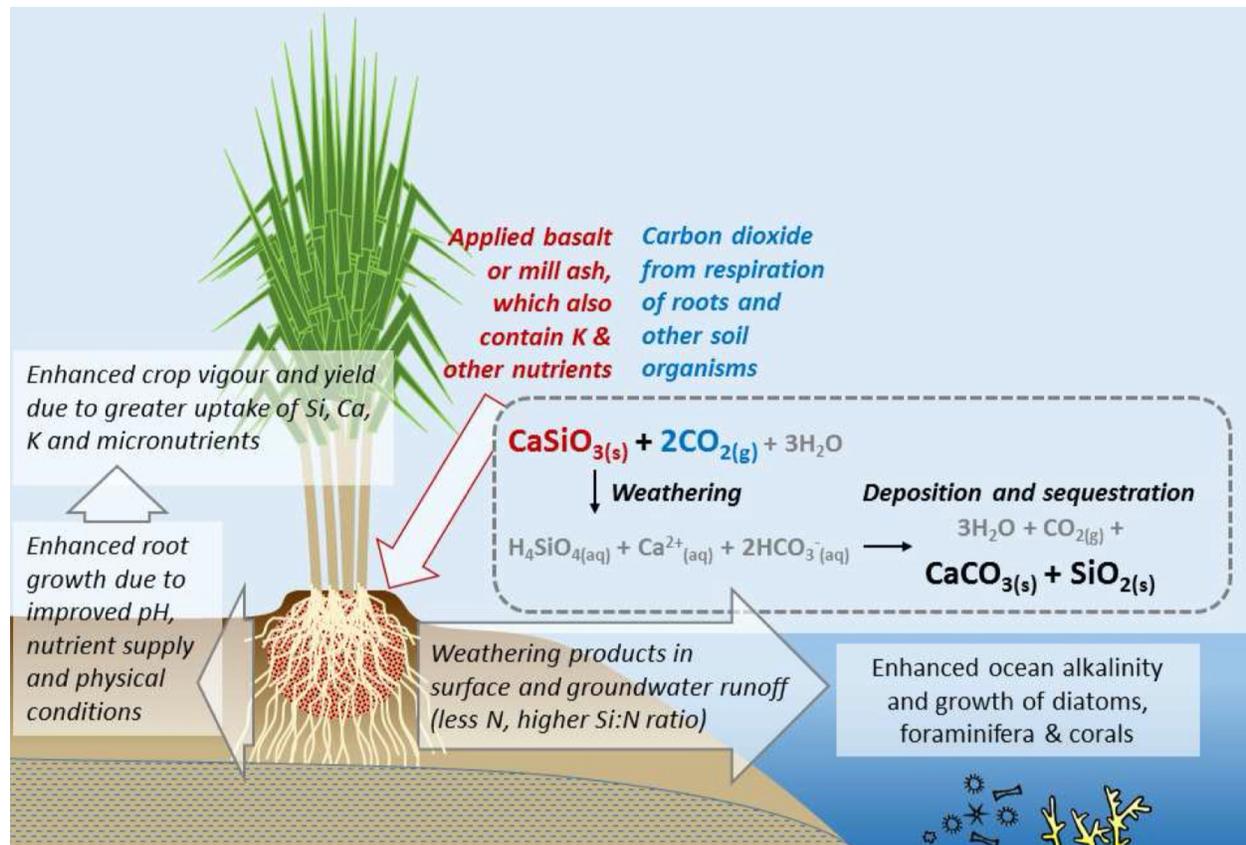


C. Enhanced Weathering using Cropland and Ocean

A form of accelerated weathering (EW) that markedly improves its desirability as a NET is spreading ground-up silicate rocks onto farmlands. This was proposed by Beerling et al (2018) and others (Schuiling & Krijgsman 2006; Kohler et al, 2010; Taylor, et al, 2016, 2017) and is outlined in the following figure.

Parts of the following is taken verbatim from Beerling et al.



Concept of farming with crops and rocks by Beerling et al (2018)

In soils, chemical breakdown of silicate rocks is accelerated during aqueous reactions with the elevated soil CO_2 environment, releasing base cations (Ca^{++} and Mg^{++}) and delivering bicarbonate (HCO_3^-) anions via runoff to surface waters and eventually the ocean. Enhanced weathering, therefore, uses the oceans to store atmospheric CO_2 as these stable dissolved inorganic alkaline forms. Given the oceans worldwide store around 38,000 Pg C, >45 times the mass of C in the current atmosphere, their future storage capacity is not an issue. The

residence time of dissolved inorganic carbon in the global ocean is around 100,000 – 1,000,000 years, making it essentially a permanent C-storage reservoir on human timescales.

There are two potential types of mineral for this use: carbonates and silicates. Beerling et al (2018) chose silicates because carbonate weathering on acidic agricultural soils can lead to a net CO₂ flux to air and carbonate minerals lack silica (Si) and other plant nutrient elements. Thus, the process of carbonate weathering on land delivers fewer benefits to climate, soils and crops.

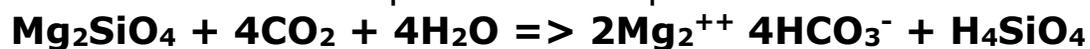
The silicate rocks are igneous, which means that they formed from cooled volcanic magma. Granite and basalt are the most common igneous rocks. Basaltic magma is what comes out when the earth's crust is cut through. As an eruption ends, the basalt "scab" heals the wound in the crust. Since it cools very quickly, the minerals have very little opportunity to grow and are very fine grained. Most of the ocean floor is basalt, and most of the continents are granite but there are continental areas where the basalt shows through.

Olivine and Dunite: Advantages and Disadvantages

The silicon rocks in question are called **mafic** and sometimes **ultramafic** – ma for magnesium and fic refers to iron. Mafic rocks are generally dark in color and heavy due to the amount of iron, magnesium, and several other relatively heavy elements they contain.

The most common ultramafic rocks are dunite, peridotite, and serpentine. Serpentine is out because it is rich in asbestos – a clear no, no. **Dunite** is best because it is rich in **olivine**. Olivine is one of the most rapidly weathering and thus CO₂ adsorbing, rocks in existence. Its chemical composition is (Mg,Fe)₂SiO₄. Subtypes are forsterite, (Mg₂SiO₄) and fayalite (Fe₂SiO₄).

The relevant equation for sequestration is:



Thus, one mole of olivine can sequester 4 moles of CO₂.

The cost of commercially mined olivine is \$50 to \$110 per short ton (1.1 metric ton), depending on grade and size (Kramer,

2020). The U.S. production of olivine is less than 100,000 metric tons/yr. We import from Norway approximately 200,000 metric tons/yr. It is mainly used in foundries for slag conditioning and foundry sand. The two U.S. companies that produce olivine are Unimin Corp (North Carolina and Washington) and Olivine Corp (Washington). The reserves in the Smokey Mountains, North Carolina are about 200,000 million metric tons, while the reserves in Washington are about 17 million metric tons. The total world production of olivine was approximately 8 million metric tons in 1999.

In a study of the financial and carbon costs of enhanced weathering using ultramafic rocks such as dunite, Moosdorf et al (2014) concluded that terrestrial enhanced weathering consumes more CO₂ than it emits for mining, crushing, grinding, transport, and application in most locations. On average, 0.5-1.0 ton of CO₂ is sequestered per ton of rock. They also stated that very large amounts of rock would be needed to control or reduce the atmospheric CO₂ concentrations substantially with enhanced weathering. Before enhanced weathering could be applied at large scales, more research is needed to assess weathering rates, potential side effects, social acceptability, and mechanisms of governance.

Strefler et al (2018) showed that enhanced weathering is an option for carbon dioxide removal that could be competitive at 60 US \$/t CO₂ removed for dunite, but only at 200 US \$/t CO₂ removed for basalt. The potential carbon removal on cropland areas could be as large as 95 Gt CO₂/a for dunite and 4.9 Gt CO₂ 2/a for basalt.

Under side effects, a synthesis by Beerling et al (2018), of published chemical analyses indicates that olivine-rich ultramafic rocks contain relatively high concentrations of either **chromium** (Cr) or **nickel** (Ni) or both. Weathering experiments reveal fast release of bioavailable Ni from olivine, and suppression of plant calcium uptake, because of competition with magnesium. Experimental work with a soil column dosed with olivine suggested accumulation of Ni and Cr in the soil profile (Renford, et al, 2015). Widespread application of olivine to agricultural soils, therefore, could introduce harmful metals into the food

chain, and the wider environment, as well as causing nutritional imbalances and warrant further research.

