

Heavy Metals in Mafic Rocks

A synthesis by Beerling et al (2018) of published chemical analyses indicates that olivine-rich ultramafic rocks contain relatively high concentrations of 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-columns dosed with olivine suggested accumulation of Ni and Cr in the soil profile (Renford, et al, 2015). By contrast, Schuiling and Krijgsman (2006) **proposed that nickel contamination would not be a problem and that most chromium would be tightly bound in very insoluble chromite grains and will not be bio-available.** Further research is needed to decide which of these conclusions is the closest to being correct.

“Mining” of Nickel from Olivine.

Olivine contains 0.2 to 0.3% nickel. **Olaf Schuiling (2018)** demonstrated that by planting plants that are **nickel hyper accumulators**, such as those in the *Alyssum* family, in the same ground that is covered with olivine, at the end of the growing season the plants can be harvested by cutting them close to the ground. When these plants are burned the ash contains about 10% nickel, which is higher than the richest nickel ores. This is a very environmentally friendly way to mine nickel and can provide an income stream to help cover the costs of EW. The *Alyssum* can then re-grow for the next season with a new spread of olivine.

As discussed below, there are huge amounts of non-cropland in the U.S. Crushed olivine could be spread on this land and also planted with *Alyssum* plants to extract and sell nickel. This could make using non-croplands for EW economically feasible. One question that needs study is, “How thick can the applied olivine non-cropland be and still sequester CO₂? If it could be up to 5 times the thickness of that applied to cropland, **it could be up to 5 times the effectiveness of EW on crops.** This would considerably enhance the effectiveness of EW. If preferentially done **in southern areas of high mean temperature**, the multiplier could be even greater.

“Mining” Chromite from Olivine

The chromium in olivine is in the form of chromite. According to Olaf Schuiling this can be recovered from pulverized olivine using shake tables or Humphrey spirals. The recovered chromite also has some economic value. Using these two approaches it may be possible to remove most of the heavy metals from olivine before spreading it on the ground.

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.

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, microreactors or small nuclear reactors), 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 dissolve CO_2 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 $<2^\circ\text{C}$.

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/ CO_2 , 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/ CO_2 (\$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.

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 $0.58\text{--}2.54 \times 10^6$ 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 $1.3\text{--}3.4 \times 10^6$ 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).

Norway

The table above(Kramer, 2020) showed that Norway is by far the greatest commercial producer of olivine at 6,300 thousand metric tons per year versus 90 thousand metric tons for the US.



The above shows the world's largest active olivine quarry, **Gusdal Pit, in Norway**. No chemicals are needed to extract the rock, nothing is underground, the process is not mining, it is surface extraction. This raises the possibility of purchasing olivine on site, ensuring it is finely ground, and immediately distributing it in the ocean.

Massive Removal of Prehistoric 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.

Cropland Abandonment and Expansion in the U.S.

Lark et al (2020) assessed annual land use change 2008–16 in the U.S. and its impacts on crop yields and wildlife habitat. They found that croplands have expanded at a rate of over one million acres per year, and that 69.5% of new cropland areas **produced yields below the national average**. Observed conversion infringed upon high-quality wildlife habitat especially relative to grassland milkweed critical for the Monarch butterfly. It also impacted on nesting opportunities for waterfowl in the Prairie Pothole Region of the Northern Great Plains. They thus demonstrated a pervasive pattern of encroachment into areas that are increasingly marginal for production, but highly significant for wildlife, and suggest that such tradeoffs may be further amplified by future cropland expansion.

