

- **Scenario 4: Domestic idealized dolomite:** This scenario is the same as Scenario 3 but using chemically pure dolomite. Dolomite contains MgO in addition to CaO, with 21% MgO and 30% CaO. Generic calcite has 0% MgO and 56% CaO. The MgO in dolomite gives it more alkalizing potential than limestone, because Mg has equal charge but lower mass than Ca. This same phenomenon leads to its greater CO<sub>2</sub> removal potential than calcite. This scenario gives us an idealized case for agricultural dolomite. As in Scenario 3, we assume 39% of the CO<sub>2</sub> contained in dolomite is emitted due to exposure to strong acid at the field site [1]. Dolomite is trucked 10 km from the quarry to the mill and 130 km to the field. Capital emissions of the quarry and mill are included.
- **Scenario 5: Domestic idealized aglime:** This scenario is the same as Scenario 2 and 3, but using real world MgO/CaO (12% / 20%) concentrations from the local River Stone Quarry, Rock Island, Joslin, IL (River Stone Quarry product sheet). Thus, we are able to model the impact of real world impurities and MgO/CaO concentrations on the life cycle emissions of real world agricultural limestone.

### 3.2 Inventory analysis

The Life Cycle Inventory (LCI) developed includes all resource inputs used to setup and maintain a quarry operation (energy, fuel, machinery, pumps, buildings), the equipment used for extraction and transportation (mining equipment, dump trucks, conveyor belts), milling the rock (conveyor belts, vertical roller mill, pelletizers), and transportation and distribution/application. We explicitly inventory from cradle-to-grave to encompass as many possible resource inputs for a complete LCI that informs our assessment and results. Our focus on providing a complete inventory across the entire process allows us to explicitly control and measure each stage of the process.

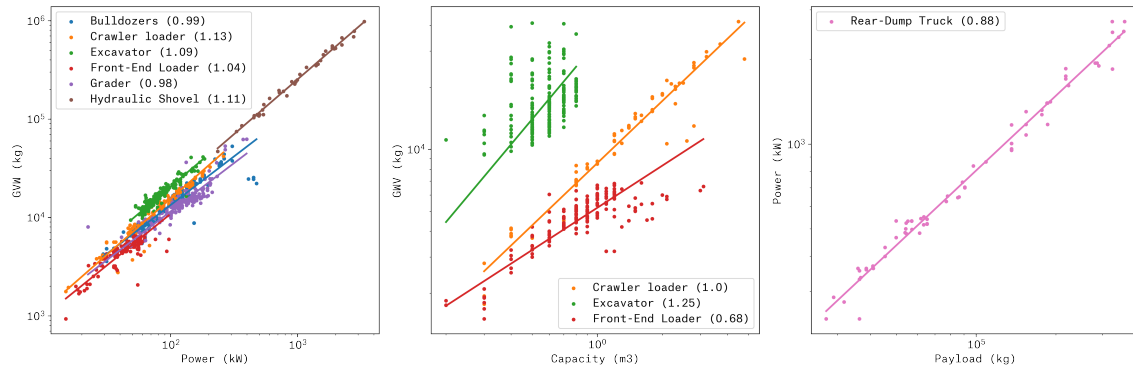
The inventory analysis was conducted as an iterative process of identifying key components at each stage related to the scope and boundaries of the system. We relied on a software tool, SHERPA for Surface Mines, which computes an internally consistent set of equipment and energy requirements to meet production targets [49]. This is the identical model that has been used to compute greenhouse gas inventories of the U.S. aggregate industry [48], as well as cost estimation for ERW endeavors [6]. A key feature of this model is an internally consistent set of mass- energy-time- and space- constrained estimates. For example, the distance from the quarry wall to the mill is accounted for, as is the speed of transport of a dump truck transporting material back and forth, and its capacity and fuel requirement. These also include accepted industry factors to account for inefficiencies and over-sizing of equipment. All inventory items were validated based on the scope and objectives set out in the LCI analysis.

### 3.3 Unit Process Descriptions

#### 3.3.1 Extraction

The rock is first extracted mechanically from the quarry using equipment already in place or through new infrastructure. All extraction is assumed to take place above the water line. The extraction process is comprised of two stages: (1) site development; (2) site operations.

**Development:** the infrastructure and equipment are built on site to support the operations at the quarry. We used data available from the manufacturers on capacity and mass to compute the emissions for steel embodied in the equipment (Fig. 16) per [2]. In addition, we accommodate the embodied emissions of the built environment, based on the area estimated for such buildings in SHERPA and emissions factors from the DOE Buildings Energy Data Book [10, 61]. In every scenario these embodied emissions are less than 0.01% of the total emissions of the ore to be used in carbon removal (e.g., 5-10 grams CO<sub>2</sub> per tonne ore). The negligible impact of capital emissions is confirmed by previous life cycle studies for quarries [62].



**Fig. 16.** Relationship between equipment size and gross vehicle weight from manufacturer data. Values in parentheses are exponents ( $b$ ) of a power law relationship  $Y=mX^b$  or  $\log(Y) = bX + \log(m)$ . An exponent of 1 indicates a linear relationship; slopes less than one show diminishing increases in GVW with capacity. These measures of GVW are used to estimate embodied emissions, based on Pimentel's [2] estimate of 109MJ per kg of steel equipment, accounting for the smelting of the primary material, manufacturing and assembly of the finished product, and repair and maintenance of the equipment during its productive lifetime.

**Operations:** In the operational phase of a quarry, rock is blasted and/or drilled to enable mechanical extraction from the rock face of the quarry. It is then loaded into a transport vehicle (dump truck, conveyor belt) to be moved to a gyratory crusher that produces a rock with a top size suitable for pulverization at the processing stage. Whereas the gyratory crusher is always located at the quarry, the processing mill can be located in the same locality as the quarry (using the same electricity emissions factor), or far remote (using a different emissions factor) depending on the scenario. The amount of CO<sub>2</sub> emissions at this stage are based on the scale of the operation, which determines the size and number of equipment used, and their associated fuel consumption, alongside the electricity demands of the gyratory crusher and ancillary equipment. The emissions intensity of electric power

depends on the location of the quarry, because the fuel mix of the grid for that locality determines the CO<sub>2e</sub> emission factors for the facility. In this study we use the regional grid power emission factors for the specific location of the quarry (power grid emission factors were compiled by [9] based on national reporting inventories). Figure 17 illustrates a representative equipment inventory for the reference quarry producing 4500 tpd / 1.35M tpy.

Capital (one-time) Carbon Expenses							
Equipment	Number	Size	GVW	Energy Required	Elec Emissions	Elec Emissions	
	-	-	kg/machine	kWh/machine	kgCO <sub>2</sub> /fleet	kgCO <sub>2</sub> /ton ore	
Drill	3	6.35 centimeter	0	0	0	0	0
Hydraulic Shovel	1	8.0 cubic meter	68148	2063370	23068	0.00114	
Rear-Dump Truck	2	52 ton	50814	1538535	34402	0.00170	
Front-End Loader	0	3.4 cubic meter	11994	363151.6667	0	0	
Bulldozers	2	175 kilowatt	23462	710377.2222	15884	0.00078	
Graders	1	115 kilowatt	12965	392551.3889	4389	0.00022	
Water Tankers	1	9500 liter	4700	142305.5556	1591	0.00008	
Service Trucks	1	1800 gvw	7500	227083.3333	2539	0.00013	
Powder Buggies	2	6800 gvw	2000	60555.55556	1354	0.00007	
Lighting Plants	0	0 None Given	0	0	0	0	
Pumps	1	11.2 kilowatt	0	0	0	0	
Pickup Trucks	3	680 kilogram	5000	151388.8889	5078	0.00025	
Gyratory Crusher	1	680 kilogram	50802	1538171.667	17197	0.00085	
Sum			237385	7187490.278	105501.011	0.0052	

Operational (per ton ore) Carbon Expenses							
Diesel Expenses							
Equipment	Number	Size	Equip Use	Fuel Use	Fuel Use	Fuel Emissions	
	-	-	Hours/Day	L/Hour	L/Day	kgCO <sub>2</sub> /tOre	
Drill	3	6.35 centimeter	18.3578	10.57	194.0	0.116	
Hydraulic Shovel	1	8.0 cubic meter	7.1905	116.28	836.1	0.499	
Rear-Dump Truck	2	52 ton	14.1152	39.78	561.5	0.335	
Front-End Loader	0	3.4 cubic meter	0	26.38	0.0	0.000	
Bulldozers	2	175 kilowatt	19.92	29.9	595.6	0.356	
Graders	1	115 kilowatt	1.9037	19.42	37.0	0.022	
Water Tankers	1	9500 liter	2	14.38	28.8	0.017	
Service Trucks	1	1800 gvw	3.9948	9.46	37.8	0.023	
Powder Buggies	2	6800 gvw	18.7957	12.87	241.9	0.144	
Lighting Plants	0	0 None Given	0	1.25	0.0	0.000	
Pumps	1	11.2 kilowatt	24	1.78	42.7	0.026	
Pickup Trucks	3	680 kilogram	6	5	30.0	0.018	
Sum					2605.4	1.556	

Fig. 17. Representative quarry equipment inventory and associated capital and operational emissions.

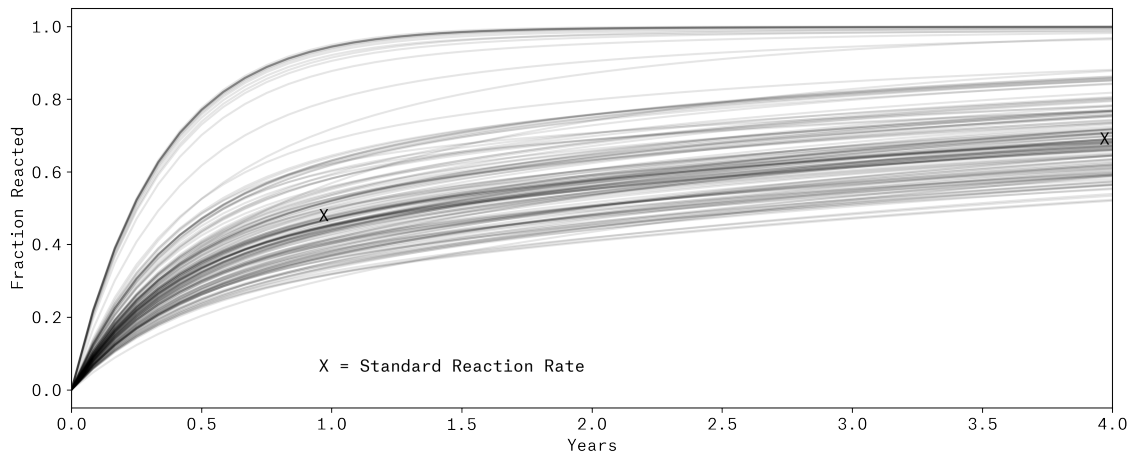
### 3.3.2 Transportation

Once the rock has been reduced to the desired top size, it is then loaded and transported from the quarry (extraction stage) to the mill (processing stage). After processing to meet the engineering requirements for production agriculture, the material is then transported to the field site and spread

on agricultural fields (application stage). Transportation is the largest emission contribution to the entire system because it requires large vehicles carrying heavy weight across potentially long distances. Depending on the location of the next stage, the emissions from this step can be reduced by combining ground transport with rail and/or waterways. Generally, there will be multiple "legs" within the system where some portion will be land, rail, or water. We explore sensitivity of emissions to a variety of scenarios to demonstrate the variance of emission contributions with different legs of transport. We do not explicitly include return trips in our analysis but address this assumption in our sensitivity analysis.

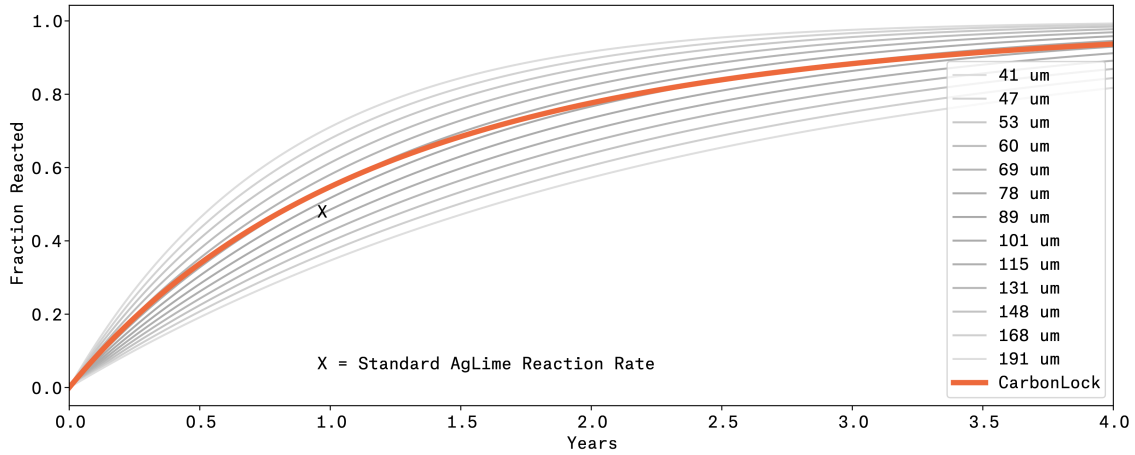
### 3.3.3 Processing

After the extraction process, the mineral is delivered to the processing stage where the "feed" size arriving from the quarry is crushed into a specific "product" size intended for final use. The equipment used to pulverize the mineral could include a ball mill or a roller mill, whose energy requirement is defined by the Bond Work Index of the material. In general silicates have higher Bond Indices than carbonates, which thus requires more energy to reach a given product size. This process, called "comminution", is common to many mineral processing efforts, and is little different between CarbonLock™ and aglime, with the exception that aglime is often a byproduct of limestone production for transportation, whereas CarbonLock™ is intended to be produced to match specific performance requirements to meet agronomic and carbon removal needs (Fig. 18 and 19). Similar to the extraction stage, we include the capital emissions generated by forging the steel of the equipment and the emission from building the buildings. The capital emissions make up about 11% of the process stage emissions and less than 2% of the total life cycle emissions.



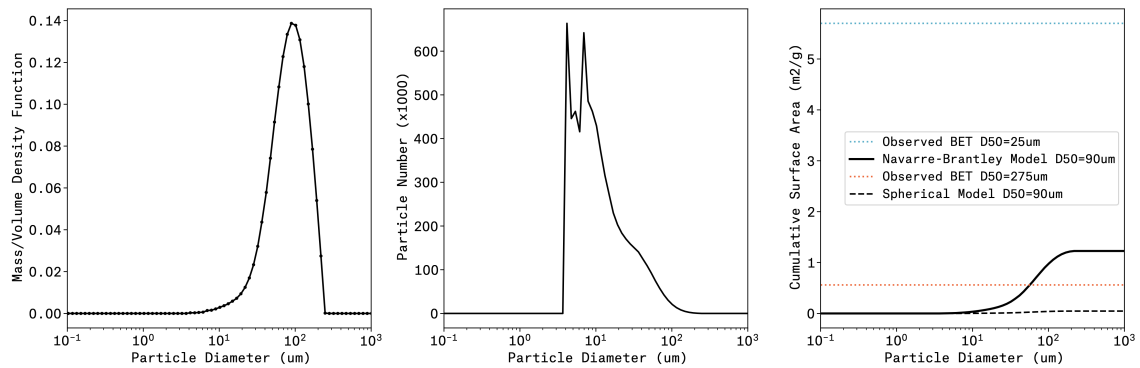
**Fig. 18.** Reaction dynamics of aglimes available in Illinois, using mesh sizes from [3] and kinetics from [4].

Comminution, and specifically the energy required to reach particle sizes with reaction speeds appropriate to the application, has been a focal point for ERW studies for many years [6, 8, 25, 63, 64]. This research has tended to focus on several interrelated phenomena, namely the reaction kinetics of the mineral (moles of mineral weathered per surface area per mass at a given



**Fig. 19.** Reaction kinetics of CarbonLock™, using empirical particle size distribution with a median particle size of 90um, and reaction kinetics from [5] as estimated in [6].