Basalt: Advantages and Disadvantages

In contrast to ultramafic olivine-rich rocks, major continental flood basalts have lower concentrations of Ni and/or Cr but significantly higher concentrations of phosphorus, suggesting their greater utility for croplands. Cultivation of crops on rich fertile soils that develop on flood basalts across continents is consistent with fewer environmental risks associated with this rock.

Basalt is widely recognized as producing productive soils because it weathers rapidly releasing elements essential for plant growth (Hinsinger, et al. 2001), including P, K, Ca, Mg and Fe. In terms of comparative weathering rates, olivine dissolution rates at oceanic pH~8 are within the range of those for basalt dissolution rates at pH 4 and above expected in soils.

Significant potential exists for deployment at scale to remove atmospheric CO₂ with ground basalt. A maximum carbon capture potential of ~0.3t CO₂/t is suggested for basalt, assuming a sufficiently fine particle size for effective dissolution on decadal time scales (Renforth, 2012). The actual particle size will depend upon the mineralogy of the basalt, climate and biological activity, and requires further investigation and verification, but initial calculations suggest particles of 10-30 μm diameter.

On this basis, basalt applications of 10 to 50 t/ha/yr to 70 × 10⁶ ha of the annual crops of corn or soy in the corn-belt of North America could sequester 0.2–1.1 PgCO₂, up to 13% of the global annual agricultural emissions, in the long run (Kantola, et al 2017).

Theoretical estimates of CO₂ capture and sequestration schemes involving global croplands and silicate rocks are very uncertain. Provisional estimates (Smith, et al, 2016), 40 suggest that amending two thirds of the most productive cropland soils (9 × 10⁸ ha) with basalt dust at application rates of 10-30 t/ha/yr could perhaps extract 0.5-4 PgCO₂/yr by 2100 depending on climate, soil and crop type. These numbers still need to account for full life cycle assessment but suggest enhanced weathering

could make a significant contribution to the negative emissions required by deep decarbonization strategies (Anderson & Peters, 2016; Rockstrom, et al. 2017; Field & Mach, 2017) and the ~ 1 Pg CO₂ eq/yr reduction from agriculture by 2030.

Involvement of extensive marginal lands classified as not productive, or cost-effective, for food crops, further increases the potential for offsetting anthropogenic CO₂ emissions, although these lands would tend to be less accessible. Better constraining the appropriate particle size particles of 10-30 μ m diameter.

A key issue affecting carbon capture efficiency is the energy cost associated with mining, grinding and spreading the ground rock, which could reduce the net carbon drawdown by 10-30%, depending mainly on grain size. Relatively high energy costs for grinding, as influenced by rock mineralogy and crushing processes, call for innovation in the industrial sector, such as grinding and milling technology powered by renewable energy sources (solar, wind, water), to significantly increase the net CO₂ benefit. The benefit will increase as future energy sources are decarbonized, the grinding process becomes more energy efficient, and by utilizing already ground waste silicate materials previously or currently produced by the mining industry. By driving down costs for grinding in this way, carbon sequestration costs would be correspondingly cheaper.

In regard to using **waste materials**, according to Renforth (2019) seven billion tons of alkaline materials are produced globally each year as a product or by-product of industrial activity. The aqueous dissolution of these materials creates high pH solutions that dissolves CO₂ to store carbon in the form of solid carbonate minerals or dissolved bicarbonate ions. He showed that these materials have a carbon dioxide storage potential of **2.9–8.5 billion tons per year by 2100**, and may contribute a substantial proportion of the negative emissions required to limit global temperature change to < 2 °C.

Current cost estimates are uncertain and vary widely, and better understanding the economics involved is a priority. The most detailed analysis for operational costs drawn-up for using a basic rock, such as basalt, gives values of US\$52-\$480 t/CO₂, with grinding and transport the dominant components (Renforth,

2012). This cost range falls below that estimated for bioenergy with carbon capture and storage (BECCS) of \$504-\$1296 t/CO₂ (\$140-\$360 t/C)(Smith, et al, 2016). Deployment costs may be partially or completely offset by gains in crop productivity, and reduced requirements for lime, fertilizer, pesticide and fungicide applications, discussed later.

Given that farmers routinely apply granular fertilizers and lime, annual applications of, for example, ground basalt (an abundant, weatherable Ca- and Mg-rich rock) is feasible at large scale with existing farm equipment.

Enhanced weathering strategies not only capture carbon but could also help restore soils and resupply impoverished reserves of trace elements important for human nutrition and crop production (Guntzer, et al 2012). The discovery of silicon transporters in several plants indicates the importance of this element. There are multiple ways in which silica helps plants in various types of environmental stress. Si fertilization makes soil phosphorus more available to plants. Seven out of the top ten crops ranked according to global production data (sugarcane, rice, wheat, barley, sugar beet, soybean, and tomatoes) are classified as Si accumulators (> 1%) and intensive cultivation and repeated removal of harvested products from the field is seriously depleting plant available Si in soils. In the US, for example, crop harvesting removes 19 million tons of Si annually (Tubana, et al (2016). Annual depletion of soil Si by continuous intensive farming, coupled with low solubility of soil Si, has led to calls for the development of viable Si-fertilization practices in the near future to increase plant available pools and maintain crop yields.

Dissolution of crushed silicates, or Si-containing mining and industrial wastes, releases Si, replenishing the plant available form. The fate and transformation of enhanced weathering derived Si in the soil-plant continuum, and its long-term biogeochemical cycling, warrant future research in the context of mitigating Si-related yield constraints on agricultural crop production.

An example of the use of crushed basalt in improving crop yields came from sugarcane trials with crushed basalt applications in excess of 20 t/ha in combination with standard NPK fertilizer

treatments increased yields by up to 30% over five successive crops on the highly weathered soils of Mauritius compared with plots receiving fertilizer and no basalt addition.

Rate of Chemical Weathering of the basaltic Deccan Traps shows CO₂ consumption rates of 0.58–2.54 × 10⁶ mol/km²/year (Dessert et al., 2001). Dissolved solid concentration in river waters, induced by basalt weathering on the Island of Réunion indicate CO₂ consumption rates of 1.3–3.4 × 10⁶ mol/km²/year (Louvat and Allègre, 1997). Such values are equivalent to the consumption of up to 130 tons of CO₂ /km²/year. With mine dumps of crushed ultramafic rocks, consumption of more than 4,000 tons CO₂/km² /year has been measured (Wilson et al., 2009).

The following table shows the relative rate of weathering of olivine versus three other silicate minerals (basalt not included) at different pHs. Clearly olivine at pH 4 weathers very rapidly.

Mineral	pH 5.5	pH 4.0
Olivine	200–400	6000–8000
Pyroxene	14–25	20–200
Hornblende	26–30	100–200
Biotite	1.5–1.8	42–53

Rates of mineral dissolution (mg m²/day) obtained in the experiments of Franke & Teschner- Steinhardt (1994).

Studies are needed of the rate of weathering of finely ground native basalt, or waste silicate rocks.

Where are the Basalt Deposits in the United States?

McGrail, B. P., et al (2006) have provided a detailed map of the U.S. showing the location of basalt flood deposits in relation to sources of CO₂ emissions. This is shown as Fig 10 in their paper.