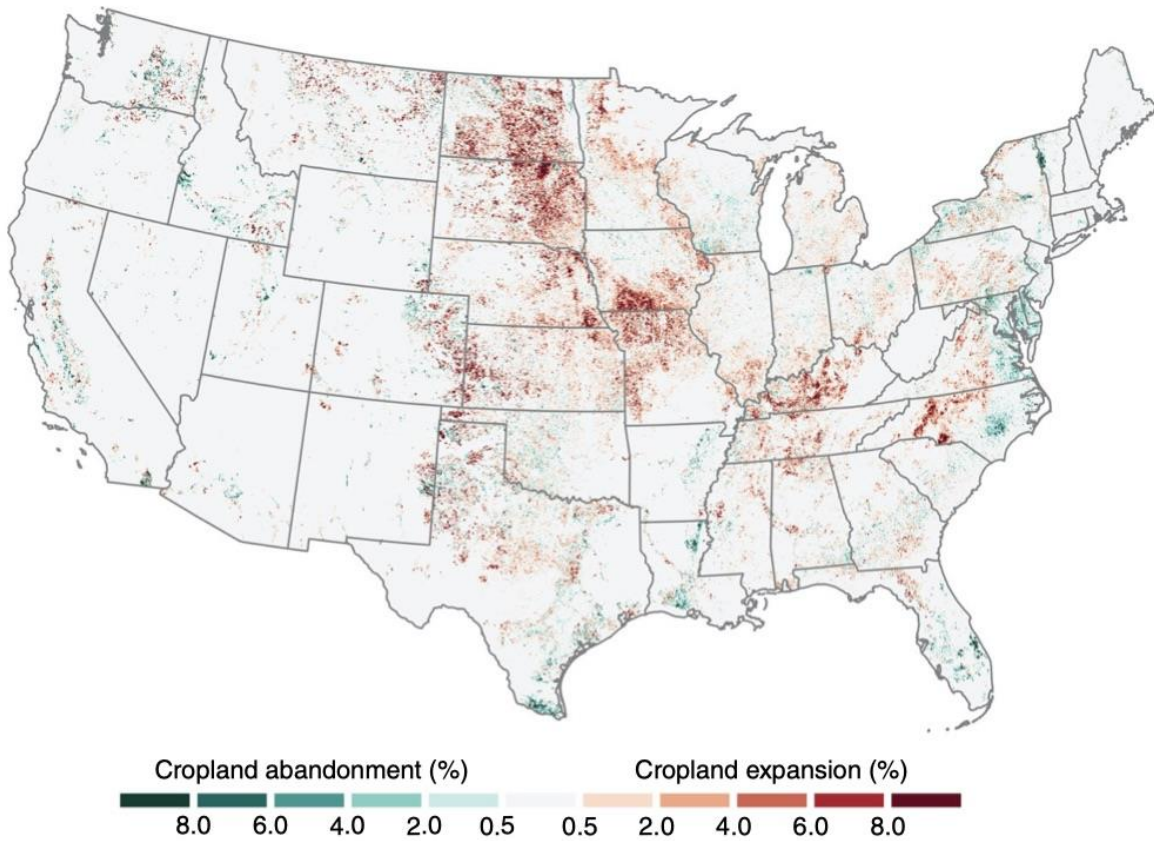
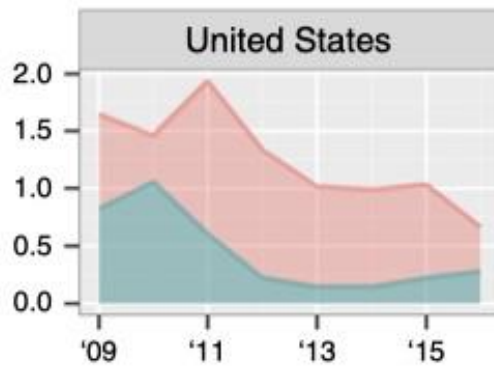


Fig. 1 Net cropland conversion 2008–16. Rates of net conversion calculated as gross cropland expansion minus gross cropland abandonment and displayed as a percentage of total land area within non-overlapping 3 km × 3 km blocks. Net conversion was most concentrated in the eastern halves of North and South Dakota, southern Iowa, and western portions of Kansas, Kentucky, and North Carolina.