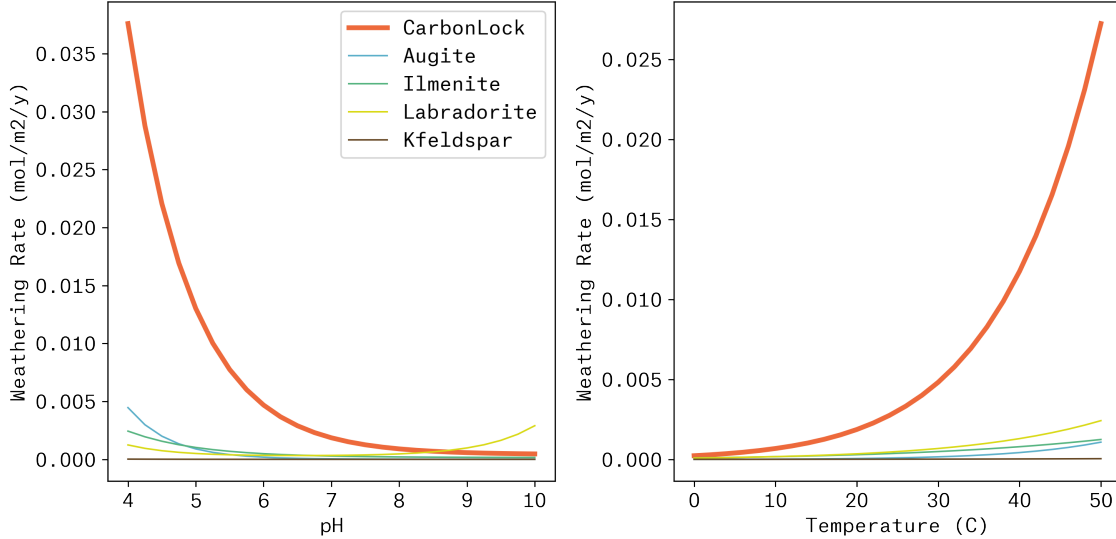
pH), the relationship between particle size distribution and surface area of pulverized minerals, and the energy required to bring minerals to the target size. An example of the relationship between particle size distribution and surface area is shown in Fig. 20. The empirical data we have collected on surface area and particle size distribution supports the fractal model of [7], which produces estimates of surface area  $\sim 20x$  higher than surface area estimated assuming spherical particles.



**Fig. 20.** Relationship between particle size distribution, surface area distribution, number density, and surface area for CarbonLock™.

The kinetic rates of chemical weathering (Fig. 21) have also been a focus of research in prior feasibility studies, because slower fundamental kinetic rates or lower acidity (higher pH) has a dramatic impact on the carbon removal potential, even aside from the cation content of the feedstock [5]. The means to overcome rate limitations determined by the crystal structure of the rock include more finely pulverizing the mineral (increasing specific surface area), and applying in warmer or more acidic conditions. Because the weathering process raises the alkalinity of the fluid surrounding the mineral by virtue of the cations released and the bicarbonate retained, the phenomenon in agriculture of removing the reaction products by rainfall inputs functions to maintain high rates of

weathering. This favorable coincidence is not shared by in-situ carbon mineralization of ore bodies or mine tailings.



**Fig. 21.** Weathering rates of various natural minerals under different acidity and temperature regimes [5].

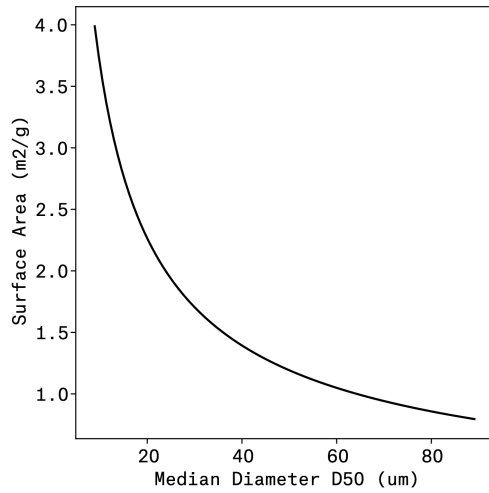
It naturally follows that one may engineer a particle size in the pulverization process that has the surface area that meets requirements for agronomic value as an aglime substitute, as well as the goal of carbon removal. Given the fractal surface area model identified above, a range of particle size distributions could be considered (Fig. 22).

The chief obstacle here is that pulverization to very fine particle sizes requires an input of energy [65], and that this energy requirement increases exponentially with decreasing particle size (Fig. 23). It can be seen from the high energy demand to reach low particle sizes, combined with stagnant reaction rates at pH >8, are a paradoxical condition that led Renforth and Henderson [66] to suggested that direct application of minerals into marine settings would be unfeasible from a life cycle perspective or a throughput perspective.

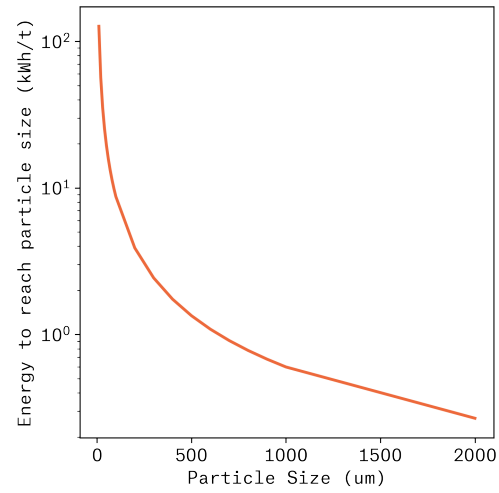
The energy demand estimate for pulverizing in ERW has tended to follow the theory of Bond [65], in which the energy required (in kWh/tOre) to reduce the size from an initial "feed" size to a final "product" size (both in  $\mu\text{m}$ ) follows Equation 1.

$$Energy = W_i \cdot \left( \frac{10}{\sqrt{PROD}} - \frac{10}{\sqrt{FEED}} \right) \quad (1)$$

We introduce one subtle change in this calculation, namely that this equation is largely focused on comminution using ball mills, whereas comminution in the cement and slag industries has transitioned primarily to roller mills (also known as Raymond mills) that have significantly lower energy requirements based around a design of continuously removing product as it meets the size threshold.



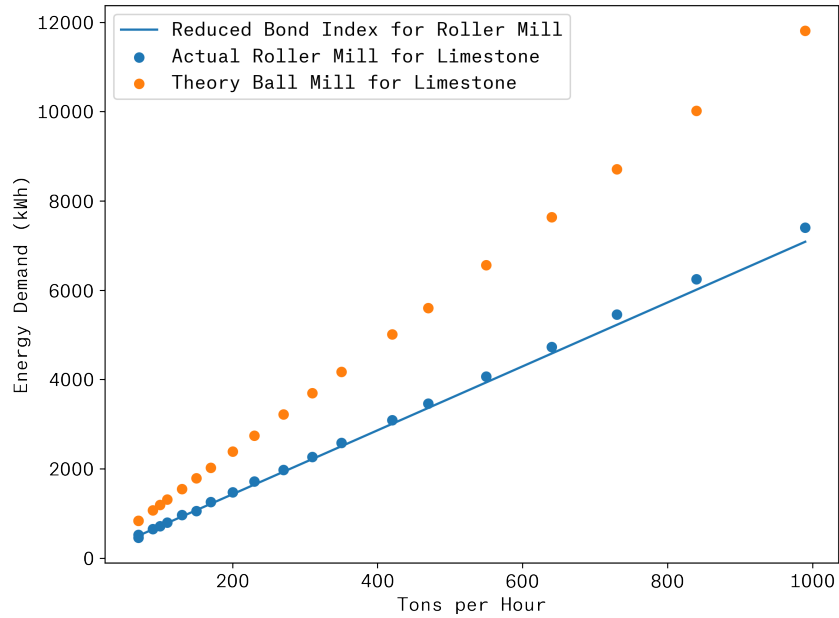
**Fig. 22.** Surface area computed from particle size distribution using the fractal model of [7].



**Fig. 23.** Energy required to pulverize to a given particle size following [8].

The energy savings is approximately 40% based on manufacturer size requirements (Fig. 24). Electricity is the energy source for this last step and as a result the total emissions from the processing stage are primarily driven by emission factors of the power grid, which is determined by the location of the mill.

We conclude this subsection by making the observation that we have focused our engineering in the processing step to create a product (Fig. 19) that reproduces the kinetics of aglime as best as possible (Fig. 18), to enable favorable market reception within the agricultural space. This also produces a throughput of carbon removal that is also favorable in the carbon removal space, namely that it is faster than the rate of organic matter accretion in soils or forests and enables repeat application in one-to-four year cycles without saturating the carbon removal process, by virtue of the loss of its reaction products.



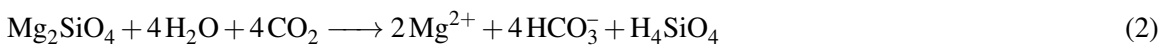
**Fig. 24.** Energy required for comminution in a roller mill versus a ball mill for a constant Bond Work Index (here, limestone), from manufacturers data sheet.

### 3.3.4 Application

The penultimate step in our process is to distribute and apply minerals to land where enhanced rock weathering can take place. We focus on agricultural soils for this study because they provide an ideal environment for weathering, and applying soil amendments are already a part of the farming operation. Since CarbonLock™ has been crushed to a specific micron size, it can be distributed much the same way that other soil amendments, such as aglime, are traditionally distributed across a field. The emissions contributed at application stage are far less than the transportation stage.

### 3.3.5 Carbon Capture and Sequestration

Once crushed silicate or carbonate rocks are spread on agricultural fields the weathering reaction takes place. This is a natural process that does not require any energy inputs and is thermodynamically irreversible. However, the weathering chemistry varies based on the mineral feedstock and each feedstock has a Mineral Potential (MP), which is the amount amount of CO<sub>2</sub> it can stoichiometrically sequester. For magnesium silicate materials, the archetypal weathering reaction takes the following form:

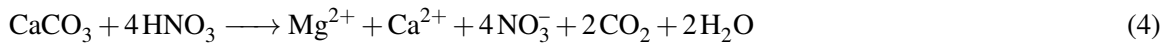




In this reaction, one mole of magnesium silicate reacts with four moles of  $\text{CO}_2$ , so two negatively charged bicarbonate  $\text{HCO}_3^-$  are created for every one divalent  $\text{Mg}^{2+}$  weathered. Given the molecular weight of  $\text{Mg}_2\text{SiO}_4$  (140g/mol) and the molecular weight of  $\text{CO}_2$  (44g/mol), weathering one metric tonne of  $\text{Mg}_2\text{SiO}_4$  removes 1.25 metric tons of  $\text{CO}_2$  from the atmosphere. Beerling (2020), citing Renforth (2012), citing O'Connor (2004), citing Goff and Lackner (1997) provides mineral potential (MP) for  $\text{CO}_2$  removal based on feedstock chemical composition in terms of  $\text{MgO}\%$  and  $\text{CaO}\%$ , shown in Equation 37.

$$MP \equiv \frac{t\text{CO}_2\text{e}}{t\text{Ore}} = \frac{MW_{\text{CO}_2}}{100\%} \cdot \left( \frac{\text{MgO}\%}{MW_{\text{MgO}}} + \frac{\text{CaO}\%}{MW_{\text{CaO}}} \right) * V \quad (3)$$

In equation 37,  $V$  is the valence of the cation (2 for Mg and Ca) and  $MW$  is the molecular weight of the mineral. As discussed in Section 1.4, Geochemistry, silicate rocks have  $V = 2$  while carbonate rocks, such as calcite ( $\text{CaCO}_3$ ) or dolomite ( $\text{CaCO}_3 \cdot \text{MgCO}_3$ ), have a net  $V = 1$ , because their dissolution includes one bicarbonate molecule per cation. Thus, the theoretical  $MP$  of carbonate rocks is half of silicate rocks. Carbonate rocks also have the potential for weathering directly with strong acids, chiefly in the form of nitric acid ( $\text{HNO}_3$ ), which results in a loss of  $\text{CO}_2$  directly from the atmosphere (Equation 4). In agricultural settings, the presence of nitric acid is abundant, owing to the use of high rates of nitrogen fertilizers applied to the fields. West and McBride estimate that 38.6% of the carbonate is lost to the atmosphere in this reaction [1]. Hamilton and Robertson go on to make an extensive study of leachates in Michigan and share data that suggests a rate 38.6% to 50.4% [44]. Additional discussion is provided in Section 1.4.



To estimate the net removal of  $\text{CO}_2$  from either carbonates or silicate weathering, we need to consider the fate of dissolved inorganic carbon (DIC) as it moves through the environment to the ocean and account for any  $\text{CO}_2$  leakage. We discuss the movement of DIC to the ocean in greater detail in Section 1.4 and Appendix A. In summary, the amount of  $\text{CO}_2$  initially absorbed from the atmosphere when the mineral is applied to the agricultural landscape ( $\text{CDR}_{\text{gross}}$ ) is determined by the mineral potential  $MP$  of the rock, multiplied by the fraction of dissolved inorganic carbon (DIC) uptake per unit of total alkalinity  $TA$  increase, at the temperature and pH conditions of the aqueous environment on land, as shown in equation 38. This equation represents the equilibrium conditions of perturbations to the carbonate system due to the mineral dissolution. The DIC then moves through terrestrial waterways to the ocean where the pH changes from the acidic conditions found on land (pH 5-6) to the colder and more alkaline conditions of the ocean (pH  $\sim$  8). Most saliently here, the DIC of the ocean has about 10%  $\text{CO}_3^{2-}$  compared to only 0.001% in soils. This means 10% of the  $\text{Mg}^{2+}$  or  $\text{Ca}^{2+}$  in solution is matched 1:1 with a  $\text{CO}_3^{2-}$  ion and a portion of  $\text{CO}_2$  is lost to the atmosphere due to this pH forcing. We interpret this as a form of leakage of sequestered carbon, and it is a standard feature of the literature on this topic [6, 30, 66]. The leakage is calculated as shown in Equations 39 and 40. With these expressions in place, we can compute  $\text{CDR}_{\text{net}}$  as  $\text{CDR}_{\text{gross}}$  minus the leakage, as shown in equation 41.

$$CDR_{gross} = MP \cdot \left. \frac{dDIC}{dTA} \right|_{land} \quad (5)$$

$$f_{Leakage} = \left. \frac{dDIC}{dTA} \right|_{land} - \left. \frac{dDIC}{dTA} \right|_{sea} \quad (6)$$

$$Leakage = -MP \cdot f_{Leakage} \quad (7)$$

$$CDR_{net} = CDR_{gross} - Leakage \quad (8)$$

As the rock is weathered, the application area is sampled to measure the draw down of carbon as well as providing verification through rare earth element fingerprinting that the CarbonLock™ was applied correctly and in the correct amounts (see Section 1.5 for more detail on monitoring, reporting, and verification). Emissions from the sample trips (once or twice a year) were omitted because the emissions were negligible compared to the other process emissions and may in practice be utilized for other agronomic purposes other than verification here. The sampling is an important step to note, however, because it provides quality assurance that the mineral potential of CarbonLock™ is realized in actuality.

### 3.3.6 Summary Carbon Balance

$CDR_{net}$  is a critical variable in this LCA because after adjusting for the Calcium Carbonate Equivalents (CCE) for each feedstock, it provides the negative emissions (sequestration) in terms of  $kgCO_2/tCCE$  for a given scenario. The other stages in the LCA generate emissions to the atmosphere as  $kgCO_2/tCCE$ . The sum of the process emissions provides the total life cycle emissions (Emissions) for a given scenario. Emissions plus  $CDR_{net}$  gives us the net impact on the atmosphere or Global Warming Potential (GWP) in terms of  $kgCO_2e/tCCE$ , as shown in Equation 9. Scenarios with negative GWP are able to remove more  $kgCO_2e/tCCE$  from the atmosphere than they generate throughout their life cycle.

$$GWP = Emissions + CDR_{net} \quad (9)$$

### **3.4 Modeling Platform and Enhanced Rock Weathering Life Cycle Assessment Model**

This section describes the Enhanced Rock Weathering Life Cycle Assessment Model (ERWM) that was developed for the purpose of providing scenario results and sensitivity analyses. Various features, functions, and limitations are also described within the modeling framework.