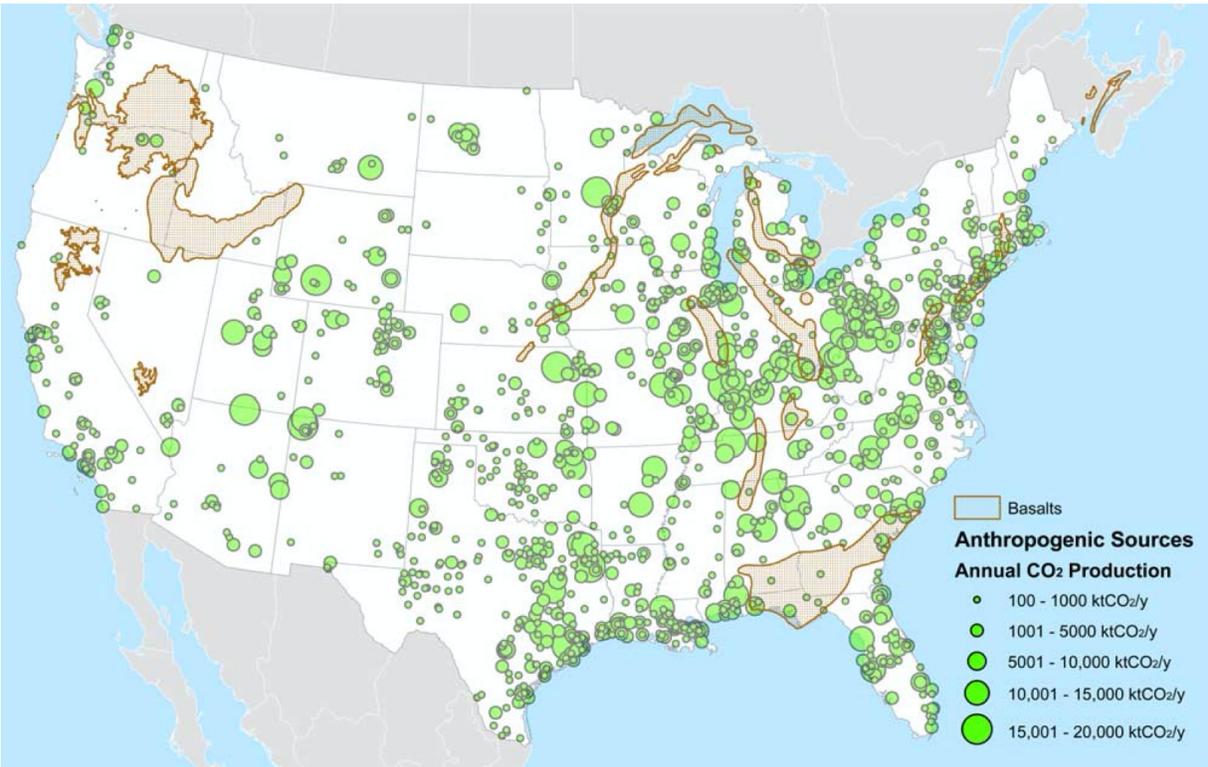


Figure 10. Distribution of major basalt formations in the United States along with distribution of CO₂ sources.

The basalt deposits are shown in brown, the sources of CO₂ in green. In their paper they proposed injecting captured CO₂ in the ground under the basalt deposits. Our focus is on extracting and grinding the basalt and spreading it on croplands. This shows strips of basalt deposits especially in the middle and South east U.S. These should be close enough to croplands to supply them with a source of basalt.

Massive Removal of Atmospheric CO₂ by Weathering

An indication of the immense ability of weathering to remove CO₂ from the atmosphere can be seen in geologic history. Oceanic anoxic events (OAEs) were times of abrupt carbon-cycle perturbations, driven by increases in atmospheric CO₂ largely the result of volcanic eruptions as evidenced by the emplacement of large igneous provinces (LIPs). The cause of oceanic hypoxia following marked increases in atmospheric CO₂ is complex

(Wignall, 2015), but an increase in the metabolism of ocean organisms due to warming plays an important role.

Between 55 and 200 million years ago there have been 9 OAEs (Percival et al, 2016). Sequestration of CO₂ in organic-rich black shales and by reaction with silicate rocks exposed on continents would ultimately restore climatic equilibrium but at the expense of significant chemical change in the oceans and over time scales of tens to hundreds of thousands of years. This long duration is a reflection of the amount of CO₂ spewed into the atmosphere amounting to upwards of 2000 ppm. Since the current CO₂ levels are 410 ppm, a decrease in atmospheric CO₂ by weathering would not take as long. In addition, the process is markedly accelerated by the grinding and fine dispersal of the basalt.

Nitrous oxide N₂O

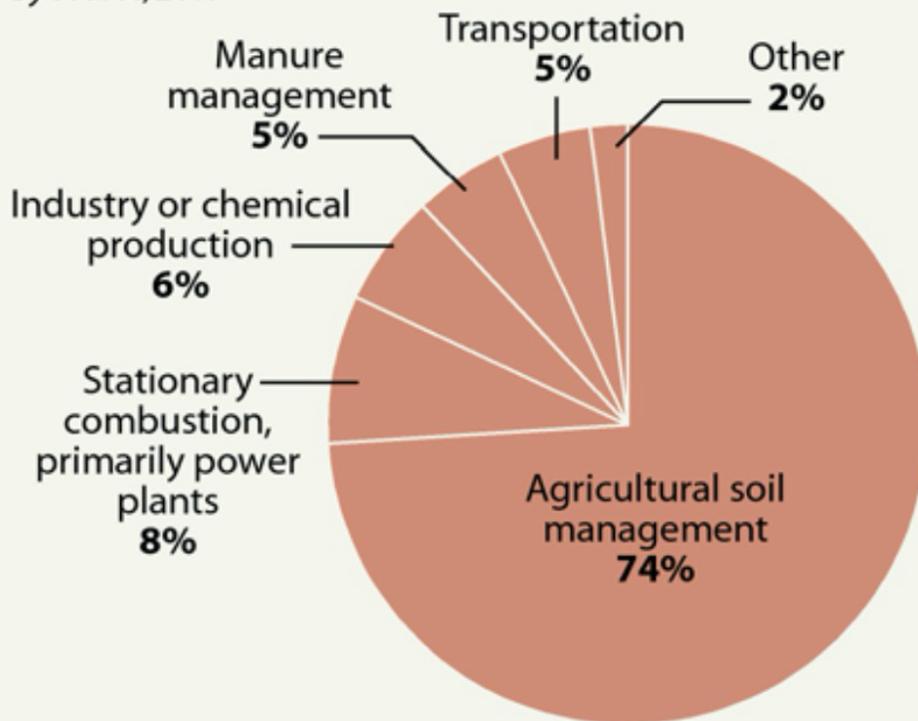
One pound of N₂O warms the atmosphere about **300 times** the amount that one pound of carbon dioxide does over a 100-year timescale. Its potency and relatively long life make N₂O a dangerous contributor to climate change. It also **depletes the ozone layer**. As shown below, about **three fourths of N₂O comes from the soil** and agricultural sources.

Where Does N₂O Come From?

Agriculture, particularly fertilized soil and animal waste, accounts for about three quarters of U.S. nitrous oxide emissions.

U.S. NITROUS OXIDE EMISSIONS

By source, 2017



SOURCE: EPA

PAUL HORN / InsideClimate News

In this regard it is of interest that a further co-benefit that may arise from the agricultural application of crushed silicate rocks to soils is **suppressing emissions of the powerful and long-lived greenhouse gas N₂O** and averting CO₂ emissions caused by liming. Liming with CaCO₃ can release CO₂ when it is applied to acidic soils (pH <6) typical of agricultural lands. In the USA, liming contributes 2% of agricultural greenhouse gas emissions.

Beerling, et al (2018) concluded that substituting a weatherable silicate rock, such as basalt, or silicate waste, for limestone, and increasing application rates over those used in

conventional liming operations, may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy.

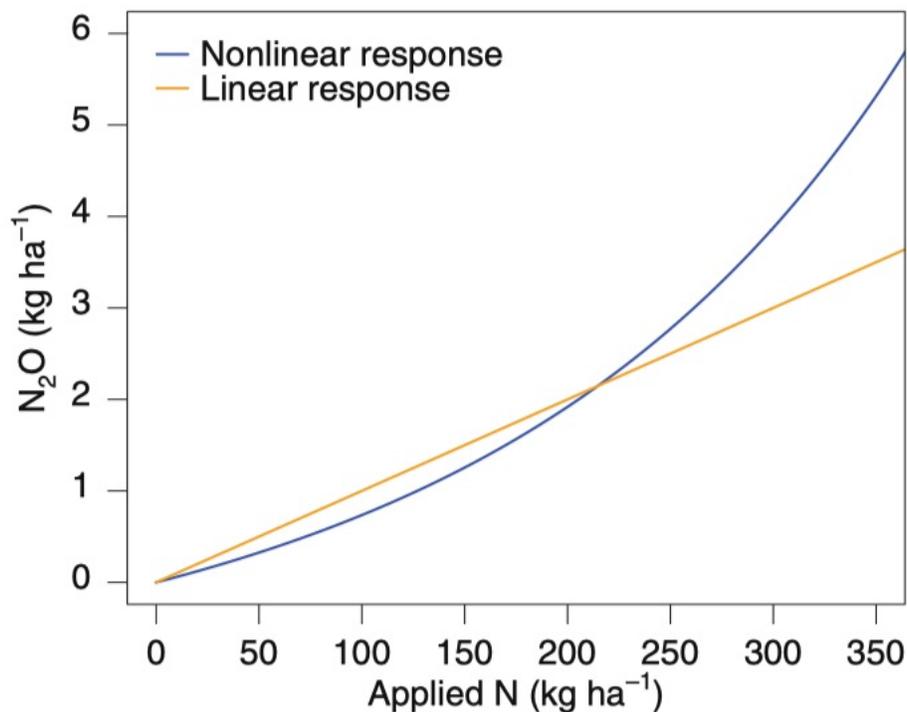
By increasing soil pH as they weather, **silicates may also reduce emissions of N₂O**, as found with liming (Gibbons, et al.2014). Preliminary tests with a replicated field experiment support this suggestion with the soil N₂O flux from heavily fertilized maize plots decreasing by ~50% with the application 10 kg m² of pulverized basalt with no effect on soil respiration (Kantola, 2016). Basalt-treated arable fields may, thus, lower the current substantial global soil atmosphere flux from croplands of 4-5 Tg N₂O-N/yr as a by-product of weathering.