This figure summarizes the ratio of cropland abandonment (green) versus cropland expansion (red).

Carbon Emissions from Cropland Expansion

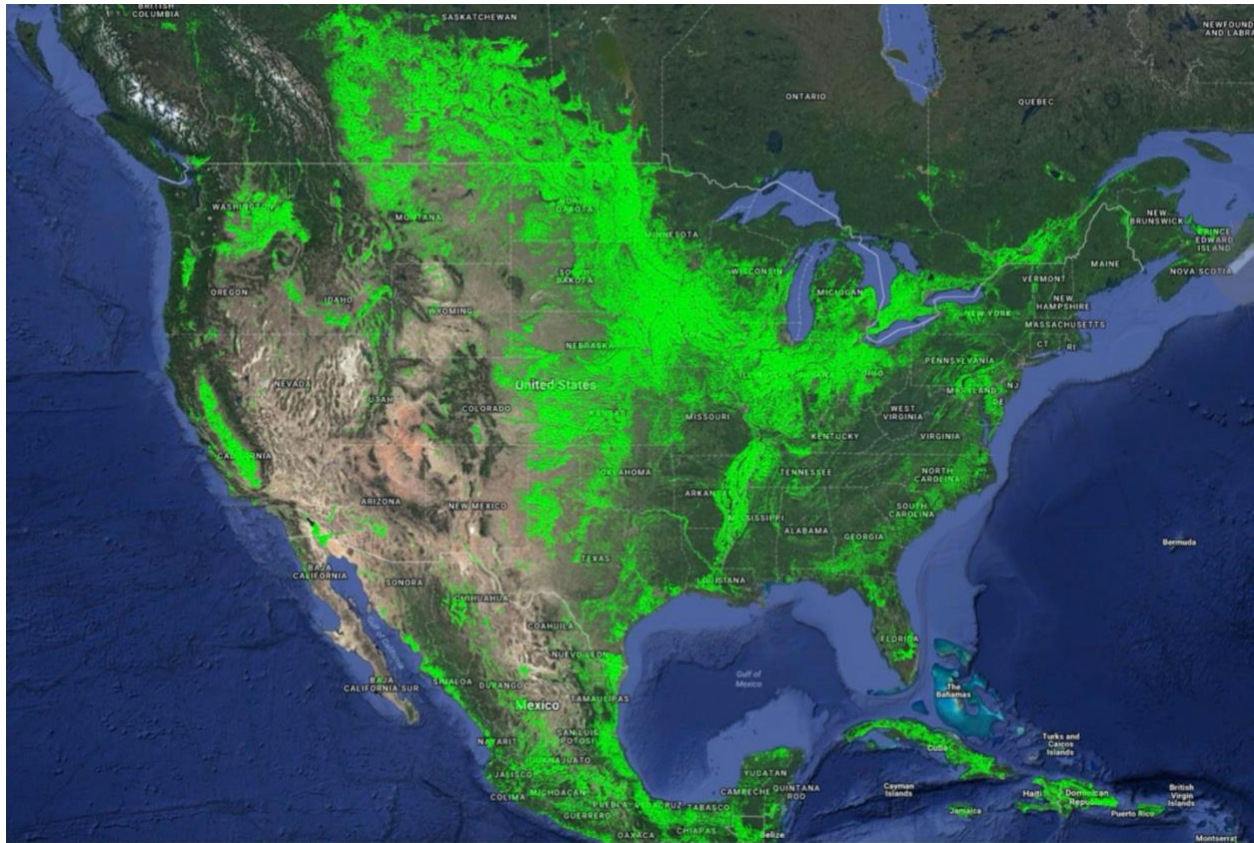
In addition to the expanded cropland being less productive, an additional disadvantage is that such expansions release significant amount of the carbon stored in grassland (Spawn et al, 2019).