The follow tabs make up the tools used to develop the spreadsheet model:

- Carbon Model
- Development
- Extraction
- Transportation
- Processing
- Application
- Agronomics
- Sequestration
- SHERPA Model

#### **3.4.1 Carbon Model Tab**

The first tab of the ERWM is the Carbon Model tool which has a variety of parameters, constants, and results resulting in the summary GWP value of Equation 9. By varying the inputs different model outputs can be generated to create LCIA scenarios. The key input parameters that can be adjusted include the type of feedstock used (various actual natural and industrial silicates and actual or idealized carbonates, which are accompanied by chemical and physical properties), which regional power grid to use for the quarry and mill, the mode of transport and distances for each leg the material is transported, details of the processing step (Bond Index, particle feed and product size, equipment and labor considerations), and finally the application rate (tOre/ha) to the field and sampling procedures. Also shown on this tab is the Mineral Potential (MP) for a given feedstock, which is calculated in the Sequestration tab. Fig. 25 shows the inputs section on the Carbon Model sheet.

Technical coefficients and emissions factors are also established on this tab. Fig. 26 shows the relevant coefficients and emission factors for the five scenarios generated in this study: Bond Index, electrical grid emissions factors for Louisiana, Illinois, and Norway, as well as building, fuel, and transportation mode emissions factors. The Carbon Model sheet contains many more emission factors (e.g., electrical grid emission factors for U.S. states and EU countries) but here we only show those relevant to the reported scenarios.

The Carbon Model tab takes all available information in each tab and summarizes the results for easier viewing. Once these parameters are set, the rest of the LCA populates the required outputs based on the user selection. Carbon costs/benefits can be viewed in this tab along with the efficiency of emissions versus sequestration. After defining and setting the parameters in the Carbon Model

Scenario-Independent Parameters		Value	Units	Emissions	Units
	Feedstock Name	Norway AFS120			
	Mineral Type	Dunite			
	Moisture Content	25%			
Quarry	Electricity Source	EU: Norway		0.01118	kgCO2e/kWh
	Scenario #	3			
	Annual Production	4.9	Mtpy		
	Fuel Source	Diesel		2.688	kgCO2e/L
	Include in LCA?	TRUE			
Processing	Processing Type	Screening			
	Electricity Source	EU: Norway		0.01118	kgCO2e/kWh
	Include in LCA?	TRUE			
	Bond index	19.6	kWh/ton		
	Feed	150	mm		
	Prod	0.09	mm		
	Efficiency over Ball Mill	0.00	0.4 if VRM		
	Heating Source	Electric			
			Distance		Mode
Transport Quarry to Mill	Leg 1	0	km	None	
	Leg 2	0	km	None	
	Leg 3	0	km	None	
Transport Mill to Field	Leg 1	8815	km	Ship: avg bulk carrier	
	Leg 2	1450	km	Barge: avg inland cargo	
	Leg 3	51	km	Truck: Articulated, 100% l	
Land Application	CaCo3 Application rate	2	tCaCO3/ha		
	Silicate Application rate	1.6	tOre/ha		
	Silicate Application rate	4.04	tOre/ac		
<b>Mineral Summary</b>					
	Feedstock	Norway AFS120			
	Moisture	25%			
	Extraction	New Product			
	Processing	Pulverized			
<b>Transportation Summary</b>					
			km		
	Ship	8,815			
	Barge	1,450			
	Rail	-			
	Truck	51			
<b>Process Emissions, kgCO2e</b>					
				per t Ore	
<b>Capital</b>	Development	0.01			
	Quarry Capex	0.00			
<b>Operational</b>	Mill Capex	0.03			
	Extraction	3.2			
	Transport Quarry to Mill	-			
	Processing	0.8			
	Transport Mill to Field	-			
	Application	1.3			
	Total Carbon Cost	5.4			
<b>Carbon Benefits, tCO2</b>					
				per t Ore	
	Mineral Efficiency (tCO2e/tOre)	0.808			
<b>System Inefficiencies</b>					
				% of CDR	
<b>Upstream</b>	Material Diversion	0.0%			
<b>Midstream</b>	Strong Acid	1.0%			
	Plant Uptake	2.0%			
<b>Downstream</b>	Riverine Precipitation	1.0%			
	Ocean Carbonate Equilibration	10.5%			
	Total System Inefficiencies	14.0%			
<b>Net Atmospheric Impact, tCO2e</b>					
				per t Ore	
Steps 1-5	Process Emissions	0.005			
Step 6	Gross CDR Potential	-0.808			
Step 7	System Losses	0.113			
CRE	Net Atmospheric Impact	-0.689			

Fig. 25. The Carbon Model input spreadsheet used to adjust the key parameters to create our study's scenarios.

tab, the next tabs breakdown each of the components from the Carbon Model.

<b>Grid Power Emissions Factors</b>			
Total includes Generation in all cases, and Transmission/Distribution as available			
	Value	Unit	Ref
US: Average	0.453	kgCO <sub>2</sub> e/kWh	CM.COM
US: Illinois (IL) MRO- East	0.390	kgCO <sub>2</sub> e/kWh	CM.COM
US: Louisiana (LA) SERC - South	0.400	kgCO <sub>2</sub> e/kWh	CM.COM
EU: Norway	0.011	kgCO <sub>2</sub> e/kWh	CM.COM

<b>Buildings Embodied Emissions Factors</b>			
	Value	Unit	Ref
Office	39	tCO <sub>2</sub> e/1000 sqft	BEDB05
Warehouse and Storage	39	tCO <sub>2</sub> e/1000 sqft	
Ref:			

<b>Bond Index</b>		
	Bond Index	Unit
Dunite	19.6	kWh/tOre
Limestone	11.61	kWh/tOre
Dolomite	11.31	kWh/tOre

<b>Transportation Emissions Factors</b>			
	Value	Unit	Ref
Truck: Rigid, >17t, 100% Laden	0.11944	kgCO <sub>2</sub> e/t-km	DEFRA
Rail (DEFRA)	0.02556	kgCO <sub>2</sub> e/t-km	DEFRA
Ship: avg bulk carrier	0.00354	kgCO <sub>2</sub> e/t-km	DEFRA
Ship: avg inland cargo	0.01323	kgCO <sub>2</sub> e/t-km	DEFRA

<b>Liquid Fuel Emissions Factors</b>			
	Value	Unit	Ref:
Diesel	2.68787	kgCO <sub>2</sub> e/L	DEFRA
Gasoline	2.31467	kgCO <sub>2</sub> e/L	DEFRA

**Fig. 26.** This figure shows the key coefficients (Bond Index) and emission factors (grid [9], buildings [10], fuel [11], and transport [11]) for the five scenarios generated for this LCA. The Carbon Model sheet contains many more emission factors (e.g., electrical grid emission factors for U.S. states and EU countries) but here we only show those relevant to the reported scenarios.

### 3.4.2 Development Tab

The Development tab, Fig. 27, provides LCI values for the size of the building structures (offices and warehouses) for the quarry and mill. The emissions factors for building construction per square foot were taken from [10, 61] The LCI values were derived using the mining software package SHERPA for a 1.35 million tOre/year quarry and mill. Each of the building structures are further broken down into value and CO<sub>2</sub> emissions used for construction. We only included the emissions from buildings themselves in our assessment; the remaining inputs such as fencing were considered outside of our system boundary. Summaries are provided at the bottom of the spreadsheet that total the emissions from site development.

### **3.4.3 Extraction Tab**

The Extraction tab (Fig. 28) breaks down the various "capital carbon" and "operating carbon" expenses in the quarrying step. Capital estimates the one-time carbon emissions embodied in the cradle-to-grave life of the equipment [2] amortized over the lifetime production of ore at the site. Operating expenses are continuous operational carbon emissions measured as per tonne ore. Machinery included drills, shovels, dump-trucks, loaders, bulldozers, graders, tankers, lights, pumps and crushers. The breakdown includes number of individual pieces of equipment in each category operating at the quarry, the hours per day they are used, their size and associated energy requirements. Some of the equipment is electric (e.g., crushers and conveyors), whereas all of the mobile equipment uses diesel fuel. We make this distinction to underscore that the results of the LCA in the extraction step do not make any assertions around the eventual use of electric vehicles to improve the emissions profile. Together the capital and operational emissions are used to quantify total CO<sub>2</sub> emissions per tonne ore. These are broken down by liquid fuel and grid electricity to allow for variations on carbon intensity of these energy sources in the Carbon Model tab.

### **3.4.4 Transportation Tab**

The transportation tab, Fig. 29, breaks down the different transportation legs from quarry to mill and then mill to field. The variable parameters include the number of legs in each step, the distance traveled in each leg (km), and the mode of transport and thus emissions intensity per kilometer-tonne. Together, these enable an estimate of the total carbon emitted per tonne transported. For each leg, the mode and transportation type, is selected from the Carbon Model tab, which include vehicle, rail, or ship. Depending on the mode and distance, the level of CO<sub>2</sub> emissions will change. The emissions factors for each transportation type is provided on the Carbon Model tab.

### **3.4.5 Processing Tab**

The processing tab, Fig. 30, outlines the stages involved in crushing and milling rock to a predetermined size for application, including both capital and operational costs. The rock processing begins with a vertical roller mill that pulverizes the rock to the desired size, followed by a pelletizer that packages the rock for storage and transportation. Capital carbon expenses arise from the production of the vertical roller mill and pelletizer, while operational carbon expenses are associated with the production rate, energy and power requirements, and resultant emissions per tonne of ore.

The capital carbon expenses specifically include the power requirements and the embodied emissions associated with the equipment used, such as mills, which are significant due to their high energy and mass requirements. Operational carbon expenses take into account the size reduction from feed to product, daily production volumes, and energy per ton of ore, which influence the hourly and per ton emissions. Additionally, the processing tab includes data on various milling and drying equipment, illustrating their individual energy requirements and carbon emissions. These include different roller mills and a ball mill with varying capacities and energy efficiencies. Emis-

sions calculations also cover scenarios using electric and natural gas heating, impacting the total emissions for each process setup.

### 3.4.6 Application Tab

The application tab, Fig. 31, provides the distribution of the product application over farmland. This tab breaks down the liters of fuel used per hour (converted from horsepower of equipment), the application rate per land area, and the land area covered by the equipment per hour. The main function of this tab outlines the liters of fuel used from the application equipment. Based on these parameters, a summary of emissions produced per land area and per tonne are provided. The Calcium Carbonate Equivalents of the feedstock is used to determine the amount of product to apply to the field.

### 3.4.7 Agronomics Tab

Mineralogically pure calcite is an idealized construct used as a reference for using lime requirement (LR) recommendations based on soil samples, and applying this to a particular feedstock available. These will generally have some impurities (actual limestone being different from idealized calcite) varied mineral content (Mg and Ca fractions in dolomite can vary widely), and even industrial byproducts such as quicklime (CaO) and blast furnace slag (CaSiO<sub>3</sub>). All of these are characterized by a calcium carbonate equivalent, or CCE [4], which is computed from their elemental composition. For consistency with this widely used methodology, and considering that the framing of this LCA is around substituting CarbonLock™ for aglime, we compute the CCE of each potential feedstock in the Agronomics tab, Fig. 32. This calculation is then used to transform all our final emissions into the functional unit tonnes Calcium Carbonate Equivalents (tCCE). The Agronomics tab also includes estimates of N-P-K of various feedstocks, to the extent that they may contain amounts of these elements that contribute to crop nutrition or offset the use of other fertilizers.

### 3.4.8 Sequestration Tab

The Sequestration tab, Fig. 33, in the LCA model provides equations and estimates for the CO<sub>2</sub> removal process. We provide derivations for all equations used in the chemistry in Appendix A. In short, the *rate* of CO<sub>2</sub> absorption by the rock is determined by the particle size of the rock and the pH of soil. We have optimized our process so that the CarbonLock™ weathers at similar rates as aglime. See Section 2.6 for more detailed discussion. The total *amount* of CO<sub>2</sub> that can be captured on land and ultimately securely stored for geological timescales in the ocean is defined by the mineral potential (MP) of the feedstock (Eq. 37), and the pH differential between the land and the ocean (Eq. 41). The land has a high capacity to store DIC per unit of alkalinity released in weathering ( $\frac{dDIC}{dT_A} \approx 1$ ), whereas the more alkaline pH of the ocean has a lower capacity ( $\frac{dDIC}{dT_A} \approx 0.85$ ). We interpret this differential as a type of leakage, which is consistent with observations of CO<sub>2</sub> fluxes in estuaries as these freshwaters carrying alkalinity meet the ocean [67]. This tab also includes the

estimate of CO<sub>2</sub> released by the carbonates as they react with strong acids (Eq. 4), and the loss of ancient C from carbonates in estuaries. Unlike leakage from silicates, where the estuarine leakage of CO<sub>2</sub> is "new" carbon, the ~ 15% of CO<sub>2</sub> released from carbonates is split between new and old carbon, contributing to the estimation of carbonates as slight emitters. The important output is the net carbon dioxide removal (Net CDR) in terms of tonnes CO<sub>2</sub> per tonnes ore.

### **3.4.9 SHERPA Modeling**

The software program SHERPA was used to extract the capital and operation values for the quarry [57] and mill [58]. We created five scenarios of different quarry sizes, ranging from 450,000 tonnes per year to 2.5 million tonnes per year. The quarry data extracted from SHERPA are shown in Fig. 34. The chosen scale for our LCA is 1.35 million tons per year, which represents an active quarry for magnesium silicates in Norway. The SHERPA model has been used for emissions profiles in the aggregate industry previously [48], and was valuable here creating a complete and internally consistent set of LCI values for the capital equipment and process requirements of the quarry and mills. After extracting the values from Sherpa using a set of extract-transform-load (ETL) scripts, we had our quarry and mill models reviewed by mining experts Kevin Stansbury, Project Manager / Process Technical Advisor, and Mark Erickson Senior Technical Advisor, Mining and Minerals Process & Senior Process Engineer at Samuel Engineering to refine the "bottom up" equipment lists against "top down" industry norms for an archetypal operation of the modeled scale.



# Development

Scenario	C
Ore / Year	1350000
Production Lifetime	15
Ore / Lifetime	20250000

Site Development	Value	Buildings 1000 Sqft	Emissions tCO2e	Emissions kgCO2e	Emissions kgCO2/tOre
Ore Haul Road (meters)	969.4				
Waste Haul Road (meters)	511.6				
Shop (square meters)	194.7	2.096	81.74	81744	0.004
Dry (square meters)	220.5	2.373	92.56	92558	0.005
Office (square meters)	230.2	2.478	96.63	96629	0.005
Warehouse (square meters)	240.4	2.588	100.94	100936	0.005
Bulk Explosive Storage (cubic meters)	0.0				
Cartridge Explosive Storage (cubic meters)	8.4				
Electrical System (kilovolt-amperes)	837.5				
Clearing (hectares)	0.1				
Mine Yard (square meters)	529.5				
Sewage Treatment (liters/day)	7191.5				
Fencing (meters)	1835.6				
Fuel Storage (liters)	79259.9				

Buldings Summary	885.8	9.535058732	371.8672905	371867	0.018
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**Fig. 27.** The development tab shows the LCI values for the quarry and mill and the emissions from building construction.