Agriculture is the main source of anthropogenic N₂O emissions, primarily through the application of synthetic nitrogen (N) fertilizers and manure on agricultural land. As the global amount of fertilizer used is expected to increase considerably over the next few decades, it is essential to establish reliable inventories of N₂O in order to define effective mitigation strategies (Makowski, D. (2019). Writing in *Nature Climate Change*, Thompson and colleagues (2019) present new global estimates of N₂O emissions and show that this greenhouse gas has increased substantially since 2009, at a faster rate than expected. Their result questions one of the main methods currently used for the inventory of N₂O emissions at the global scale.

To mitigate N₂O emissions effectively, we must first understand their origin (Makowski, D. (2019). Emissions of N₂O to the atmosphere are mostly caused by nitrification and denitrification reactions. In terrestrial ecosystems, the driving processes are soil microbial activities, which are influenced by both natural factors and human management, in particular the application of synthetic and organic fertilizers. Soil N availability plays a key role in these processes, and N₂O emissions accelerated steadily during the twentieth and twenty-first centuries with the increasing use of nitrogenous fertilizer in crop fields. N fertilization is now recognized as a major source of

anthropogenic emissions of N_2O , having contributed significantly to global warming.

In the bottom up, IPCC approach, the hypothesis of a linear relationship between N_2O emissions and applied N fertilizers has been questioned in several field studies. Instead, there may be a nonlinear response, with an acceleration of emissions as N application increases, probably because a higher proportion of N goes unused by crops in the case of high doses of fertilizer.



Comparison of linear and nonlinear response of N_2O emission to applied N. The linear response tends to underestimate emission for high levels of applied N.

Thompson and colleagues used a top-down method based on atmospheric measurements. Here the level of increase was substantially higher than previous estimates — more than double that of the IPCC default approach — indicating a faster N_2O growth rate than expected.

The results also revealed contrasting emission trends among regions. Emissions increased sharply in China and, to a lesser extent, South Asia and Brazil. These results are consistent with the large increases in N inputs and surplus N in crops that have occurred in these regions over the past two decades. On the other hand, N₂O emissions remained stable in the United States and Europe over the same period. Thus, a substantial decrease in N₂O emissions could occur if these regions avoided excessive N fertilization. This will require international agreements and is outside the purview of the Comings Foundation.

Breider, et al (2019) showed that when pH was reduced, the N₂O production rate during nitrification measured at subarctic stations increased significantly while nitrification rates remained stable or decreased. Contrary to previous findings, these results suggest that the effect of ocean acidification on N₂O production during nitrification and nitrification rates are probably uncoupled. Collectively, these results suggest that if seawater pH continues to decline at the same rate, ocean acidification could increase marine N₂O production during nitrification in the subarctic North Pacific by 185 to 491% by the end of the century.

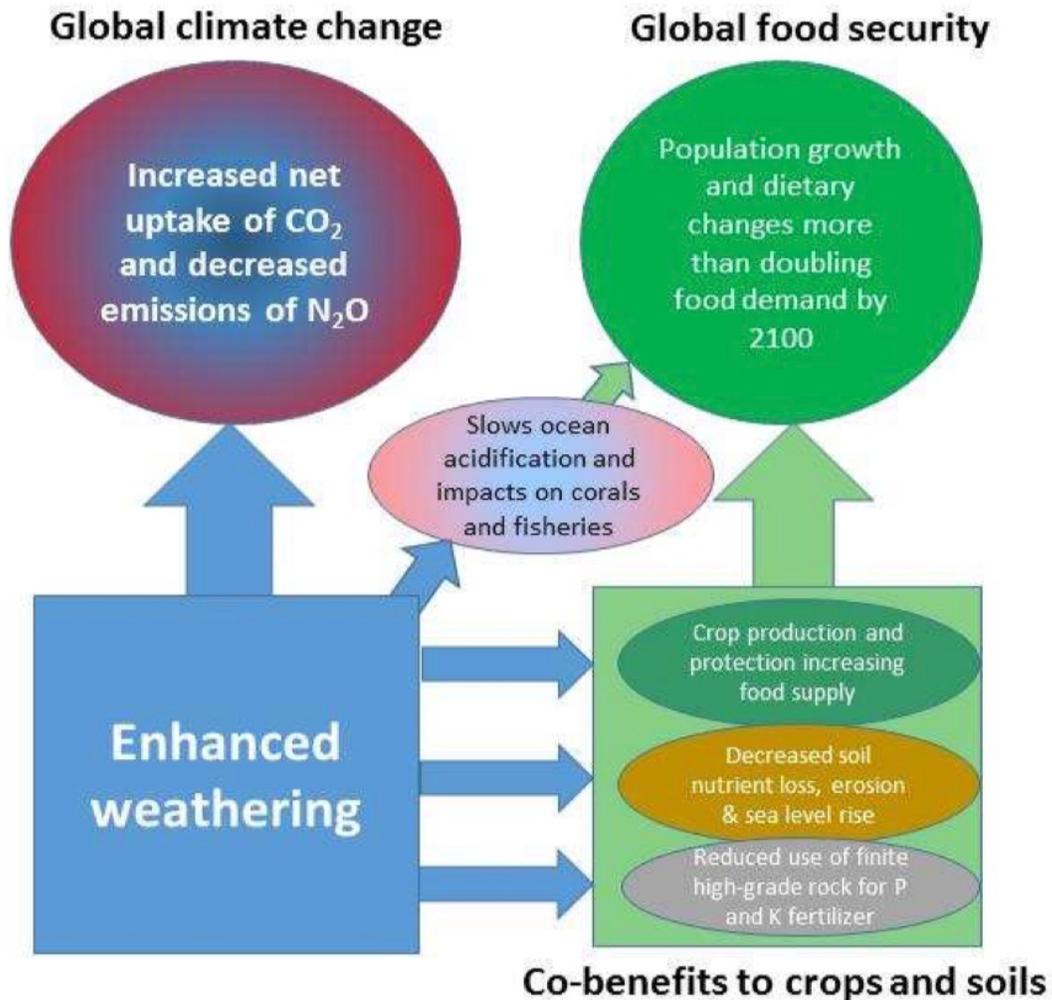
Enhanced weathering of cropland both decreases the production of N₂O by cropland and combats ocean acidification which has a secondary effect of decreasing the marine production of N₂O. Thus, this approach could decrease N₂O both on land and in the sea.

Advantages of Enhanced Weathering on Cropland

An additional consideration relating to the overall outlook of EW is the recent report by Bellamy and Geden (2019) who argued that, contrary to widely held assumptions, methods for CO₂ reduction do not have to be deployed at large global scales to be relevant for climate policy. In regard to governance they suggest that it will primarily emerge 'bottom up' with companies, cities and countries utilizing these techniques and not be comprehensively coordinated 'top down' globally. Namely, since many NETs involve individual countries and areas, any governance should be local (ground up) and not globally (top down) (Lenzi, 2018). Such local governance will be small scale.

Another way of putting it is: every little bit helps – monitor the bits locally. In this regard, we will initially focus on EW in the U.S.

A summary of the advantages of crop weathering is shown below.