So, how is this relevant to the use in EW on cropland. A major finding was that the expanded croplands performed more poorly than regular cropland. Could this be corrected by the use of ground olivine or basalt on these lands? The expanded cropland involved a total of over 10 million acres. Such treatment might also reverse some of the negative effects on wildlife. Perhaps equally or more relevant would be the spreading of ground olivine or basalt on the abandoned cropland simply to sequester CO₂ independent of improving cropland.

Non-cropland in the US

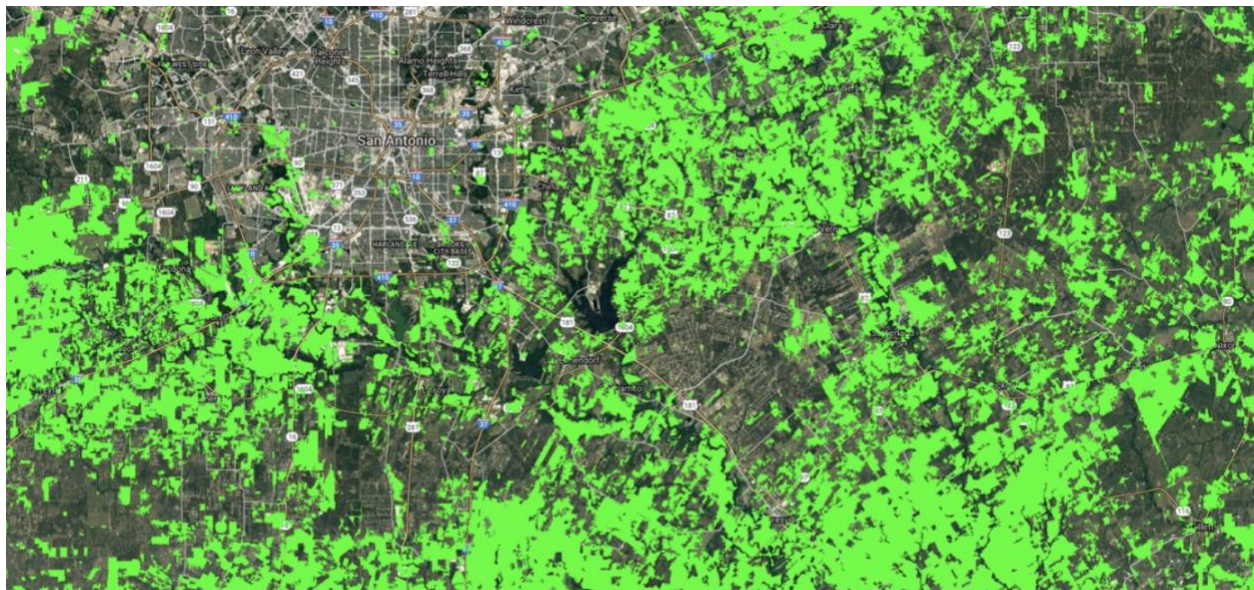
The above showed the abandoned cropland in the US. The real issue is how much non-forest non-cropland is there in the US? The following map shows the cropland in the US. By default, also shows the non-cropland, which is extensive.

This map shows U.S. croplands in a nominal 30-m resolution derived primarily with Landsat imagery for the year 2015. The United States has 166 million hectares of net cropland area and is ranked second in the world after India, which has 180 million hectares of croplands. This is part of the GFSAD30 Project Landstat (USGS).