# Extraction

Scenario	C
Ore tons per day	4500
Fuel Emissions	2.688 kgCO2e/L
Electricity Emissions	0.011 kgCO2e/kWh

## Capital (one-time) Carbon Expenses

Equipment	Number	Size	GVW	Energy Required	Elec Emissions	Elec Emissions
	-	-	kg/machine	kWh/machine	kgCO2/fleet	kgCO2/ton ore
Drill	3	6.35 centimeter	0	0	0	0
Hydraulic Shovel	1	8.0 cubic meter	68148	2063370	23068	0.00114
Rear-Dump Truck	2	52 ton	50814	1538535	34402	0.00170
Front-End Loader	0	3.4 cubic meter	11994	363151.6667	0	0
Bulldozers	2	175 kilowatt	23462	710377.2222	15884	0.00078
Graders	1	115 kilowatt	12965	392551.3889	4389	0.00022
Water Tankers	1	9500 liter	4700	142305.5556	1591	0.00008
Service Trucks	1	1800 gw	7500	227083.3333	2539	0.00013
Powder Buggies	2	6800 gw	2000	60555.55556	1354	0.00007
Lighting Plants	0	0 None Given	0	0	0	0
Pumps	1	11.2 kilowatt	0	0	0	0
Pickup Trucks	3	680 kilogram	5000	151388.8889	5078	0.00025
Gyratory Crusher	1	680 kilogram	50802	1538171.667	17197	0.00085
Sum			237385	7187490.278	105501.011	0.0052

## Operational (per ton ore) Carbon Expenses

Diesel Expenses						
Equipment	Number	Size	Equip Use	Fuel Use	Fuel Use	Fuel Emissions
	-	-	Hours/Day	L/Hour	L/Day	kgCO2/tOre
Drill	3	6.35 centimeter	18.3578	10.57	194.0	0.116
Hydraulic Shovel	1	8.0 cubic meter	7.1905	116.28	836.1	0.499
Rear-Dump Truck	2	52 ton	14.1152	39.78	561.5	0.335
Front-End Loader	0	3.4 cubic meter	0	26.38	0.0	0.000
Bulldozers	2	175 kilowatt	19.92	29.9	595.6	0.356
Graders	1	115 kilowatt	1.9037	19.42	37.0	0.022
Water Tankers	1	9500 liter	2	14.38	28.8	0.017
Service Trucks	1	1800 gw	3.9948	9.46	37.8	0.023
Powder Buggies	2	6800 gw	18.7957	12.87	241.9	0.144
Lighting Plants	0	0 None Given	0	1.25	0.0	0.000
Pumps	1	11.2 kilowatt	24	1.78	42.7	0.026
Pickup Trucks	3	680 kilogram	6	5	30.0	0.018
Sum					2605.4	1.556

Electrical Expenses						
	Size	Idle Power	Max Rate	Actual Rate	Actual Energy	Elec Emissions
	kW	kW	tOre/hour	tOre/hour	kW	kgCO2/tOre
Gyratory Crusher	500	50	500	375.0	387.5	0.012
Lighting					0.0	0.000
Buildings	500				500	0.015
						0.026
Total Electricity						0.012
Total Fuel						1.556
Total Quarry						1.568

**Fig. 28.** The extraction tab shows the LCI and emissions for forming the steel used in the quarry capital equipment and the operations LCI and emissions for operating the quarry.

# Transportation

Operational (per ton ore) Carbon Expenses				
Quarry to Mill	Mode	Distance km	Emissions kgCO2/tOre-km	Carbon Emitted kgCO2/tOre
Leg 1	Truck: Rigid, >17t, 100% La	1.00	0.12	0.12
Leg 2	None	-	-	-
Leg 3	None	-	-	-
Total				0.12

Operational (per ton ore) Carbon Expenses				
Mill to Field*	Select:	Distance km	Emissions kgCO2/tOre-km	Carbon Emitted kgCO2/tOre
Leg 1	Ship: avg bulk carrier	8,815.00	0.00	31.20
Leg 2	Ship: avg inland cargo	1,450.00	0.01	19.19
Leg 3	Truck: Rigid, >17t, 100% La	51.00	0.12	6.09
Total				56.47

\* mean trip distance

**Fig. 29.** The transport tab shows the transport mode, distance, and associated emissions for moving the rock from the quarry to the mill and from the mill to the field.

# Mill

Scenario	C
Ore tons per day	14999
Electricity Emissions	0.011 kgCO2e/kWh

## Capital (one-time) Carbon Expenses

Equipment	Power Req kWh	Mass kg	Embodied Energy kWh/machine	Embodied Emissions kgCO2/fleet	Emissions per ton kgCO2/ton ore
Mill	22794	6719693	203457379	2274653	0.032825
Sum					0.032825

## Operational (per ton ore) Carbon Expenses

Equipment	Feed Size um	Product Size um	Production tOre/day	Duty Production Cycle hours/day	Production tOre/hour	Energy Req kWh/tOre	Power Req kW	Emissions kgCO2/hr	Emissions kgCO2/tOre
Mill (Complete Flowsheet)	150000	90	14999	23	724.6	30.2	22794.4	254.8	0.352
Sum									0.352

## Operational (per ton ore) Carbon Expenses

Equipment	Capacity tph	Capacity mtph	Total HP	Total kW	Total kWh	Total Ore	Energy Req kWh/tOre	Emissions kgCO2/tOre
Screening							4.0	0.045
Bradley BM30 Roller Mill	25.0	22.7	1050	783.0	4807606.3	139229	34.5	0.386
Bradley BM60 Roller Mill	45.0	40.8	1797	1340.0	8227874.7	250612.2	32.8	0.367
Mesto Premier Ball Mill	150.0	136.1	5505	4105.1	25205592.8	835374.1	30.2	0.337

## Dryer Emissions

Equipment	Energy Req kWh/tOre	Emissions kgCO2/tOre
Electric	70	0.8
Natural Gas Dryer		14.8
Natural Gas BM30		14.0
Natural Gas BM60		14.2
Natural Gas Ball Mill		14.8

## Calculated Processing Emissions

Scenarios	Potential Emissions kgCO2/tOre	Actual Emissions kgCO2/tOre
Mill (Flowsheet)	0.35	-
Mill (Flowsheet) + Electric Heat	1.13	-
Mill (Flowsheet) + NG Heat	15.15	-
Screening	0.04	-
Screening + Electric Heat	0.83	0.83
Screening + NG Heat	14.84	-
BM30 Roller Mill	0.39	-
BM30 Roller Mill + Electric Heat	1.17	-
BM30 Roller Mill + NG Heat	14.39	-
BM60 Roller Mill	0.37	-
BM60 Roller Mill + Electric Heat	1.15	-
BM60 Roller Mill + NG Heat	14.57	-
Ball Mill	0.34	-
Ball Mill + Electric Heat	1.12	-
Ball Mill + NG Heat	15.14	-
Total		0.83

**Fig. 30.** The processing tab shows the capital equipment and operational energy required to run the mill along with their associated emissions.

# Application

Application	Equipment has L/hour attribute. ha/t *hour/ha * L/hour * kgCO2/L = kgCO2/ton		
50 hp = 5.87 Lph	LPH		5.87
5 min per acre per 2 tons	min per acre / 2l		5
	acre per hour / 2		12
	L per acre		0.489167
	L per ha		1.208755
	kgCO2/ha/2tons		3.248977
	2ton application:		1
	kgCO2/ha		3.248977
	kgCO2/ton		<b>1.624489</b>

**Fig. 31.** The application tab calculates the operational energy required to spread the material on agricultural fields.

# Agronomics

<b>Mineral Potential</b>	Select:	
Feedstock:	Norway AFS120	
Mineral	Dunite	
P2O5 %:	0.00	
K2O %:	0.03	
NPK Equivalent:	<b>0-0-0.03</b>	mass N-P2O5-K2O per mass of amendment
MWfeedstock	57.60	
MWcaco3	50.77	
CaCO3 Equivalent	<b>0.881</b>	equivalent neutralizing potential per mass amendment

**Fig. 32.** The agronomics tab is a calculator used to determine the amount of silicate rock that needs to be applied to the field to have the equivalent pH neutralizing effect of agricultural limestone.

# Sequestration

Mineral Potential	Select:	Typical Range	Ref
Feedstock:	Norway AFS120		
Mineral	Dunite		
Carbonate?	FALSE		
MgO %:	48.87	0-50	ActLabs analysis
CaO %:	0.13	0-50	ActLabs analysis
HNO3 reaction %	0%	38%	WB05 = 38%; HR07 = 52%
Mineral Potential, tCO2e / tOre:	1.077	0-1.2	

Land Parameters			
Net Valence	2	2 if silicate, 1 if carbonate	
Land pH	5.5		
Land Temperature (°C)	25		
Land Temperature (°K)	298.2		

Ocean Parameters			
Ocean pH:	8.08	7.9-8.25	ROYSOC05
Ocean Salinity:	35	34-35	NOAA NCEI
Ocean Temperature (°C)	16.1	16-19	NCDC
Ocean Temperature (°K)	289.3	16-19	NOAA NCEI
pCO2	400	390-410	NOAA GML

Land Calculations	
Kh	0.03402
pKw	12.543
pK1	5.971
pK2	9.385
Kw	2.86E-13
K1	1.07E-06
K2	4.12E-10
h	3.16228E-06
s	1.36E+01
dTA/dh	-1.46E+06
dDIC/dh	-1.46E+06
dDIC/dTA	0.99974

Ocean Calculations		
Kh	0.04395	
pKw	14.643	
pK1	5.940	
pK2	9.078	
pKb	8.702	
Kw	2.28E-15	
K1	1.15E-06	
K2	8.36E-10	
Kb	1.98E-09	
h	8.31764E-09	
s	1.76E+01	
TB	4.16E-04	
dTA/dh	-4.09E+11	
dDIC/dh	-3.51E+11	
dDIC/dTA	0.85666	0.70-0.85

Net Calculations		
Gross CDR, tCO2e / tOre:	1.077	
Leakage, %:	0.143	0.15-0.30
New CO2 loss from pH, tCO2e/tOre	-0.154	
Old CO2 loss from pH, tCO2e/tOre	0.000	
Old CO2 loss from HNO3 Rxn	0.000	
Net CDR, tCO2e / tOre:	0.923	

$K_w$ , equilibrium constant of water, defined as:

$$K_w := [H^+][OH^-]$$

Computed as:

$$\ln K_w = 148.9652 - 13847.26/T - 23.6521 \ln T + [118.67/T - 6.977 + 1.0495 \ln T]S^{1/2} - 0.01615S$$

$K_h$ , the solubility of CO<sub>2</sub> in water, defined as:

$$[CO_2] = K_h \cdot f[CO_2]$$

Computed as:

$$\ln K_h = 9345.17/T - 60.2409 + 23.3585 \ln T / 100 + S[0.023517 - 0.00023656T + 0.00047036(T/100)^2]$$

$$K_1 = \frac{[H^+][HCO_3^-]}{[CO_2]}$$

and

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

Computed as:

$$\ln K_1 = 2.83655 - 2307.1266/T - 1.5529413 \ln T - (0.207608410 + 4.0484/T)\sqrt{S} + 0.0846834S - 0.00654208S^{3/2} + \ln(1 - 0.0010055)$$

and

$$\ln K_2 = -9.226508 - 3351.6106/T - 0.2005743 \ln T - (0.106901773 + 23.9722/T)\sqrt{S} + 0.1130822S - 0.00846934S^{3/2} + \ln(1 - 0.0010055)$$

The constant for boric acid is defined as:

$$K_B = \frac{[H^+][B(OH)_4^-]}{[B(OH)_3]}$$

It is computed as:

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

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

Next compute the derivative  $dDIC/dh$ :

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

Finally multiply  $dDIC/dh$  by the inverse of  $dTA/dh$  to calculate  $dDIC/dTA$ :

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

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

$$\frac{dTA}{dh} = -s \cdot \left( \frac{K_1}{h^2} + 4 \cdot \frac{K_1 K_2}{h^3} \right) - \frac{K_B B_T}{K_B + h^2} - \frac{K_w}{h^2} - 1 \quad (3.23)$$

Fig. 33. The sequestration tab calculates the net carbon dioxide removal (CDR<sub>net</sub>) for a given scenario.

Live Sherpa

Eion Corp

(Values in \$Millions)

Scenario	1	2	3	4	5	3
Sheet Name	A	B	C	D	E	Live
Shifts	1	1	1	1	1	1
Hours / Shift	12	12	12	12	12	12
Ore / Day	1,500	3,000	4,500	5,999	7,499	4,500
Days / Year	300	300	300	300	300	300
Annual Production	450,000	900,000	1,350,000	1,799,700	2,249,700	1,350,000
Project Lifetime	15	15	15	15	15	15
Project Production	6,750,000	13,500,000	20,250,000	26,995,500	33,745,500	20,250,000
<b>Summary</b>						
Total Capital Budget	7,542,881	12,029,774	13,756,769	17,958,451	21,011,807	13,756,769
Capital Budget / Annual Ton \$	16.76 \$	13.37 \$	10.19 \$	9.98 \$	9.34	10.2
Total Operating Costs / Year	3,506,586	6,211,995	7,231,614	9,093,063	10,498,674	7,231,614
Total Operating Budget / Anni \$	7.79 \$	6.90 \$	5.36 \$	5.05 \$	4.67	5.4
Supplies	550,032	1,100,124	1,645,179	2,195,274	2,745,363	1,645,179
Hourly Labor	1,722,084	2,727,696	2,727,696	3,335,619	3,624,651	2,727,696
Salaried Labor	577,665	952,290	1,036,395	1,376,865	1,376,865	1,036,395
Equipment Operation	338,025	867,159	1,164,924	1,358,664	1,797,369	1,164,924
Miscellaneous	318,780	564,726	657,420	826,641	954,426	657,420
Power Rate \$	0.0695 \$	0.0695 \$	0.0695 \$	0.0695 \$	0.0695 \$	0.0695

**Fig. 34.** The software program SHERPA was used to extract the capital and operation values for the quarry. We created five scenarios of different quarry sizes, ranging from 450,000 tonnes per year to 2.5 million tons per year. The chosen scale for our LCA is 1.35 million tonnes per year, which represents the active silicate quarry in Norway.

### 3.5 Data Sources and Quality Assessment

In addition to the geographic, temporal, and technology coverage already discussed, the following additional data quality requirements were considered when creating our LCI and LCIA [19]:

- Precision
- Completeness
- Representativeness
- Consistency
- Reproducibility

When considering precision, we captured a range of values whenever appropriate, e.g., reported ocean pH is a 7.0-8.25 [68]. We then included highly sensitive variables (such as transport and ocean pH) in our sensitivity analysis where we examined if the extreme values resulted in changes to our overall conclusions. When considering completeness, we extended our system boundary to include carbon emissions from the construction of quarry and mine buildings as well as the steel to forge the capital equipment, which to our knowledge was not included in prior considerations of this system [6, 48]. Also, because our product is a raw mineral that is quarried and then applied to agricultural fields without the addition of additional mass inputs, our system boundary includes 100% of the product inputs and outputs by mass. When considering representativeness, we modeled scenarios that represented the real world geographic location and transportation routes of our products. For example, when modeling CarbonLock™ we chose an active site in Norway as the quarry and for aglime we chose an active limestone quarry in Illinois. We also considered the representativeness of our quarry and mill processes extensively by using an industry software package called SHERPA

[57, 58]. SHERPA is used by the industry in pre-feasibility studies such as this to model real world quarry and mill construction and operations. We then had the model inputs we extracted from SHERPA reviewed by two industry engineers to ensure that our model was representative. For considering consistency, we applied the same assumptions and scope across our scenarios and products. The similarity between the process stages of CarbonLock™ and aglime resulted in a high degree consistency across our product models. Finally, for reproducibility, when data are taken from the public domain literature, the sources have been referenced according to the ISO 14040 standard. We also provide in-depth discussion and mathematical and chemical equations for the weathering of silicate and carbonate to allow third parties to reproduce the same results.