From Beerling, et al (2018)

More broadly, if proven effective, and undertaken carefully to minimize undesirable impacts, enhanced weathering may have untapped potential for addressing the United Nations **Sustainable Development Goals (SDGs)** adopted by 193 countries in 2015. For example, we highlight how sequestering CO₂ constitutes action on climate change (SDG 13), restoring

soils and promoting sustainable agriculture contributes to zero hunger (SDG 2), helping protect the oceans from acidification conserves global resources in life below water (SDG 14), reducing agrochemical usage and recycling wastes helps with sustainable consumption and production (SDG 12), and improving agricultural production and restoring degraded soils contributes to land sparing (SDG 15) (see above figure)

However, there is an urgent need to address unanswered technical and social questions and develop rigorous audited testing in the field where the full elemental cycles can be closed, efficacy of CO₂ capture quantified, and the risks, benefits, socioeconomics, techno-economics, and ethics assessed.

When compared to other NET approaches enhanced weathering on cropland has several advantages:

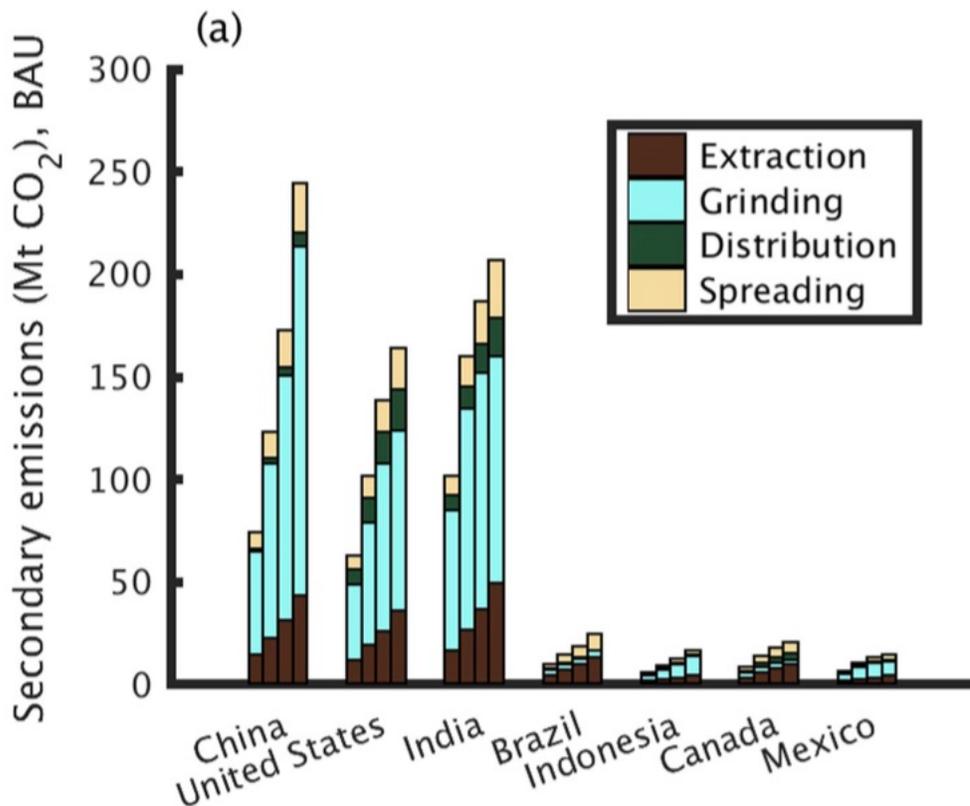
- It solves the problem of how to safely store the captured CO₂. Most other NETs struggle with this issue.
- It helps to decrease ocean acidification.
- This in turn may decrease marine production of N₂O.
- It decreases the soil production of N₂O.
- It does not compete with regular croplands.
- In fact, it improves existing croplands.
- It replaces leached out silicon improving plant resistance.
- It is cheaper than most other NETs.
- It avoids the restrictions of regulatory groups compared, for example, to ocean fertilization and SRM (solar radiation management). Namely, it can be governed locally.
 - If paired with solar, wind or other carbon negative energy sources it reduces the issue of the cost of grinding and mining.

Update Weathering of Cropland

After the above review was completed it led us to conclude that enhanced weathering on cropland was one of the best NETs. After this, two articles appeared in the July 9, 2020 issue Nature. The primary article was again by Beerling et al, (2020) entitled "Potential for large-scale CO₂ removal via enhanced rock weathering with croplands." It was accompanied by a News and

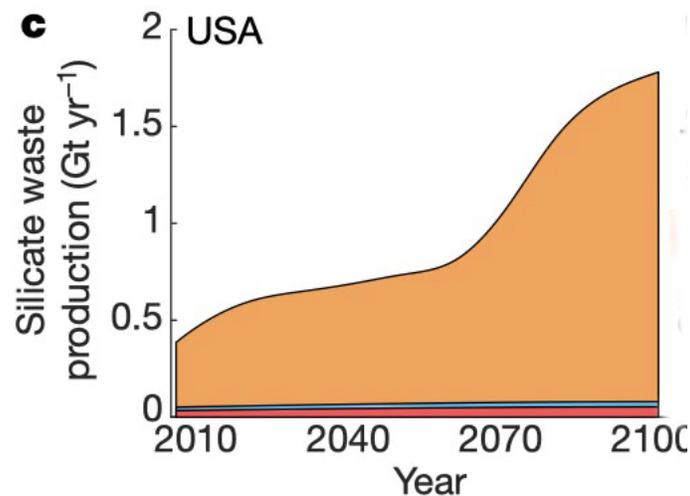
Views comment on the Beerling paper by Lehmann and Possinger (2020) entitled "Atmospheric CO₂ removed by rock weathering." Combined, this was a real kick for ERW (enhanced rock weathering).

Beerling et al, examined the potential of different countries to use ERW. They concluded that ERW would cost, on average, US\$160–190 per ton of CO₂ in the United States, Canada and Europe, and \$55–120 per ton of CO₂ in China, India, Mexico, Indonesia and Brazil. Furthermore, the authors report that China, the United States and India — the three largest emitters of CO₂ from fossil-fuel use — have the highest potential for CO₂ removal using this method. One of their important conclusions was the relative cost of extraction, grinding, distribution and spreading. In the figure below, the Y axis was in terms of secondary emission (i.e. carbon cost) of these four processes. While not directly related to cost, it was a reasonable estimate of cost.



This showed that the cost of grinding contributed significantly to the total cost of this NET. The intriguing aspect of this analysis is that the use of dedicated solar, wind or even modular nuclear reactors could significantly reduce the cost of this NET.

An additional reduction of costs could come from reducing the extraction part by the use of products of various industrial processes. For example the use of artificial silicon and calcium-rich cements used in construction and the by-product of slag from steel manufacturing could provide an important source of these materials. It was predicted that these sources of silicates would increase over the century (see figure below).



Forecast of increases in national bulk silicate production over the next century. Simulated future increases in bulk artificial silicate by products: slag, cement, kiln dust and cement demolition waste (**orange**), slag and kiln (**blue**) and slag (**red**). production during the twenty-first century are given for the USA.

When crushed basalt or other silicate material is added to soil, it slowly dissolves and reacts with CO₂ to form carbonates. These either remain in the soil or move towards the oceans. The authors argued that this method would enable between 0.5 billion and 2 billion tons of CO₂ to be removed from the atmosphere each year. The added rock contains essential plant nutrients,

such as calcium and magnesium, as well as potassium and micronutrients that promote crop production in several ways.

Increasing soil pH alone would substantially boost crop yields in many regions of the world, because it is possible that low pH constrains crop production on more than 200 million hectares of arable and orchard soils (von Uexküll & Mutert, 1995). This area is equivalent to about 20% of the total extent of these soils (967 million hectares). Consequently, on a global scale, **acidity is the most important soil constraint for agriculture** (Wood, et al, 2000).

Co-deployment of enhanced rock weathering with other soil-based sequestration approaches might both reduce limitations and maximize synergies (Amann & Hartmann, 2019). It was proposed that carbon markets might be required to help finance this, and other, approaches (Lehmann and Possinger, 2020).

The note by Lehmann and Possinger included a photograph showing what the process of spreading finely ground basalt would look like.



Application of silicate material to cropland (Lehmann and Possinger, 2020).