Cropland and non-cropland in the US

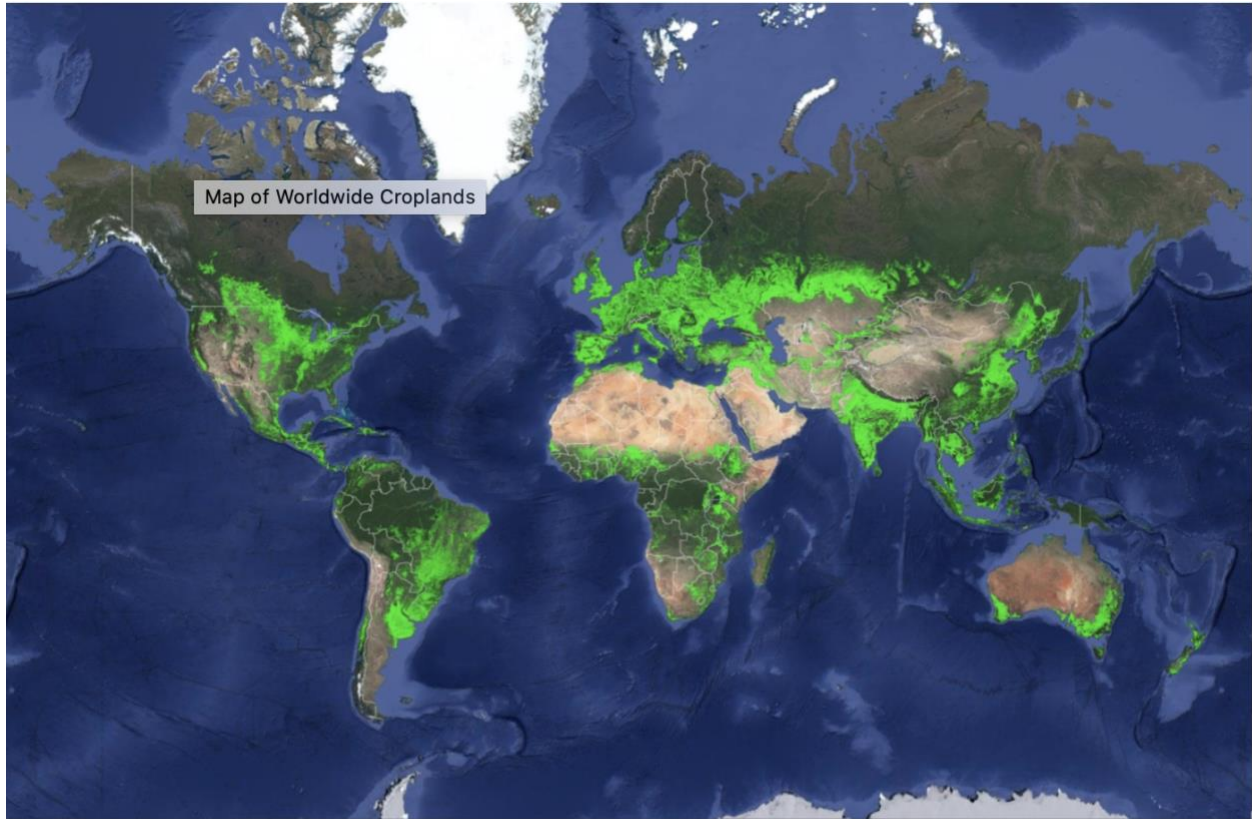
The following figure shows the power of the Landstat technology to investigate details of cropland and non-cropland.



This map shows croplands in Texas in a nominal 30-meter resolution. This is part of the GFSAD30 Project.

The resolution of Landstat allows the investigation at the level of individual farms. This will be invaluable in planning the sites and extent of ER on cropland.

The following figures cover the whole world.



This map shows cropland distribution across the world in a nominal 30-meter resolution. This is the baseline product of the GFSAD30 Project.

The combined above figures show that if EW needs to involve both croplands and non-croplands, huge areas of land are potentially involved.