### **3.6 Results of Inventory Completeness Check**

We conducted a Completeness Check of our Life Cycle Inventory Model by modeling the unit processes described in Section 3.3 and calculating the environmental relevance. Unit processes that made up greater than 1% of the total emissions were included in the study. We also decided to include the quarry and mill capital emissions even though they were less than 1% of the total emissions in our Proposed Product System to ensure that our assessment was comprehensive and comparable to our Comparison Product System. Section 2.8 provides more detailed discussion on unit processes we identified for exclusion. Fig. 35 shows the mass balance, emissions, and the percent of total emissions for each stage.

### **3.7 Life Cycle Inventory Model Sensitivity Check**

We completed a sensitivity analysis on our Life Cycle Inventory Model by varying individual parameter inputs by either doubling their value or setting them to their realistic physical extremes. The two parameters that have the greatest impact were doubling the transport distances and increasing the ocean pH from 8.08 to 8.25. Doubling the transportation distances doubled the transportation emissions and increasing the pH reduced the sequestration potential of the mineral. We also modelled doubling the capital emissions for the mill and quarry and reduced the final product size from 90 microns to 45 microns. Reducing the size of the product was the parameter that had the greatest increase on mill emissions. Both doubling the capital emissions and reducing the product size had very minor impacts on the GWP results. The results of our sensitivity analysis are shown in Fig. 40 and discussed in Section 5.1.

### **3.8 Allocation**

CarbonLock™ and the comparison products of agricultural limestone and dolomite are extracted from a quarry, pulverized, and applied as a final product to agricultural fields. This process is fairly unique in that it progresses from cradle-to-grave without generating co-products. Thus, there is no allocation step necessary in this LCA. Future studies of CarbonLock™ may want to view the marketable audited carbon removal credit as a co-product to the soil amendment but the focus of



	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Quarry and Mill in Norway	Quarry in Norway, Mill in USA	US Calcite	US Dolomite	US AgLime
<b>Mass:</b>					
Extraction (tOre Out)	1.042	1.042	1.042	1.042	1.042
Processing (tOre Out)	1.000	1.000	1.000	1.000	1.000
Processing (tOre Recycled)	0.042	0.042	0.042	0.042	0.042
Mineral Potential (kgCO <sub>2</sub> /tCCE)	-1,222	-1,222	-270	-294	-176
Leakage (kgCO <sub>2</sub> e/tCCE)	175	175	247	269	161
<b>Sequestration (kgCO<sub>2</sub>/tCCE)</b>	<b>-923</b>	<b>-923</b>	<b>-23</b>	<b>-25</b>	<b>-15</b>
<b>Emissions: Capital (kgCO<sub>2</sub>e/tCCE)</b>					
Development	0.02	0.02	0.02	0.02	0.02
Quarry Capex	0.01	0.01	0.18	0.17	0.19
Mill Capex	0.02	0.67	0.38	0.34	0.40
<b>Emissions: (kgCO<sub>2</sub>e/tCCE)</b>					
Extraction	1.8	1.8	2.0	1.8	2.1
Transport Quarry to Mill	0.1	0.1	0.6	0.5	0.6
Processing	0.2	6.3	3.5	3.2	3.7
Transport Mill to Field	63.9	84.2	15.5	14.3	16.5
Application	1.8	1.8	1.6	1.5	1.7
<b>Total Emissions (kgCO<sub>2</sub>e)</b>	<b>68</b>	<b>95</b>	<b>24</b>	<b>22</b>	<b>25</b>
<b>Percent of Total Emissions</b>					
<b>Capital</b>					
Development	0.0%	0.0%	0.1%	0.1%	0.1%
Quarry Capex	0.0%	0.0%	0.8%	0.8%	0.8%
Mill Capex	0.0%	0.7%	1.6%	1.5%	1.6%
<b>Operational</b>					
Extraction	2.6%	1.9%	8.3%	8.2%	8.4%
Transport Quarry to Mill	0.1%	0.1%	2.5%	2.3%	2.4%
Processing	0.3%	6.6%	14.6%	14.5%	14.8%
Transport Mill to Field	94.0%	88.6%	64.6%	65.0%	66.0%
Application	2.6%	1.9%	6.7%	6.8%	6.8%

**Fig. 35.** This figure shows the Completeness Check of the Proposed Product Systems compared to the Comparison Product Systems. The top sections show the mass balance of CO<sub>2</sub> through the system and the emissions of each stage. The bottom section shows the percent total emissions of each stage. Our analysis shows that we satisfy and exceed our requirement of including stages that have greater than 1% environmental significance.

Carbon Costs, kgCO <sub>2</sub> e		per t Ore	per tCCE	
<b>Capital</b>	Development	0.02	0.02	
	Quarry Capex	0.01	0.01	
	Mill Capex	0.02	0.02	
<b>Operational</b>	Extraction	1.6	1.8	
	Transport Quarry to Mill	0.1	0.1	
	Processing	0.2	0.2	
	Transport Mill to Field	56.4	63.9	
	Application	1.8	1.8	
	<b>Total Carbon Cost</b>		<b>60.0</b>	<b>68</b>
	<b>Net Atmospheric Impact, tCO<sub>2</sub>e/tCCE</b>			<b>per tCCE</b>
CO <sub>2</sub> Mineral Sequestration (kgCO <sub>2</sub> /tCCE)			-1047	
Carbon Life Cycle Emissions (kgCO <sub>2</sub> e/tCCE)			68	
Net Impact on Atmosphere (GWP - kgCO <sub>2</sub> e/tCCE)			<b>-979</b>	

**Fig. 36.** The LCIA output of our model is displayed on the Carbon Model spreadsheet tab. Negative GWP means that the carbon removed from the atmosphere by the feedstock exceeds the process emissions, i.e., net carbon is sequestered, and vice versa for positive GWP. Scenario 1 output is shown in this figure. The CO<sub>2</sub> mineral sequestration is reported as (kgCO<sub>2</sub>/tCCE) rather than carbon equivalents because only CO<sub>2</sub> is absorbed by the ore.

this study is to provide a direct comparison to the aglime system.

## 4. Life Cycle Impact Assessment

This study is a Green House Gas analysis, which is an LCA that only considers the midpoint impact category of Global Warming Potential (GWP). As such, we use the 100-year time horizon global warming potentials (GWP-100) relative to CO<sub>2</sub> from Table A-1 of 40 CFR Part 98 [59] as the characterization factors for our LCA [60]. Optional elements of LCIA (normalisation, grouping, weighting and data quality analysis) were not required for our study because we only analyze the GWP impact category. For our LCIA we primarily rely on well-established existing emission factors, such as emission factors for fuel and electric power grids, that use GWP-100 to derive their emission factors in terms of kgCO<sub>2</sub>e per unit. For example, we use DEFRA’s transportation emission factors [11] and Carbon Footprint’s collection of regional power grid emission factors [9].

The Carbon Model tab in our spreadsheet model contains the emission factors needed for our model. The emission factors relevant to our LCIA scenarios are shown in Fig. 26. The Carbon Model tab, also displays the output for each stage of the LCIA model and the total net impact on the atmosphere (GWP), shown in Fig. 36. Negative GWP values indicate carbon is removed from the atmosphere and sequestered, while positive values indicate that the process emissions exceed the carbon dioxide removed by the feedstock.

## 4.1 Data Quality Assessment

In this study we endeavored to provide a comprehensive cradle-to-grave life cycle assessment of CarbonLock™ and its comparative products agricultural limestone and dolomite. All LCAs, however, have limitations and key assumptions within their models. The key assumptions and parameters that drive our model are: 1.) The mineral potential (MP) of feedstock drives the total theoretical CO<sub>2</sub> that a feedstock can absorb. 2.) The actual CO<sub>2</sub> that is removed by a feedstock is driven by the soil chemistry, terrestrial water chemistry, and ocean chemistry. We consulted with numerous experts and extensively researched the geochemistry of ERW to ensure that our models are reasonable and accurate. Appendix A, the Introduction, and Section 3.3.5 provide detailed explanations of the chemistry of ERW. 3.) Transport is a key driver of the life cycle emissions of ERW and our transportation assumptions greatly influence the model results. To ensure our transportation assumptions are reasonable we use transport modes and distances between real world quarries and an actual and representative test field site. We consulted with logistic companies to ensure our assumptions were reasonable and accurate. 4.) We also made important assumptions on mill and quarry operations, in particular how the Bond Work Index of a feedstock influences the energy use and emissions of the mill. We extensively used the quarry and mill capital and operations models from the software package SHERPA to derive our assumptions for the quarry [57] and mill [58]. We also consulted with mining engineers to ensure that our assumptions are reasonable and accurate. 5.) Finally, the location of the quarry and mill and their associated power grid emission factors are important assumptions that impact the model output. We chose modeling scenarios that use different realistic locations for the quarry and mill and their specific regional power grid emissions factors, which were sourced from [9].

Some key limitations of our model are: 1.) We only consider the LCIA impact category of Global Warming Potential (GWP) in terms of kgCO<sub>2</sub>e/tCCE. We do not consider other impact categories, such as eutrophication and acidification. Given that our primary focus is on carbon removal from the atmosphere, we believe this is a reasonable limitation. Future studies may explore other impact categories, with ocean acidification being one of primary interest because CarbonLock™ will likely reduce impacts of ocean acidification directly by transporting alkalinity to the ocean and potentially raising the saturation state of calcifying organisms. 2.) We also do not consider land use change in this model. CarbonLock™ does not require changes in the agricultural land use or practice changes in agriculture that would, for example, require new or different equipment. Furthermore, the example quarry in Norway currently produces 1.35 million tons of ore a year on approximately 65 hectares of land. In terms of land use changes, this is a very small amount of land compared to the amount of CarbonLock™ sequestration potential. 3.) Finally, we do consider the emissions in constructing buildings and forging the steel of capital equipment, but other labor and capital activity are outside our system boundary. Our analysis and the LCA study of surface quarries by Landfield and Karra [62] found the capital emissions to be a small fraction of the total life cycle emissions.

<b>Scenarios</b>					
	<b>Scenario 1</b>	<b>Scenario 2</b>	<b>Scenario 3</b>	<b>Scenario 4</b>	<b>Scenario 5</b>
	<b>Quarry and Mill in Norway</b>	<b>Quarry in Norway, Mill in USA</b>	<b>US Calcite</b>	<b>US Dolomite</b>	<b>US AgLime</b>
<b>Carbon Costs, kgCO<sub>2</sub>e/tCCE</b>					
<b>Capital</b>					
Development	0.02	0.02	0.02	0.02	0.02
Quarry Capex	0.01	0.01	0.18	0.17	0.19
Mill Capex	0.02	0.67	0.38	0.34	0.40
<b>Operational</b>					
Extraction	1.8	1.8	2.0	1.8	2.1
Transport Quarry to Mill	0.1	0.1	0.6	0.5	0.6
Processing	0.2	6.3	3.5	3.2	3.7
Transport Mill to Field	63.9	84.2	15.5	14.3	16.5
Application	1.8	1.8	1.6	1.5	1.7
<b>Total Emissions (kgCO<sub>2</sub>e)</b>	<b>68</b>	<b>95</b>	<b>24</b>	<b>22</b>	<b>25</b>
<b>Net Atmospheric Impact, kgCO<sub>2</sub>e/tCCE</b>					
CO <sub>2</sub> Mineral Sequestration (kgCO <sub>2</sub> /tCCE)	-1047	-1047	-23	-23	-16
Carbon Life Cycle Emissions	68	95	24	22	25
<b>Net Impact on Atmosphere (GWP)</b>	<b>-979</b>	<b>-952</b>	<b>1</b>	<b>-1</b>	<b>10</b>

**Fig. 37.** The LCI inputs used to parameterize our LCA scenarios.

## 4.2 Life Cycle Impact Assessment Results

In this LCIA we examine the GWP ( $\text{kgCO}_2\text{e/tCCE}$ ) of CarbonLock™ under two different transportation and mill location scenarios and compare them to three aglime scenarios. In the CarbonLock™ scenarios, raw silicate rock is mined in Norway and transported by ship to the United States and then to the field site by inland barge and truck or by rail and truck. In Scenario 1, the mill for crushing and formulating the rock is located in Norway and in Scenario 2, the mill is located in Louisiana. Norway has very low power grid emissions ( $0.011 \text{ kgCO}_2\text{e/kWh}$ ) because of its renewable energy profile, while the Louisiana power grid has moderate emissions ( $0.400 \text{ kgCO}_2\text{e/kWh}$ ), as shown in Fig. 26. We chose Norway to be the location of the quarry because it currently hosts the largest active quarry of the industrial mineral that is used in CarbonLock™ from which Eion Corp will source its feedstock for the foreseeable future. The mill for processing raw rock into CarbonLock™ may be located in Norway or the United States. Given the low energy grid emissions in Norway, Scenario 1 represents a best case scenario for CarbonLock™ even with the long transportation distance from Norway to the United States. Scenario 2 represents the most realistic scenario with the mill being located in the United States. Scenarios 3, 4, and 5 provide a comparison of CarbonLock™ to the current standard practice of mining limestone or dolomite in a regional quarry in Illinois, U.S.A. and trucking it to the mill and then the field site within 130 km (80 miles) of the quarry. Scenarios 3 and 4 use chemically pure limestone and dolomite and scenario 5 uses real world MgO/CaO concentration analyzed from River Stone Quarry, Rock Island, Joslin, IL. Section 4.2 provides additional descriptions of the scenarios. Fig. 37 shows the LCI of the key parameters for each scenario in a side-by-side comparison.

- **Scenario 1: Quarry and Mill in Norway:** High Mg content silicate rock is quarried and milled in Norway and then transported to New Orleans, New Orleans to Peoria IL by inland ship (1,450km), Peoria IL to field site (50km) by truck.
- **Scenario 2: Quarry in Norway, Mill in USA:** This scenario is the same as Scenario 1 but the mill is located in New Orleans using U.S. electricity emission factors and the inland ship is replaced with less efficient rail.
- **Scenario 3: U.S. Calcite:** In this scenario we model chemically pure calcium carbonate (limestone) to represent an ideal case for agricultural lime.
- **Scenario 4: U.S. Dolomite** This scenario is the same as Scenario 3 but using chemically pure dolomite.
- **Scenario 5: U.S. AgLime** This scenario is the same as Scenario 2 and 3, but using real world MgO/CaO (12% / 20%) concentrations from the local River Stone Quarry, Rock Island, Joslin, IL.