In conclusion, by using zero carbon dedicated sources of energy for grinding, by using commercial waste sources of silicates, and by using carbon credits it is likely that the costs of enhanced weathering using cropland, per ton of CO₂ sequestered, could be dramatically reduced.

Contribution by the Comings Foundation

This NET approach raises some a number of questions. We would provide grant funds to obtain the answers. These questions include:

- a) There are many types of basalt. Which ones would be the best?
- b) Where in the US can they be mined?
- c) Where are stockpiles of aggregate waste basalt that can be used?
- d) As stated by Beerling et al (2020) national inventories of the location, availability and extent of this resource are required to assess the potential contribution of this resource to CDR via ERW. Need to develop a US inventory.
- e) Where are the stockpiles of waste silicates from mining?
- f) How much would cost per ton CO₂ be if solar or wind energy was used for grinding?
- g) Could carbon free sources of energy (solar, wind) be made available in these areas?
- h) What is the weathering rate of finely ground basalt?
- i) How to get farmers to switch from lime to basalt?
- j) Can we use the same companies that distribute lime to distribute crushed basalt?
- k) What are the governing issues, if any?
- l) What are the prospects and mechanisms of spreading this technology to other countries?
- m) Long term ERW studies are needed (Beerling, et al 2020).
- n) Is the statement of Strefler, J. et al (2018) that dunite (olivine) is many fold more effective than basalt true?

We would also ask these researchers to set up moderate sized plots of land, grow various crops on that land, spread both pulverized basalt and pulverized olivine and follow up to

determine what chemicals are released, what chemicals are taken up by the plants, and the effects on crop yield. In relation to olivine does it result in unacceptable levels of chromium, or other toxic metals in the crops?

Three of the co-authors of the Beerling et al paper, Stephen P. Long, Evan DeLucia and Ilsa Kantola were from the Carl R. Woese Institute for Genomic Biology and/or the Department of Plant Biology, both at the University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. (which happens to be where I took my undergraduate work) We could offer them grant funds to study the above questions.

For the section on using the ocean go past the references

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Putting Mafic Rocks in the Ocean

An alternative to spreading **mafic** rocks on cropland is spreading them into the ocean. The rationale for this approach is outlined below. However, in the following section, a number of different rocks will be mentioned. Thus, first is a brief introduction to the relevant mineralogy.

Mafic rocks **Ma** = magnesium **fic** = ferric iron containing. Most mafic minerals are dark in color, and common rock-forming mafic minerals include **olivine, pyroxene, amphibole, and biotite**. Common mafic rocks include basalt, diabase and gabbro.

Ultramafic rocks are igneous and meta-igneous rocks with a very low silica content (less than 45%), generally >18% MgO, high FeO, low potassium, and are composed of usually greater than 90% mafic minerals (dark-colored, high magnesium and iron content). The Earth's mantle is composed of ultramafic rocks.

Peridotite is a dense, coarse-grained igneous rock consisting mostly of the minerals olivine and pyroxene. Peridotite is ultramafic, as the rock contains less than 45% silica. It is high in

magnesium (Mg^{2+}), reflecting the high proportions of magnesium-rich olivine, with appreciable iron.

Pyroxenes are a group of dark-colored rock-forming minerals found in igneous and metamorphic rocks throughout the world. They form under conditions of high temperature and/or high pressure.

Pyroxene minerals are defined by their chemical composition and crystal structure. Their generalized chemical composition is described by the formula XYZ_2O_6 where **X** can be Ca, Na, Fe^{++} , Mg, Zn, Mn or Li. **Y** can be Mg, Fe^{+++} , Cr, Al, Co, Mn, Sc, Ti or Vn. **Z** can be Si, Al or a combination of both. A wide range of cation substitutions can occur in the X and Y positions.

Augite, diopside, jadeite and **spodumene** are four of the best-known members of the pyroxene group; however, the pyroxene group has many other members.

Augite is a rock-forming mineral that commonly occurs in mafic and intermediate igneous rocks such as **basalt, gabbro, andesite,** and **diorite**. It is found in these rocks throughout the world, wherever they occur. Augite is also found in ultramafic rocks and in some metamorphic rocks that form under high temperatures. Augite has a chemical composition of $(\text{Ca,Na})(\text{Mg,Fe,Al})(\text{Si,Al})_2\text{O}_6$.

Andesite is the name used for a family of fine-grained, extrusive igneous rocks that are usually light to dark gray in color. They often weather to various shades of brown, and these specimens must be broken for proper examination.

Aragonite is a carbonate mineral, one of the three most common naturally occurring crystal forms of calcium carbonate, CaCO_3 (the other forms being the minerals calcite and vaterite). It is formed by biological and physical processes, including precipitation from marine and freshwater environments.

Basalt is a dark-colored, fine-grained, igneous rock composed mainly of plagioclase and pyroxene minerals. It most commonly forms as an extrusive rock, such as a lava flow, but can also form in small intrusive bodies, such as an igneous dike or a thin sill. It has a composition similar to gabbro. The difference between basalt and gabbro is that basalt is a fine-grained rock while gabbro is a coarse-grained rock.

Diopside is a rock-forming pyroxene mineral with a chemical composition of $\text{MgCaSi}_2\text{O}_6$. It occurs in igneous and metamorphic rocks at many locations around the world.

Diabase The name "diabase" is used for a dark gray to black, fine-grained, intrusive igneous rock that has a composition similar to basalt and gabbro. The difference between basalt, diabase, and gabbro is in their grain size - which was determined by their cooling rates.

Diorite is the name used for a group of coarse-grained igneous rocks with a composition between that of granite and basalt. It usually occurs as large intrusions, dikes, and sills within continental crust.

Dunite is an igneous rock, of ultramafic composition, with coarse-grained texture.

Feldspar is the name of a large group of rock-forming silicate minerals that make up over 50% of Earth's crust. They are found in igneous, metamorphic, and sedimentary rocks in all parts of the world. Feldspar minerals have very similar structures, chemical compositions, and physical properties. Common feldspars include orthoclase (KAlSi_3O_8), albite ($\text{NaAlSi}_3\text{O}_8$), and anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$).

Jadeite is an aluminum-rich pyroxene, while nephrite is a magnesium-rich amphibole. Both can form jade. The two minerals have very similar physical properties in the eye of the

average person. The chemical composition of jadeite is $\text{NaAlSi}_2\text{O}_6$ or $\text{Na}(\text{Al},\text{Fe}^{3+})\text{Si}_2\text{O}_6$

Gabbro is composed mainly of calcium-rich plagioclase feldspar (usually labradorite or bytownite) and pyroxenes (usually **augite**). Minor amounts of **olivine** might also be present in the rock.

Harzburgite, is an ultramafic, igneous rock. It is a variety of peridotite consisting mostly of the two minerals **olivine** and low-calcium (Ca) **pyroxene** (enstatite); it is named for occurrences in the Harz Mountains of Germany.

Olivine is the name of a group of rock-forming minerals that are typically found in mafic and ultramafic igneous rocks such as basalt, gabbro, dunite, diabase, and peridotite. They are usually green in color and have compositions that typically range between Mg_2SiO_4 and Fe_2SiO_4 . Many people are familiar with olivine because it is the mineral of a very popular green gemstone known as peridot.

Peridotite is a dense, coarse-grained igneous rock consisting mostly of the minerals **olivine** and **pyroxene**. Peridotite is ultramafic, as the rock contains less than 45% silica. It is high in magnesium (Mg^{2+}), reflecting the high proportions of magnesium-rich olivine, with appreciable iron.

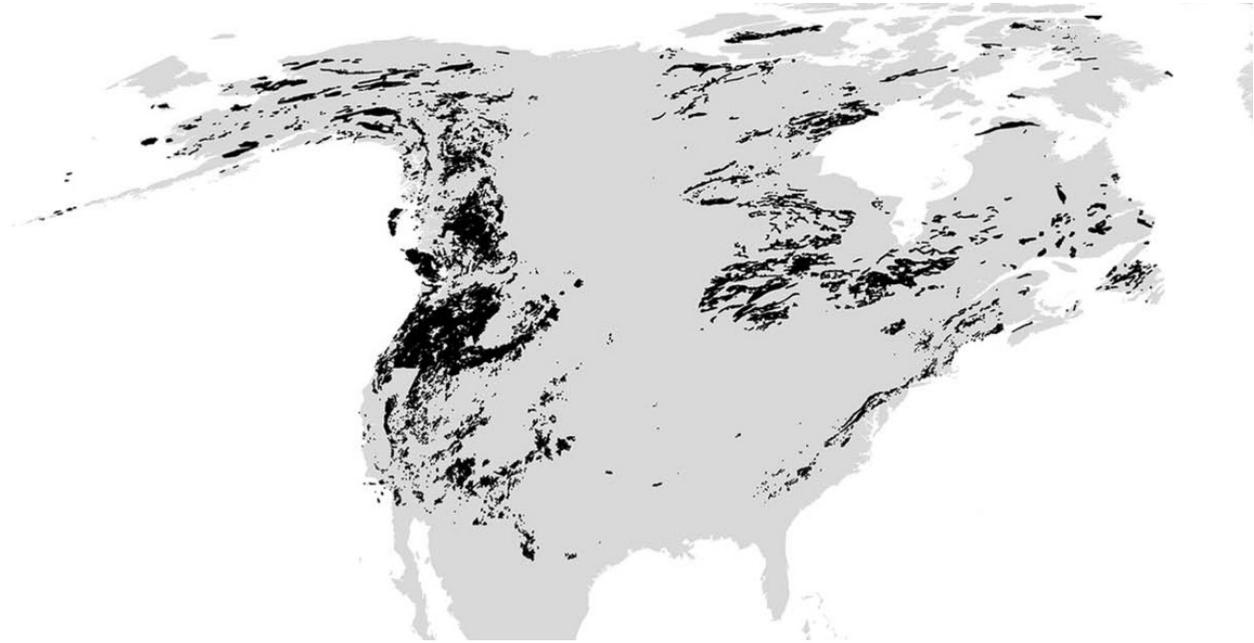
Plagioclase is the name of a group of feldspar minerals that form a solid solution series ranging from pure albite, $\text{Na}(\text{AlSi}_3\text{O}_8)$, to pure anorthite, $\text{Ca}(\text{Al}_2\text{Si}_2\text{O}_8)$.

Putting Mafic rocks in the Ocean (again)

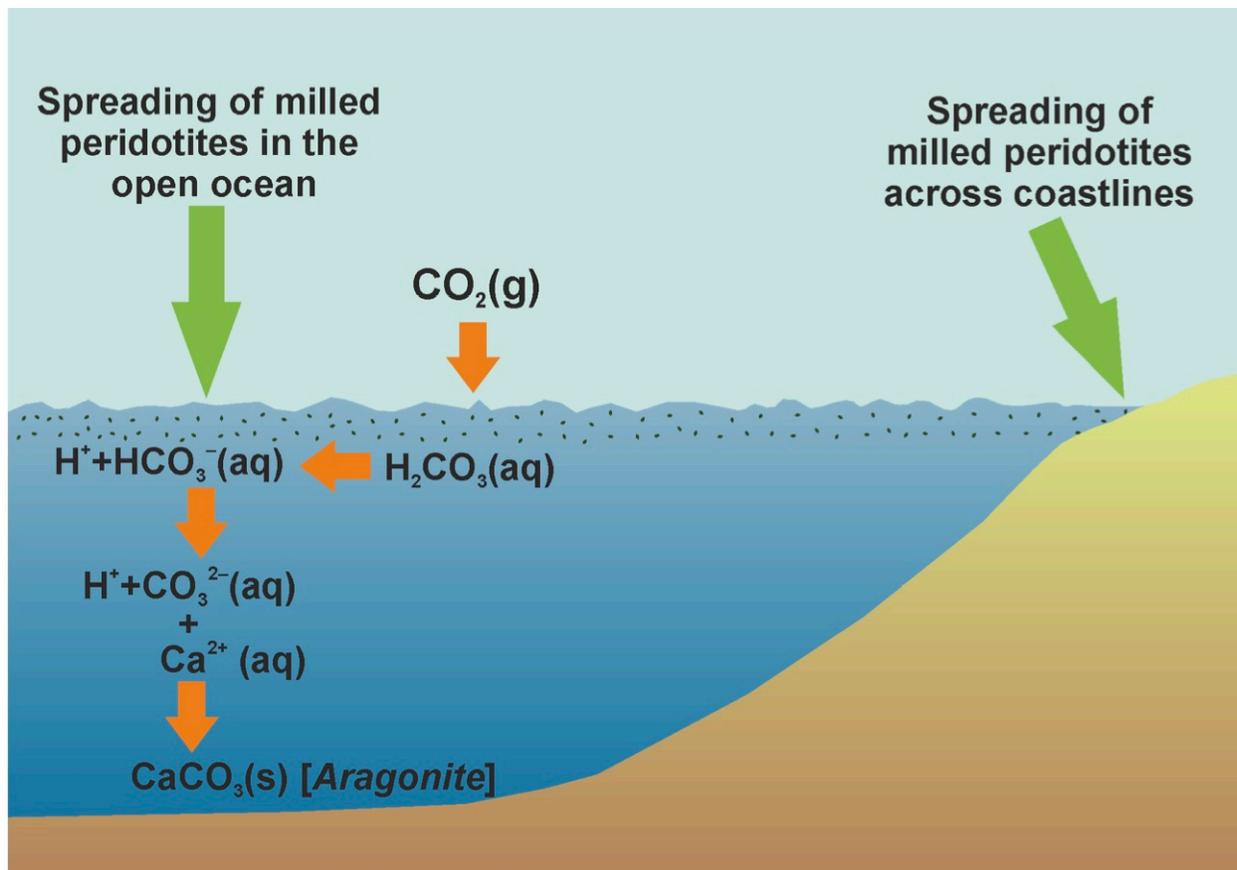
So, now that we have had a primer on the relevant minerals, it is time to examine the subject of putting ground-up mafic rocks directly into the ocean.

One of the questions relevant to spreading mafic rocks on farmlands in the U.S. is: **Where would the basalt rocks come**

from? The following map shows the identified sources of rocks with mafic minerals, like basalt or gabbro, for the American continents taken from Hartman et al (2012, 2013).



This shows that some of the highest concentrations are close to the Pacific coast. By contrast, there are very few sites in the Midwest where most of the farming is. This raises the question of whether it would be more efficient to dump finely ground mafic rocks directly into the ocean. A number of studies have been published on this subject. The following figure is from Rigopoulos et al: Carbon sequestration via enhanced weathering of peridotites and basalts in seawater (2017).



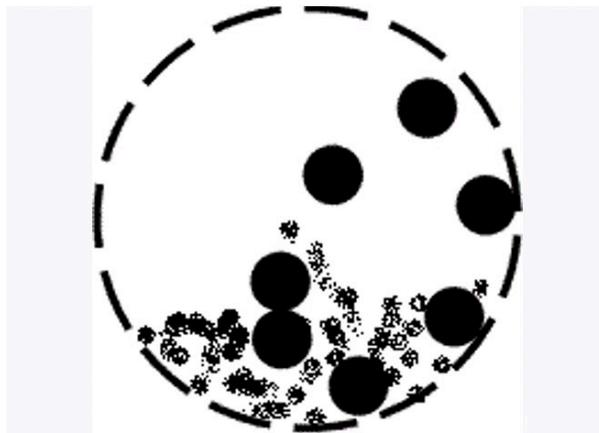
This study was designed to assess the potential drawdown of CO₂ directly from the atmosphere by the enhanced weathering of peridotites and basalts in seawater. Experimentally measured dissolution rates by Wolff-Boenisch et al. (2011) suggested that ground mafic and ultramafic rocks could lead to the efficient carbon dioxide mineralization in seawater.

In the Rigopoulos et al (2017) study, pulverized, and ball-milled **dunite**, **harzburgite** and **olivine** basalt were reacted in artificial seawater in batch reactor systems open to the atmosphere for two months. The results demonstrate that the **ball-milled dunite and harzburgite changed dramatically the chemical composition of the seawater within a few**

hours, inducing CO₂ drawdown directly from the atmosphere and ultimately the precipitation of aragonite (see above figure). In contrast, pulverized but un-milled rocks, and the ball-milled basalt, did not yield any significant changes in seawater composition during the two-month experiments.

These results demonstrate that **ball-milling can substantially enhance the weathering rate of peridotites in marine environments, promoting the permanent storage of CO₂** as environmentally benign carbonate minerals through enhanced weathering. The precipitation of Mg-silicate clay minerals, however, could reduce the efficiency of this carbon sequestration approach over longer timescales.

What is ball-milling?