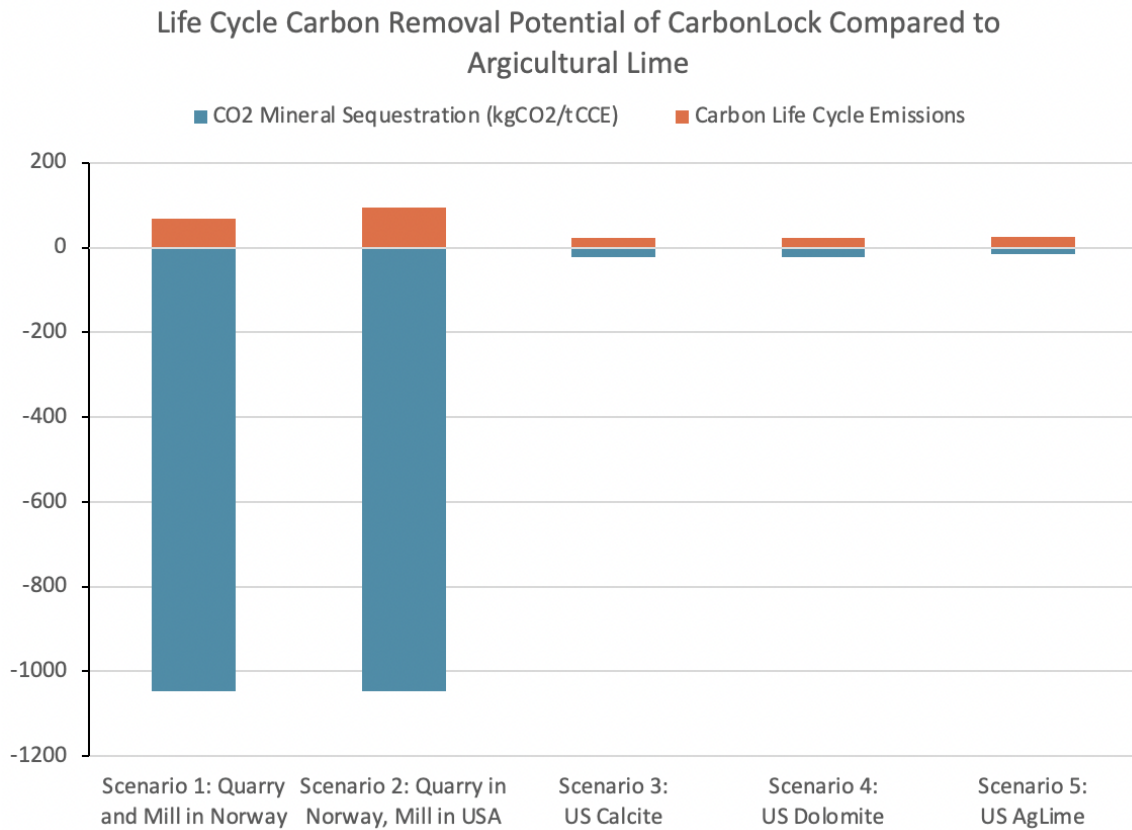
The LCIA results from our Enhanced Rock Weathering Life Cycle Assessment Model (ERWM) are shown in Fig. 38. In the first section, the Carbon Costs show the emissions in  $\text{kgCO}_2\text{e/tCCE}$  for each process stage. The capital emissions are summarized first, followed by the operational emissions. The capital and process emissions are then summed to provide the total Carbon Life

<b>Scenarios</b>					
	<b>Scenario 1</b>	<b>Scenario 2</b>	<b>Scenario 3</b>	<b>Scenario 4</b>	<b>Scenario 5</b>
	<b>Quarry and Mill in Norway</b>	<b>Quarry in Norway, Mill in USA</b>	<b>US Calcite</b>	<b>US Dolomite</b>	<b>US AgLime</b>
<b>Carbon Costs, kgCO<sub>2</sub>e/tCNE</b>					
<b>Capital</b>					
Development	0.02	0.02	0.02	0.02	0.02
Quarry Capex	0.01	0.01	0.18	0.17	0.19
Mill Capex	0.02	0.67	0.38	0.34	0.40
<b>Operational</b>					
Extraction	1.8	1.8	2.0	1.8	2.1
Transport Quarry to Mill	0.1	0.1	0.6	0.5	0.6
Processing	0.2	6.3	3.5	3.2	3.7
Transport Mill to Field	63.9	84.2	15.5	14.3	16.5
Application	1.8	1.8	1.6	1.5	1.7
<b>Total Emissions (kgCO<sub>2</sub>e)</b>	<b>68</b>	<b>95</b>	<b>24</b>	<b>22</b>	<b>25</b>
<b>Net Atmospheric Impact, kgCO<sub>2</sub>e/tCNE</b>					
CO <sub>2</sub> Mineral Sequestration (kgCO <sub>2</sub> /tCNE)	-1047	-1047	-23	-23	-16
Carbon Life Cycle Emissions	68	95	24	22	25
<b>Net Impact on Atmosphere (GWP)</b>	<b>-979</b>	<b>-952</b>	<b>1</b>	<b>-1</b>	<b>10</b>

**Fig. 38.** The LCIA outputs generated using our Enhanced Rock Weathering Life Cycle Assessment Model. Negative Net Impact on the Atmosphere (GWP) values indicate that the carbon removal from ERW exceeds the capital and process emissions from extraction, transport, milling, and application.

Cycle Emissions for each scenario. The next section, provides the net atmospheric impact (GWP in terms of  $\text{kgCO}_2\text{e/tOre}$ ) by adding the total process emissions to the amount of  $\text{CO}_2$  removed from the atmosphere through ERW. If the total net impact on the atmosphere is negative then the carbon dioxide removal is greater than the life cycle emissions.

## 5. Life cycle interpretation



**Fig. 39.** This graph shows the total life cycle emissions and carbon removal for each scenario. CarbonLock™ removes far more carbon (blue bar) from the atmosphere than it emits (red bar). Limestone and dolomite emit roughly the same or slightly more carbon than they sequester.

The goal of this study was to develop a Life Cycle Inventory (LCI) and Assessment (LCA) Model for the extracting, processing, transporting, and applying Eion Corp’s CarbonLock™ to agricultural fields for carbon capture, utilization, and sequestration through enhanced rock weathering (ERW). Our goal was to investigate whether the net carbon removed per tonne of CarbonLock™ exceeds that of its cradle-to-grave life cycle emissions and to provide a comparison to the current industry standard for managing the pH of agricultural soils—limestone and dolomite. Figure 39 shows the total life cycle emissions and removed carbon for each scenario. CarbonLock™ is clearly carbon negative even with the long transatlantic transport. In Scenario 2, moving the mill to the

more carbon intensive U.S. power grid and using less efficient rail transport in the United States only slightly increases total life cycle emissions. Current practices of using lime and dolomite are at best slight emitters.

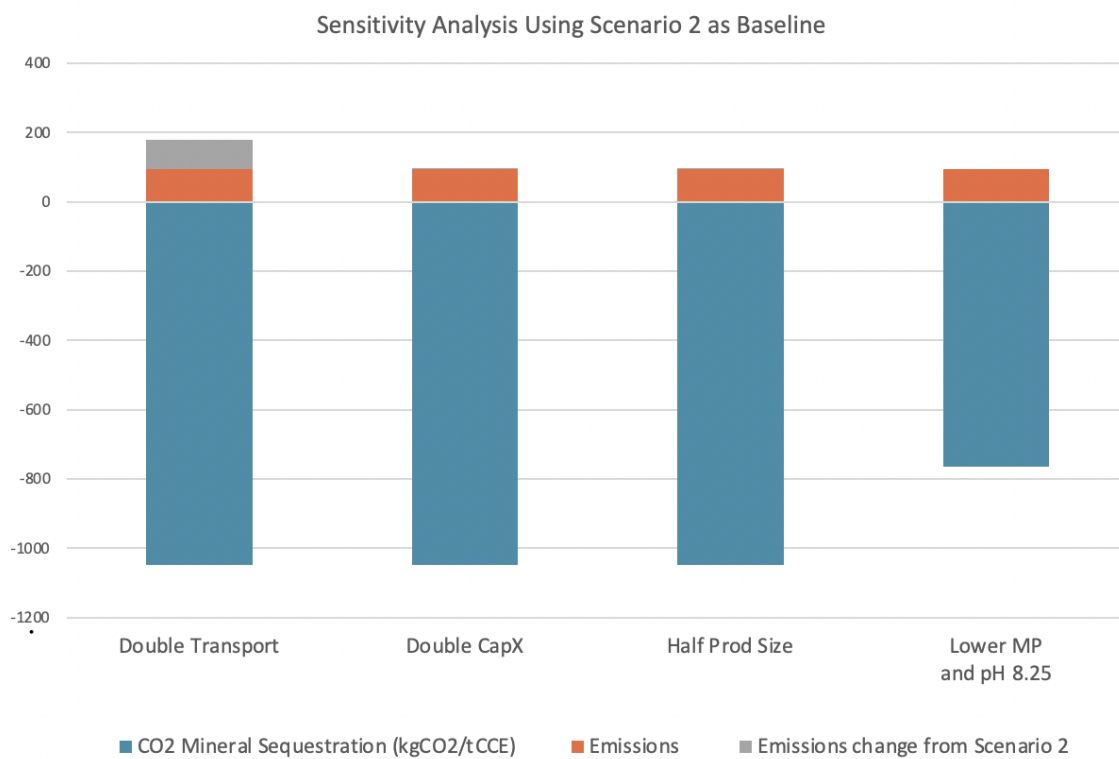
## 5.1 Sensitivity Analysis

A sensitivity analysis of our CarbonLock™ LCA shows that the carbon removal and sequestration potential CarbonLock™ is very robust. Transportation emissions from the quarry to the mill and from the mill to field site represent 88% of the total emissions. As we discussed previously, we did not include return trips in our initial assessment. The sensitivity analysis in Fig. 40 shows that when transportation distances are doubled the carbon removed by CarbonLock™ still greatly exceeds the process emissions. To drive this point home further, Fig. 41 shows how many kilometers one would need to transport CarbonLock™ for the emissions from CarbonLock™ to equal the amount of carbon removed. Even with the least carbon efficient mode of transport, truck, CarbonLock™ could be transported over 7,000 km. For comparison, the distance from New York to Los Angeles is approximately 4,500 km. Under the most efficient mode of transport, bulk ocean carrier, CarbonLock™ could be transported almost six times around the world before it became a net carbon emitter. This means that the raw material for CarbonLock™ can be sourced from virtually anywhere in the world, transported by ship to any continent, and transported to any reasonable field site and still remove more carbon from the atmosphere than it emits.

Our sensitivity analysis in Fig. 40 also shows what happens to the emissions profile in Scenario 2 if the capital emissions from the quarry and mill's buildings and equipment are doubled. As we expected and is supported by the literature, increases in capital emissions are negligible—doubling the size of the quarry and mill only increases emissions by 1 kgCO<sub>2</sub>e/tCCE). Finally, we also assessed the impact of halving the size of the final material produced by the mill. As discussed in Section 3.3.3, as the size of the particle from the mill is reduced the weathering rate increases but so does the energy requirements for the mill. Reducing the final particle size from 90 microns to 45 microns only increases emissions by 3 kgCO<sub>2</sub>e/tCCE or 0.3% of the CO<sub>2</sub>e removed from the atmosphere by CarbonLock™.

The sensitivity analysis shows that CarbonLock™ is resilient to changes in its emissions profile. The second consideration are changes to the carbon removal potential of the system, which is most greatly influenced by two key parameters: the mineral potential (MP) of the silicate rock and the sequestration potential of the ocean. The mineral potential of the silicate rock is determined by its MgO/CaO composition. We have confirmed through chemical analysis the mineral potential of the feedstock mined at the quarry in Norway, which has high ratios of MgO/CaO and a mineral potential of 1,077 kgCO<sub>2</sub>/tOre. We also analyzed samples of other high-Mg silicate feedstocks from four other resources located outside of Norway. The feedstock with the lowest MgO/CaO ratio had a mineral potential of 941 kgCO<sub>2</sub>/tOre. The MP, however, is the theoretical maximum kgCO<sub>2</sub>/tOre that could be removed by that feedstock. The limiting factor for how much carbon is removed from the atmosphere is the pH of the ocean, which is explained in detail in Section 1.4 and Appendix A. For our baseline scenarios, we assume an ocean pH of 8.08. The highest ocean pH, which is uncommon but does occur is, 8.25 [68]. Increasing the pH of the ocean in our model reduces the





**Fig. 40.** Sensitivity analysis showing changes to the LCIA results when key emissions and carbon removal parameters are changed using Scenario 2 as the baseline. In all scenarios CarbonLock™ remains a significant carbon sink.

Transport distances for net CDR to reach 0 for scenario 2		
Mode	(km)	(Times around the equator)
Truck: Rigid, >17t, 100% Laden	7,024	0.2
Truck: Articulated, 100% laden	14,357	0.4
Rail (DEFRA)	32,821	0.8
Ship: avg inland cargo	63,399	1.6
Ship: avg bulk carrier	237,043	5.9

**Fig. 41.** This figure shows how far CarbonLock™ in Scenario 2 could be transported by each transport mode before its life cycle CO<sub>2</sub>e emissions are equal to its carbon dioxide removal (CDR) potential.

net carbon dioxide removal (CDR<sub>net</sub>) of Scenario 2 from 923 kgCO<sub>2</sub>/tOre to 876 kgCO<sub>2</sub>/tOre. We combine these two changes, lower MP and higher pH, in the fourth sensitivity scenario shown in Fig. 40. Even with these changes in the carbon removal potential of CarbonLock™, it remains a considerable carbon sink.

## 6. Critical Review

In accordance with the ISO 14040 standard, this study has been reviewed by an independent third-party reviewer, Dr. Timothy M. Smith. Dr. Smith (timsmith@umn.edu) is a professor of sustainable systems management and International Business at the University of Minnesota. His Critical Review can be found in Appendix B. In response to Dr. Smith’s review we conducted the following changes to our model and report:

1. We adjusted our functional unit from tOre to tonnes Calcium Carbonate Equivalents (tCCE), which more accurately represents the functional unit of substitution of CarbonLock™ for aglime.
2. We expanded our discussion and explanation of the sequestration process in terrestrial waters and ultimately the ocean.
3. We expanded our sensitivity analysis to include a scenario that demonstrates the range of mineral potential in the CarbonLock™ feedstock.

## 7. Conclusion

The results of this LCA show that CarbonLock™ is effective at removing carbon from the atmosphere and is highly resilient to variations in the supply chain impacting its ability to be net carbon negative. In Scenario 2, which closely represents a commercial supply chain for CarbonLock™ CarbonLock™ sequesters -923 kgCO<sub>2</sub>/tOre and only emits 84 kgCO<sub>2</sub>/tOre for a net CDR of -

839 kgCO<sub>2</sub>/tOre. In other words, CarbonLock™ removes more than ten times as much CO<sub>2</sub> as it emits. Transporting CarbonLock™ composes 89% of its life cycle emissions and even after doubling the transportation distances in our sensitivity analysis, CarbonLock™ still had a net CDR of -764 kgCO<sub>2</sub>/tOre. Our sensitivity analysis highlights that CarbonLock™ could be transported from virtually any continent by ship and then trucked inland over a thousand kilometers and still be carbon negative. Carbonate-based aglime, on the other hand, is at best a slight carbon emitter. Thus, this LCA shows that CarbonLock™ is an effective and resilient means of CCUS that can remove CO<sub>2</sub> at the gigaton scale while simultaneously replacing aglime, a carbon-emitting product.

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## A. Appendix A: ERW Chemistry

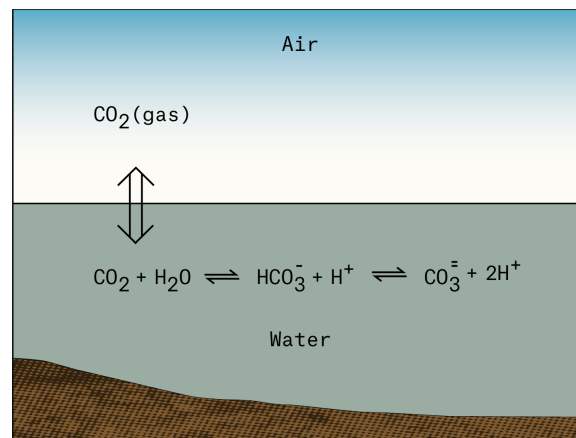
### A.1 Introduction

Enhanced rock weathering (ERW) is the process by which the natural process of  $\text{CO}_2$  removal by mineral weathering and geologic storage in the ocean is engineered to proceed at a pace relevant to contemporary decarbonization goals. Adding certain silicate rocks to the soil system releases Mg and Ca from the rocks, which increases the mineral-derived alkalinity of soil water and drives the dissolution of additional inorganic carbon (DIC) from the atmosphere into the soil water (Fig. 42). Water that leaches out of the soil (and corresponding DIC) enters freshwater systems. Some of this DIC then reaches saline ocean water, where it has a lifetime of approximately 500,000 years.

Here, we present the fundamental carbonate budget, demonstrating the theoretical foundations of ERW. We follow the flow of DIC backwards, starting in the ocean, to freshwaters, to soil solution to calculate the storage potential and leakage of  $\text{CO}_2$ . We also describe a trace-element approach to measure the amount of mineral applied, and the rate of mineral dissolution and associated carbon dioxide removal.

### A.2 Geochemical Fundamentals

In this section, we walk through the carbonate system parameters, explorations of carbonate chemistry, carbonate chemistry in the ocean, freshwater carbonate chemistry, and carbonate chemistry in the soil system.



**Fig. 42.** Figure showing that  $\text{CO}_2$  in the atmosphere is in equilibrium with the  $\text{CO}_2$  in the ocean. The ocean  $\text{CO}_2$  equilibrates with the carbonate and bicarbonate in the ocean [12].



### A.2.1 Carbonate System Parameters

CO<sub>2</sub> in the atmosphere is dissolved into the ocean, where it can speciate into other forms including carbonate (CO<sub>3</sub><sup>2-</sup>) and bicarbonate (HCO<sub>3</sub><sup>-</sup>). The dissolution of gaseous, atmospheric CO<sub>2</sub> into dissolved CO<sub>2</sub> 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<sub>2</sub> 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,  $K_h$ , the solubility of CO<sub>2</sub> in water is defined as:

$$[\text{CO}_2] = K_0(T,S) \cdot p\text{CO}_2 \quad (10)$$

Computed as:

$$\ln K_h = 9345.17/T - 60.2409 + 23.3585 \ln(T/100) \quad (11)$$

$$+ S[0.023517 - 0.00023656T + 0.00047036(T/100)^2]$$

where T is temperature in °K, S is salinity in UNITS, and units are mol/kg. The partial pressure,  $p\text{CO}_2$  can be closely approximated by the fugacity of [CO<sub>2</sub>],  $f[\text{CO}_2]$  [? ].

Once dissolved, CO<sub>2</sub> speciates into the other forms of DIC (including carbonate CO<sub>3</sub><sup>2-</sup> and bicarbonate HCO<sub>3</sub><sup>-</sup>) 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:

$$K_1 = \frac{[\text{H}^+][\text{HCO}_3^-]}{[\text{CO}_2]} \quad (12)$$

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

$$K_2 = \frac{[\text{H}^+][\text{CO}_3^{2-}]}{[\text{HCO}_3^-]} \quad (13)$$

These constants can be computed as:

$$\ln K_1 = 2.83655 - 2307.1266/T - 1.5529413 \ln T \quad (14)$$

$$- (0.207608410 + 4.0484/T)\sqrt{S}$$

$$+ 0.0846834S - 0.00654208S^{3/2} + \ln(1 - 0.001005S)$$

and

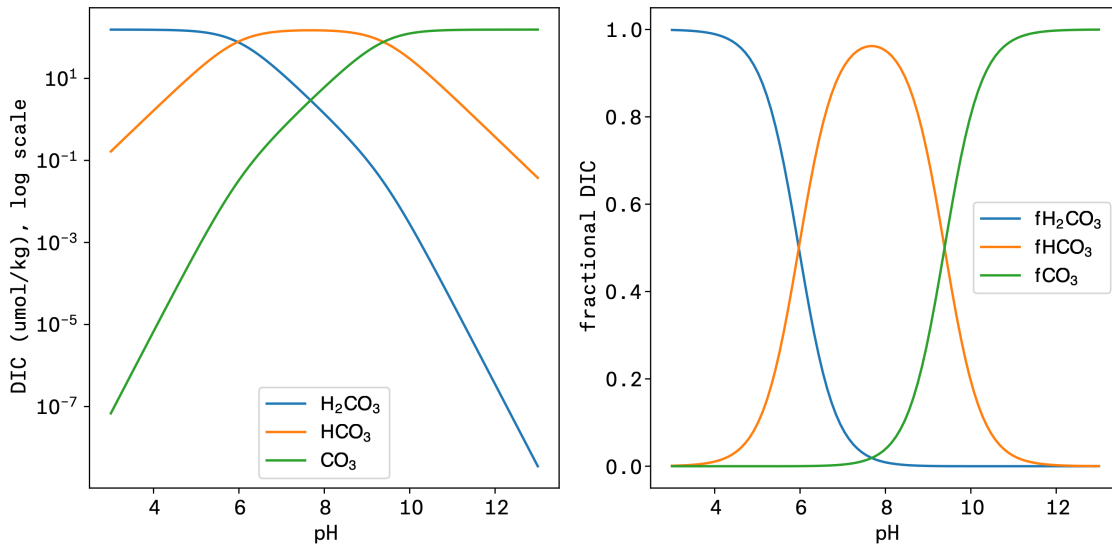
$$\ln K_2 = -9.226508 - 3351.6106/T - 0.2005743 \ln T - (0.106901773 + 23.9722/T)\sqrt{S} + 0.1130822S - 0.00846934S^{3/2} + \ln(1 - 0.001005S) \quad (15)$$

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

Dissolved organic carbon (DIC) is the sum of all dissolved forms, including  $\text{CO}_2$ ,  $\text{HCO}_3^-$ , and  $\text{CO}_3^{2-}$ , and is notated as DIC or  $\sum \text{CO}_2$ , as defined in the following equation:

$$\text{DIC} = [\text{CO}_2] + [\text{HCO}_3^-] + [\text{CO}_3^{2-}] \quad (16)$$

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  $[\text{H}^+]$  in the water, and therefore impacts the pH. These relationships are shown in Figure 43 below.



**Fig. 43.** DIC speciation vs. pH, showing  $\text{CO}_2$ ,  $\text{HCO}_3^-$ , and  $\text{CO}_3^{2-}$ , 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:

$$\text{CA} = [\text{HCO}_3^-] + 2 * [\text{CO}_3^{2-}] \quad (17)$$

$\text{CO}_3^{2-}$  has twice the influence on CA as  $\text{HCO}_3^-$  because it has two negative charges, while  $\text{HCO}_3^-$  only has one.

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

$$[\text{H}^+] = [\text{HCO}_3^-] + 2 \cdot [\text{CO}_3^{2-}] + [\text{OH}^-]. \quad (18)$$

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:

$$\text{TA} = [\text{HCO}_3^-] + 2 \cdot [\text{CO}_3^{2-}] + [\text{OH}^-] - [\text{H}^+] \quad (19)$$

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

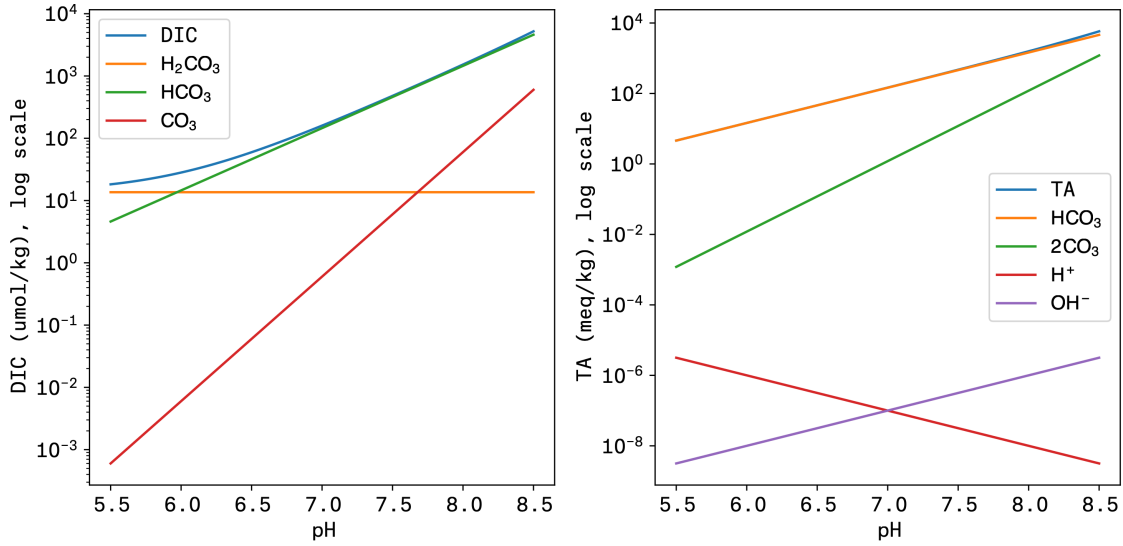
$$\text{TA} = \sum_j z_j [c_j] \quad (20)$$

where  $c_j$  is an ion of interest,  $c$  is the concentration of that ion (units mol/kg)  $z$  is the valence of that ion (1, 2, or 3, positive or negative), hence 2 for  $[\text{CO}_3^{2-}]$  and -1 for  $[\text{H}^+]$ .

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  $\text{CO}_2$ , 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  $\text{H}^+$  ions equivalent to the excess of proton acceptors over proton donors in one kg of sample. Bases formed from acids with  $\text{p}K_a=4.5$  are proton acceptors, while acids with  $\text{p}K_a < 4.5$  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



**Fig. 44.** Carbonate species as they comprise DIC (left) and total alkalinity (right) across a range of pH.

anions can be computed as a charge. To maintain electroneutrality, the sum of the positive charges must equal the sum of the negative charges.

$$\begin{aligned}
 & [Na^+] + 2 * [Mg^{2+}] + 2 * [Ca^{2+}] + [K^+] + [H^+] \\
 & - [Cl^-] - 2 * [SO_4^{2-}] - [NO_3^-] - [HCO_3^-] - 2 * [CO_3^{2-}] - [B(OH)_4^-] - [OH^-] = 0
 \end{aligned} \tag{21}$$

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

## A.2.2 Explorations of Carbonate Chemistry

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 (positively charges) over conserved anions (negative charges). Conserved in this context means that they don't 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:

$$\begin{aligned}
 TA = & [Na^+] + 2 [Mg^{2+}] + 2 [Ca^{2+}] + [K^+] + \dots + \\
 & - [Cl^-] - 2 [SO_4^{2-}] - [NO_3^-]
 \end{aligned} \tag{22}$$

The importance of this expression is that it relates a change in TA by way of a conserved cation, such as  $[\text{Mg}^{2+}]$  or  $[\text{Ca}^{2+}]$  originating from mineral dissolution, to a change in TA that includes carbonate terms, i.e.  $[\text{HCO}_3^-]$  and  $[\text{CO}_3^{2-}]$ . The sum of total charges remain constant even while the forms of DIC change. Below, we will develop an expression for this change,  $d\text{DIC}/d\text{TA}$ , 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  $[\text{HCO}_3^-]$  and divalent  $[\text{CO}_3^{2-}]$ , which causes the stoichiometric ratio to value between 1:2 (two  $[\text{HCO}_3^-]$  per  $[\text{Mg}^{2+}]$  or  $[\text{Ca}^{2+}]$ ) at lower pH down to 1:1 (one  $[\text{CO}_3^{2-}]$  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  $[\text{HCO}_3^-]$  and  $[\text{CO}_3^{2-}]$  varies with acidity, the answer is not straightforward. Nonetheless, we will arrive at an analytical expression for  $d\text{DIC}/d\text{TA}$  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 leakage of  $[\text{CO}_2]$  back into the atmosphere.

First, simplify the expressions for DIC and TA to be functions of  $[\text{CO}_2]$  and  $[\text{H}^+]$  alone. For convenience (and consistency with Zeebe [12]) we'll use notation where  $s = [\text{CO}_2]$  and  $h = [\text{H}^+]$ .

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

$$[\text{OH}^-] = \frac{K_w}{h} \quad (23)$$

From (3.5) express  $[\text{HCO}_3^-]$  as:

$$[\text{HCO}_3^-] = s \cdot \frac{K_1}{h} \quad (24)$$

From (3.5) and (3.6) express  $[\text{CO}_3^{2-}]$  as:

$$[\text{CO}_3^{2-}] = s \cdot \frac{K_1 K_2}{h^2} \quad (25)$$

These allow us to express DIC and TA as:

$$DIC = s \cdot \left[ 1 + \frac{K_1}{h} + \frac{K_1 K_2}{h^2} \right] \quad (26)$$

$$TA = s \cdot \frac{K_1}{h} + s \cdot 2 \cdot \frac{K_1 K_2}{h^2} + \frac{K_w}{h} - h \quad (27)$$

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

$$\frac{dTA}{dh} = -s \cdot \left( \frac{K_1}{h^2} + 4 \cdot \frac{K_1 K_2}{h^3} \right) - \frac{K_w}{h^2} - 1 \quad (28)$$

Next compute the derivative  $dDIC/dh$ :

$$\frac{dDIC}{dh} = -s \cdot \left( \frac{K_1}{h^2} + 2 \cdot \frac{K_1 K_2}{h^3} \right) \quad (29)$$

Finally multiply  $dDIC/dh$  by the inverse of  $dTA/dh$  to calculate  $dDIC/dTA$ :

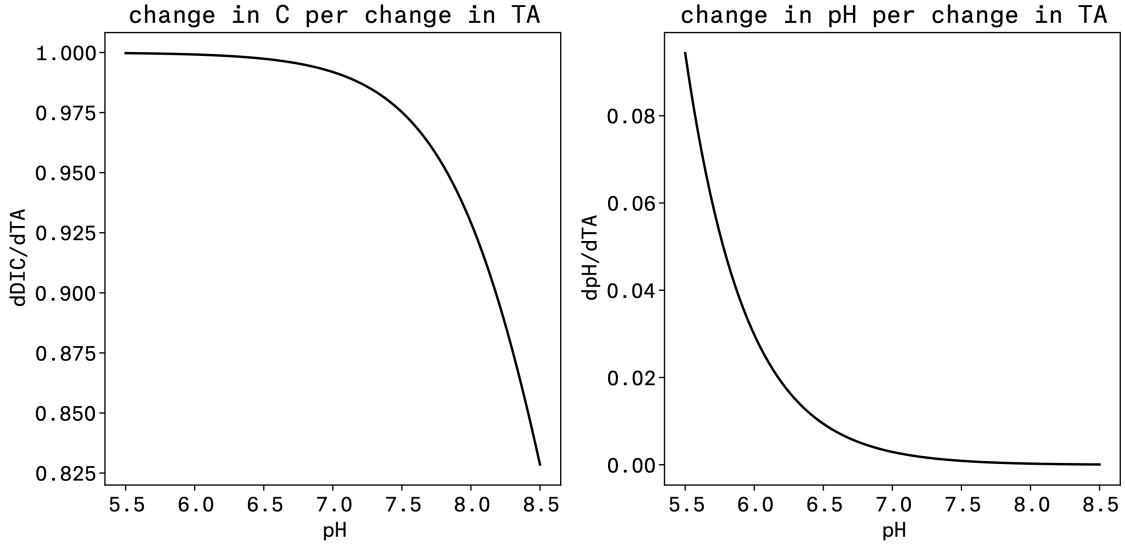
$$\frac{dDIC}{dTA} = \frac{dDIC}{dh} \cdot \frac{dh}{dTA} \quad (30)$$

What these calculations show is that (at constant temperature and salinity) at lower pH values, the C storage per cation introduced is higher than the C 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  $\text{CO}_3^{2-}$ , not just  $\text{HCO}_3^-$  (Figure 45a). At lower pH, the change in pH is also more significant per unit TA than at higher pH (Figure 45b).

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.

$$\frac{dpH}{dTA} = -\log_{10}(e) \cdot \frac{1}{h} \cdot \frac{dh}{dTA} \quad (31)$$

Figure 45 shows that across any value of pH, additions in alkalinity always result in positive increases in pH and thus reductions in acidity.



**Fig. 45.** Change in derivatives of carbonate system with respect to changes induced by a change in alkalinity. Derivatives of DIC (left) and pH (right).

### A.2.3 Carbonate Chemistry in the Ocean

In the ocean, dissolved boric acid contributes to the alkalinity budget. Total boron, that is the sum of  $B(OH)_3$  and  $B(OH)_4^-$ , 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:

$$K_B = \frac{[H^+][B(OH)_4^-]}{[B(OH)_3]} \quad (32)$$

It is computed as:

$$\begin{aligned} \ln K_B = & \left( -8966.9 - 2890.53S^{1/2} - 77.942S + 1.728S^{3/2} - 0.0996S^2 \right) / T \\ & + 148.0248 + 137.1942S^{1/2} + 1.62142S \\ & - \left( 24.4344 + 25.085S^{1/2} + 0.2474S \right) \ln T + 0.053105S^{1/2}T \end{aligned} \quad (33)$$

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

$$\frac{dT_A}{dh} = -s \cdot \left( \frac{K_1}{h^2} + 4 \cdot \frac{K_1 K_2}{h^3} \right) - \frac{K_B B_T}{K_B + h^2} - \frac{K_w}{h^2} - 1 \quad (34)$$

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:

$$pA = [HCO_3^-] + 2 * [CO_3^{2-}] + [B(OH_4)^-] + [OH^-] - [H^+] \quad (35)$$

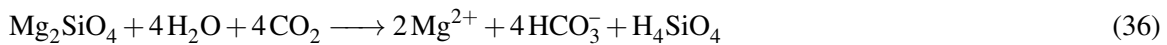
The equilibrium constants in the carbonate equations depend on pressure and temperature, which vary throughout the water column. Thus, as carbon sinks from the surface to deeper waters, these values change. However, when only the temperature and pressure change (and not salinity), DIC and TA are constant.