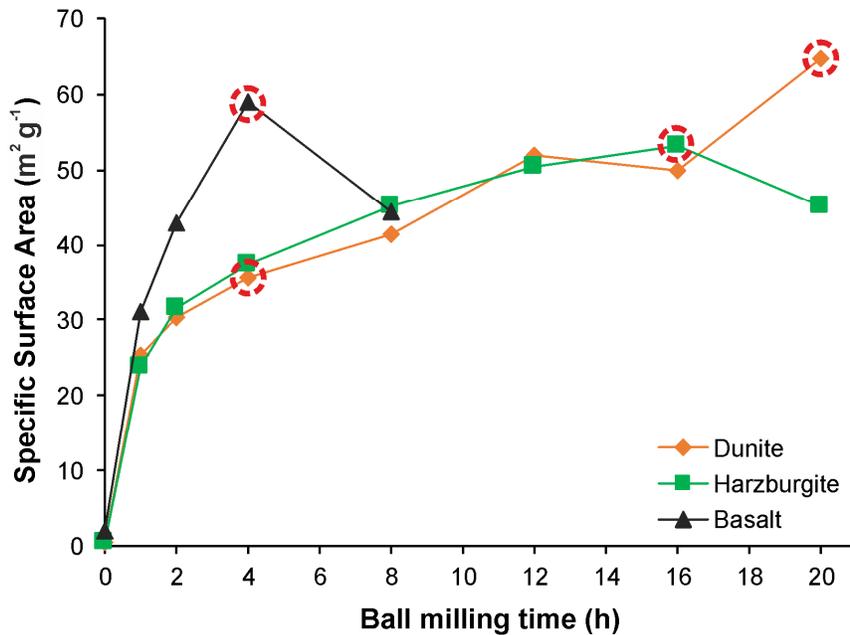


A ball mill is a type of grinder used to grind or blend materials for use in paints, pyrotechnics, ceramics, and selective laser sintering. It works on the principle of impact and attrition: size reduction is done by impact as the balls drop from near the top of the shell.

A ball mill consists of a hollow cylindrical shell rotating about its axis. The axis of the shell may be either horizontal or at a small angle to the horizontal. The grinding media are the balls, which may be made of steel (chrome steel), stainless steel, ceramic, or rubber. The inner surface of the cylindrical shell is usually lined with an abrasion-resistant material such as

manganese steel or rubber lining. Less wear takes place in rubber lined mills.

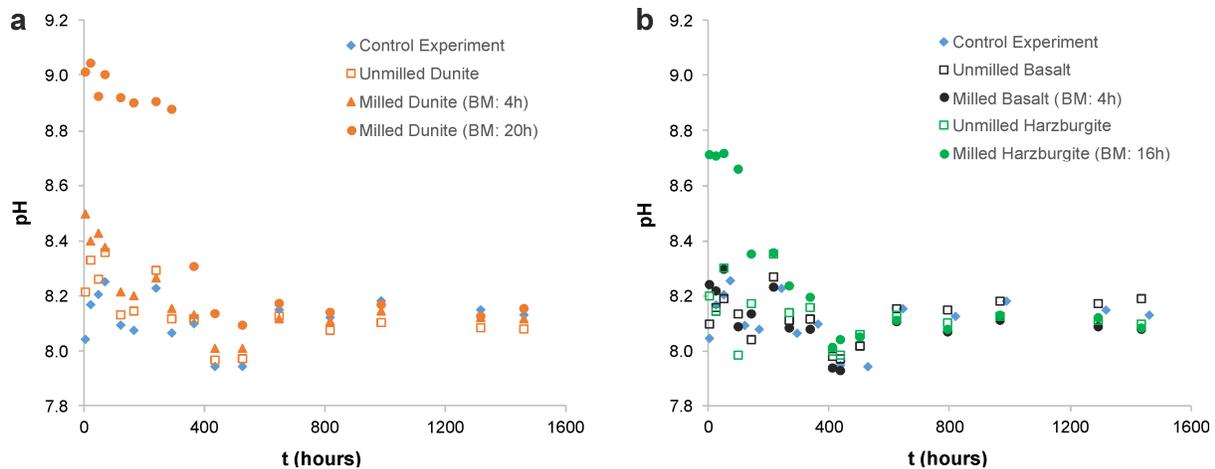
The effect of various times in the ball-mill was measured by the BET method (adsorption of N_2 at 77 K) and was carried out in a Micromeritics Gemini III Surface Area and Pore size Analyzer in order to determine the specific surface area (m^2/g).



BET (m^2/g) specific surface area versus ball milling time for the studied rock materials (red circles show the milled samples used during the experiments). The BET values for the milled basalt and dunite samples were acquired from Rigopoulos et al. (2015) and Rigopoulos et al. (2016), respectively.

This showed that it takes about 12 hours to grind these rocks to a size that maximizes the desired effect.

The following figure shows that in seawater milled dunite (a) and milled Harzburgite (b) show a pH of 8.7 to 9.0. Milled basalt and the controls showed a pH of 8.0 to 8.2. This is the pH range of natural seawater (Marion et al., 2011).



Temporal evolution of the reactive fluid pH: (a) Control experiment, and experiments with unmilled and milled dunite; (b) Control experiment, and experiments with unmilled and milled basalt and harzburgite.

This is relevant to the relative effect of these three milled minerals in combating ocean acidification.

The conclusions of this study were:

- Peridotites induced CO₂ drawdown directly from the atmosphere via mineralization.
- The basalt did not yield any significant changes in seawater composition.
- The precipitation of sepiolite could reduce the carbon sequestration efficiency.

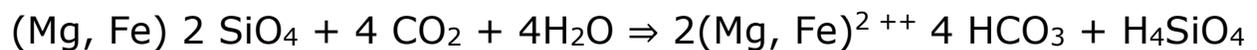
So, what is **sepiolite**? It is also known as meerschaum, is a soft white clay mineral, often used to make tobacco pipes (known as meerschaum pipes). It is a complex magnesium silicate, a typical chemical formula for which is $Mg_4Si_6O_{15}(OH)_2 \cdot 6H_2O$, it can be present in fibrous, fine-particulate, and solid forms. Only small amounts of it were formed in the grinding process.

Griffioen (2017) examined the effect of Fe rich versus Mg rich olivine. They concluded the efficiency of olivine weathering depended on the Mg/Fe fractions of olivine and precipitation of secondary minerals. For Fe-rich olivine, CO₂ may be released to the atmosphere and ocean pH might decrease during oxic olivine weathering. Ocean alkalinization pH only happens when more than 1 mol/kg H₂OMg-rich olivine weathers. The abundance of Mg

compared to Fe depends on the rock but is about 90% in the most abundant dunite.

Maintenance of supersaturation for calcite or aragonite as holds in seawater reduces the efficiency by about a factor of two compared to the efficiency without secondary precipitation. Precipitation of **sepiolite** as Mg silicate reduces the efficiency even more. Kohler et al (2013) concluded that If dissolved in the surface ocean, olivine sequesters **0.28 g carbon per g of olivine dissolved, similar to land-based enhanced weathering**. Silicic acid input, a byproduct of the olivine dissolution, alters marine biology because silicate is in certain areas the limiting nutrient for diatoms. As a consequence, their model predicted a shift in phytoplankton species composition towards diatoms, altering the biological carbon pumps. Enhanced olivine dissolution, both on land and in the ocean therefore needs to be considered **as ocean fertilization**. From dissolution kinetics we calculate that only olivine particles with a grain size of the order of 1 μm sink slowly enough to enable a nearly complete dissolution. The energy consumption for grinding to this small size might reduce the carbon sequestration efficiency by $\sim 30\%$.

Olivine (Mg_2SiO_4) is an abundantly available magnesium silicate which weathers according to the reaction (Schuiling and Krijgsman 2006)



This formula suggests that 4 mol of CO_2 are sequestered by 1 mol of olivine, equivalent to 1.25 t of CO_2 (or 0.34 t of C) per ton of olivine.

What the Comings Foundation can do.

The above suggests a two-pronged approach to the use of finely ground Mg rich mafic rocks to combat climate change:

- spreading these rocks on crop land
- spreading these rocks onto the ocean

As described above we propose to provide a grant to a group of scientists at the University of Illinois to explore how to start actually carrying out this approach in Midwest farms. We could either have them also explore spreading mafic rocks in the ocean or advising us on who to contact on the west coast and awarding a separate grant for that approach.

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