Ocean alkalinity is roughly -2.5. As pH increases, with no other changes to the system, carbonate alkalinity will decrease (Figure 46).

### A.3 Quantifying Potential Geochemical CO<sub>2</sub> Removal

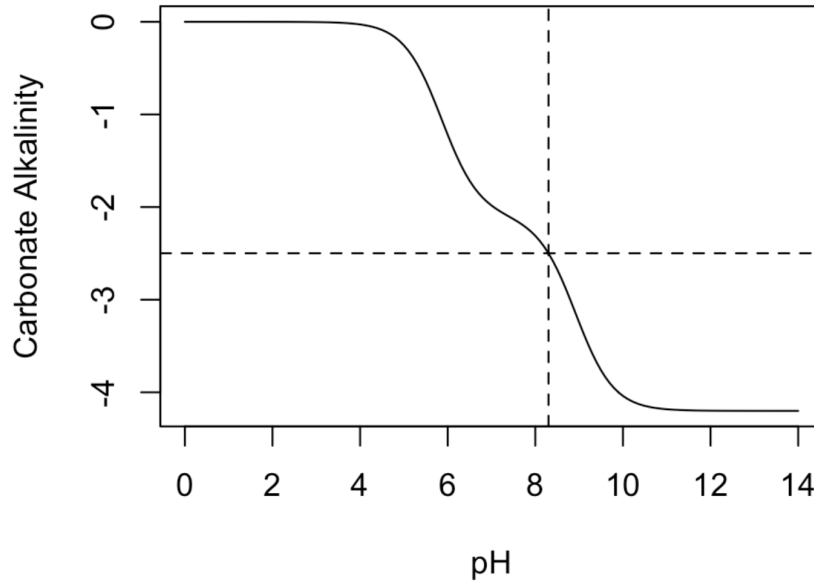
#### A.3.1 Mineral Potential

Once crushed silicate or carbonate rocks are spread on agricultural fields the weathering reaction takes place. This is a natural process that does not require any energy inputs and is thermodynamically irreversible. However, the weathering chemistry varies based on the mineral feedstock and each feedstock has a Mineral Potential (MP), which is the amount amount of CO<sub>2</sub> it can stoichiometrically sequester. For magnesium silicate materials, the archetypal weathering reaction takes the following form:



In this reaction, one mole of magnesium silicate reacts with four moles of CO<sub>2</sub>, so two negatively charged bicarbonate  $HCO_3^-$  are created for every one divalent  $Mg^{2+}$  weathered. Given the molecular weight of  $Mg_2SiO_4$  (140g/mol) and the molecular weight of CO<sub>2</sub> (44g/mol), weathering one metric tonne of  $Mg_2SiO_4$  removes 1.25 metric tons of CO<sub>2</sub> from the atmosphere. Beerling (2020) [6], citing Renforth (2012) [30], citing O'Connor (2004) [25], citing Goff and Lackner





**Fig. 46.** This figure shows carbonate alkalinity vs. pH. The dashed lines show where pH=8.3, and carbonate alkalinity = -2.5.

(1997) [69] provides mineral potential (MP) for CO<sub>2</sub> removal based on feedstock chemical composition in terms of MgO% and CaO%, shown in Equation 37.

$$MP \equiv \frac{tCO_2e}{tOre} = \frac{MW_{CO_2}}{100\%} \cdot \left( \frac{MgO\%}{MW_{MgO}} + \frac{CaO\%}{MW_{CaO}} \right) * V \quad (37)$$

### A.3.2 Leakage

In equation 37,  $V$  is the valence of the cation (2 for Mg and Ca) and  $MW$  is the molecular weight of the mineral. To estimate the net removal of CO<sub>2</sub> from silicate weathering, we need to consider the fate of dissolved inorganic carbon (DIC) as it moves through the environment to the ocean, and account for any CO<sub>2</sub> leakage. Following the derivation in A.2 the amount of CO<sub>2</sub> initially absorbed from the atmosphere when the mineral is dissolved in an acidic soil, ( $CDR_{gross}$ ) is determined by the mineral potential  $MP$  of the rock, multiplied by the fraction of dissolved inorganic carbon (DIC) uptake per unit of total alkalinity  $TA$  increase (Eq 30), at the temperature and pH conditions of the aqueous environment on land, as shown in equation 38. This equation represents the equilibrium conditions of perturbations to the carbonate system due to the mineral dissolution. The DIC then moves through terrestrial waterways to the ocean where the pH changes from the acidic conditions found on land (pH 5-6) to the colder and more alkaline conditions of the ocean (pH ~ 8). Most saliently here, The DIC of the ocean has about 10% CO<sub>3</sub><sup>2-</sup> compared to only 0.001% in soils (Figure 43). This means 10% of the Mg<sup>2+</sup> or Ca<sup>2+</sup> in solution is matched 1:1 with a CO<sub>3</sub><sup>2-</sup> ion and

a portion of  $\text{CO}_2$  is lost to the atmosphere due to this pH forcing. We interpret this as a form of leakage of sequestered carbon, and it is a standard feature of the literature on this topic [6, 30, 66]. The leakage is calculated as shown in Equations 39 and 40. With these expressions in place, we can compute  $\text{CDR}_{\text{net}}$  as  $\text{CDR}_{\text{gross}}$  minus the leakage, as shown in equation 41.

$$\text{CDR}_{\text{gross}} = MP \cdot \left. \frac{d\text{DIC}}{d\text{TA}} \right|_{\text{land}} \quad (38)$$

$$f_{\text{Leakage}} = \left. \frac{d\text{DIC}}{d\text{TA}} \right|_{\text{land}} - \left. \frac{d\text{DIC}}{d\text{TA}} \right|_{\text{sea}} \quad (39)$$

$$\text{Leakage} = -MP \cdot f_{\text{Leakage}} \quad (40)$$

$$\text{CDR}_{\text{net}} = \text{CDR}_{\text{gross}} - \text{Leakage} \quad (41)$$

### A.3.3 Worked Example

Consider a standard reference material, a magnesium silicate with 47.45% MgO and 0.22% CaO. The Mineral Potential of this silicate is 1.047 tCO<sub>2</sub>/tOre per Eq 37. Let us apply to a soil with pH 5.5 at a standard temperature of 25°C, with an ultimate destination in the ocean at pH 8.08 and 16.1°C (global mean oceanic values), and a boundary condition for atmospheric pCO<sub>2</sub> of 400ppm (Fig. 47). Applying the equations in Section A.2, we compute the constants and  $d\text{DIC}/d\text{TA}$  for land (Fig. 48) and ocean (Fig. 49). These calculations result in a leakage of 14.3% (Fig. 50). In reality, these reactions will not be under conditions representing the mean ocean, nor will they be under conditions at an exact transition boundary between a river and the ocean. Instead, the parameters will depend on a dynamic turbulent mixing process that is intermediate between the two extremes. Research is underway within the scientific community using numerical simulation models combining biogeochemistry and ocean fluid dynamics to refine the understanding of this parameter.

Land Parameters	
Land pH	5.5
Land Temperature (°C)	25
Land Temperature (°K)	298.2
Ocean Parameters	
Ocean pH:	8.08
Ocean Salinity:	35
Ocean Temperature (°C)	16.1
Ocean Temperature (°K)	289.3
pCO <sub>2</sub>	400

Fig. 47. Land and ocean parameters for the carbon sequestration model.

Land Calculations	
Kh	0.03402
pKw	12.543
pK1	5.971
pK2	9.385
Kw	2.86E-13
K1	1.07E-06
K2	4.12E-10
h	3.16228E-06
s	1.36E+01
dTA/dh	-1.46E+06
dDIC/dh	-1.46E+06
dDIC/dTA	0.99974

Fig. 48. Land calculations for the CO<sub>2</sub> removal model.

Ocean Calculations	
Kh	0.04395
pKw	14.643
pK1	5.940
pK2	9.078
pKb	8.702
Kw	2.28E-15
K1	1.15E-06
K2	8.36E-10
Kb	1.98E-09
h	8.31764E-09
s	1.76E+01
TB	4.16E-04
dTA/dh	-4.09E+11
dDIC/dh	-3.51E+11
dDIC/dTA	0.85666

Fig. 49. Ocean calculations for the CO<sub>2</sub> removal model.

Net Calculations	
Gross CDR, tCO <sub>2</sub> e / tOre:	1.047
Leakage, %:	0.143
Net CDR, tCO <sub>2</sub> e / tOre:	0.897

Fig. 50. Net Carbon Dioxide Removal (CDR) per tonne of ore.

## B. Appendix B: Critical Review

### B.1 Critical review of the goal and scope definition

The goal and scope are clearly defined and consistent with the intended application. The goal of the study unambiguously states two overall objectives (1) “to investigate if the sequestered carbon per tonne of CarbonLock™ exceeds that of its cradle to grave life cycle emissions”, and (2) “to provide a comparison to the current industry standard for managing the pH of agricultural soils—limestone and dolomite”. In addition, the stated reason for carrying out the study and the intended audience is also clearly disclosed, “the target audience for this report are reviewers for the U.S. Treasury’s 45Q carbon credits program”, as Eion Corp is seeking approval to receive carbon credits for CO<sub>2</sub> sequestered using CarbonLock™.

The scope of the LCI/LCIA is clearly described; reviewer comments are as follows:

- *The functions of the studied product systems:*  
The functions of the product system are discussed in detail within section 1.2-1.6, primary functions of the product, though complex in their delivery, are the provisioning of alkalinity to agricultural soils to manage soil pH levels in support of increased crop yields and the removal and sequestration of atmospheric CO<sub>2</sub>.
- *The functional unit:*  
The functional unit for this study is described as “one tonne of ore (t Ore)”. While the study report clearly states the reasons for its selection (e.g., “scales across different time-scales and scenarios”), the functional unit should, as far as possible, relate to the functions of the product rather than to the physical product. For example, the practitioner may wish to consider, for example, “annual t Ore to raise soil pH by 1 in U.S. agricultural croplands”, rather than “t Ore”. In this way, it better addresses the obligatory properties, the duration of the product performance, and the comparative products assessed.
- *System boundaries criteria and justification:*  
The system boundary is adequately presented in Figures 8 and 9, and appears to include all major processes (>1% anticipated emissions), including extraction, transport, processing, application, and sequestration. Hydrology processes associated with the fate and transport of sequestered CO<sub>2</sub> through groundwater, surface water, estuary and to the eventual sea (sink) and potential leakage is acknowledged, with literature-based assumptions provided, though it is recommended that these processes receive additional scrutiny.
- *Allocation procedures:*  
No co-products are assessed in the current report and no allocation is performed in this LCA.
- *Impact categories:*  
The study only considers the LCIA impact category of Global Warming Potential (GWP) in terms of kgCO<sub>2</sub>e/tOre (later, to the functional unit of metric ton of Calcium Carbonate Equivalent, tCCE).
- *Methodology for impact assessment and interpretation:*  
Study only considers one impact category (GWP), no normalization conducted, using GWP ref: IPCC AR5, 100-year time horizon; accounting for carbon climate feedback.

- *Initial data and data quality requirements:*  
Data and data quality appear to be reasonably considered and are based on largely acceptable sources and methods. The study relies heavily on the SHERPA model for data outputs of extraction and processing, with the transportation and application inventories based on data taken from the public domain literature and referenced according to the ISO/TR 14049:2000(E) standard.
- *Assumptions and limitations:*  
Assumptions and limitations are presented in section 3.8 and appear to be inclusive of key issues of potential importance to the studies interpretation.
- *Critical review:*  
A peer review of an interim report was conducted by Dr. Timothy Smith, Professor of Bio-products & Biosystems Engineering (March 3-8, 2022). While this review does not explicitly determine conformance to ISO 14040 and 14044, based on the scientific and technical judgement of the reviewer, the review found no evidence of significant errors, omissions or manipulations that would affect the LCA's conformance with the standards. The methods presented and used to carry out the life cycle assessment are scientifically and technically robust and valid.

## **B.2 Critical review of the inventory analysis**

Inventories developed for the study appear reasonable and sufficient disaggregation for the purposes laid out in the project's scope and purpose (e.g., comparative simulation). The study created its own spreadsheet-based models for calculation, making it somewhat difficult to verify calculations within each aggregated process tab.

- For development/capital at quarry and mill production, inventories relied heavily on the SHERPA model, with input/validation provided by expert engineering review. While this study deviates from previous literature-based LCAs of these technologies, in that it uses its own (and arguably better, more disaggregated) process inventories, the study would benefit from greater detailed reporting of data sources. For example, it is unclear whether the SHERPA model includes CO<sub>2</sub> calculations, or if emissions factors at each of the disaggregated processes are based on outside literature or LCA background data sources.
- Transportation and application inventories are fairly straight forward and appear sufficient give the scope and purpose of the study.
- Geographical representativeness is accounted for in parameterization and incorporates system differences across the electricity generation mix and transport differences between extraction, production, and application stages. It is unclear the degree to which emissions factors utilized account for transmission and distribution losses or geographical variation with regard to process heat.
- Given the relatively cursory nature of this review, factual validation of data was restricted to comparisons of key inputs with earlier measurements and similarly conducted previous LCA studies. Similarly, checks on calculations were constrained to the chemical equations provided by the study authors. Review of these relationships and resulting sequestration results would require empirical validation beyond the scope of this review.

### **B.3 Critical review of the impact assessment**

As previously stated, characterization and the characterization/emissions factors applied within the study's spreadsheet models could be better documented in a transparent manner and value-choices, along with assumptions made during their selection (e.g. to supplement Fig. 22). That said, and given that this is a new technology without established empirical research or experience to inform system performance in practice, the characterization of CO<sub>2</sub> sequestration and leakage is largely theoretical. While largely outside of the scope of this study, the sequestration and storage potential of this technology will likely be influenced significantly by the amount of CO<sub>2</sub> a mineral stock can stoichiometrically sequester and the hydrological movement of the dissolved inorganic carbon (DIC) as it moves through the environment to the ocean. Calculations for these stages are presented with adequate transparency, with typical ranges provided for key parameters (e.g. Mineral Potential (1.077, range= 0-1.2) and leakage percent (14.3%, range 15-30%). It is difficult to assess from the study the validity of these values, though some insight is gained through sensitivity analysis.

### **B.4 Critical review of the interpretation**

The results of this study are interpreted appropriately in relation to the goal and scope of the study. The interpretation includes adequate coverage of data quality assessment and a sensitivity analysis. In addition, sufficient care was taken by the authors to consider possible limitations of conclusions made. Given, the purpose and scope of the study, interpretations and conclusions are driven largely by scenario selection and sensitivity analysis. The processes and characterization of mineral extraction and processing are well understood and reasonably applied to this context. These stages are also, relatively insignificant to the overall interpretation and conclusions presented by the study (e.g., ERW can capture and sequester significant amounts of CO<sub>2</sub> from the atmosphere and store it, ultimately and indefinitely, in oceans). It is the opinion of this reviewer, that the veracity of this interpretation and conclusion deserves more attention in the sensitivity analysis presented. While the existing analysis addresses variability assumptions related to MP and pH assumptions in application, a broader assessment across the range of MP and key parameters of the hydrology system (e.g., movement over time DIC to the ocean and potential leakage) seems appropriate, as these impacts are 4-5 times those of processing stages in key scenarios.