Nitrous oxide N₂O

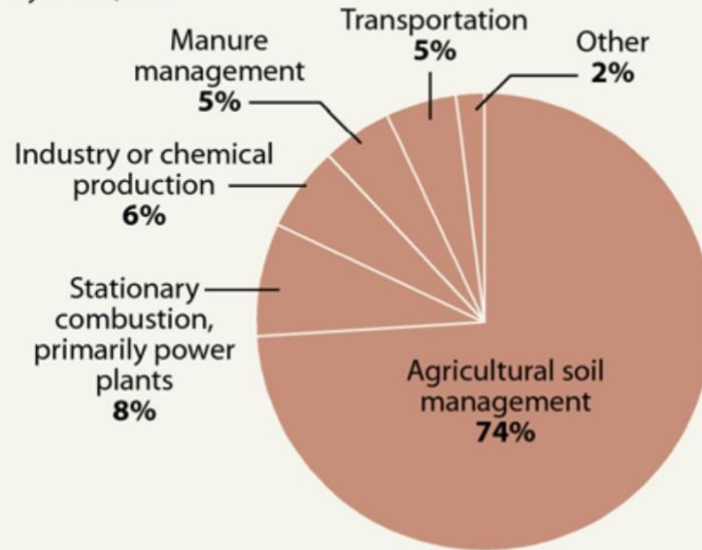
One pound of N₂O warms the atmosphere about 300 times the amount that one pound of carbon dioxide does over a 100- year timescale. Its potency and relatively long life make N₂O a dangerous contributor to climate change. It also depletes the ozone layer. As shown below, about three fourths of N₂O comes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

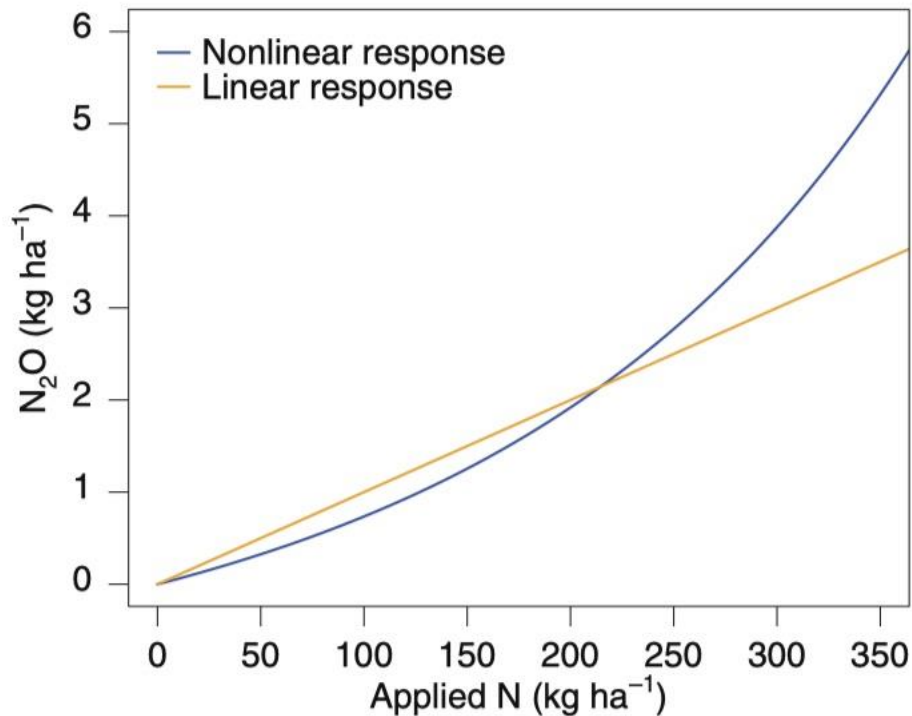
Beerling, et al (2018) concluded that substituting a weatherable silicate rock, such as basalt, or silicate waste, for limestone, and increasing application rates over those used in conventional liming operations, may offer a pragmatic, rapidly deployable global carbon cycle intervention strategy.

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). Thus, **basalt-treated arable fields may 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 N₂O, having contributed significantly to global warming.

In the bottom up, IPCC approach, the hypothesis of a linear relationship between N₂O 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 N₂O 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 N₂O 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.

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

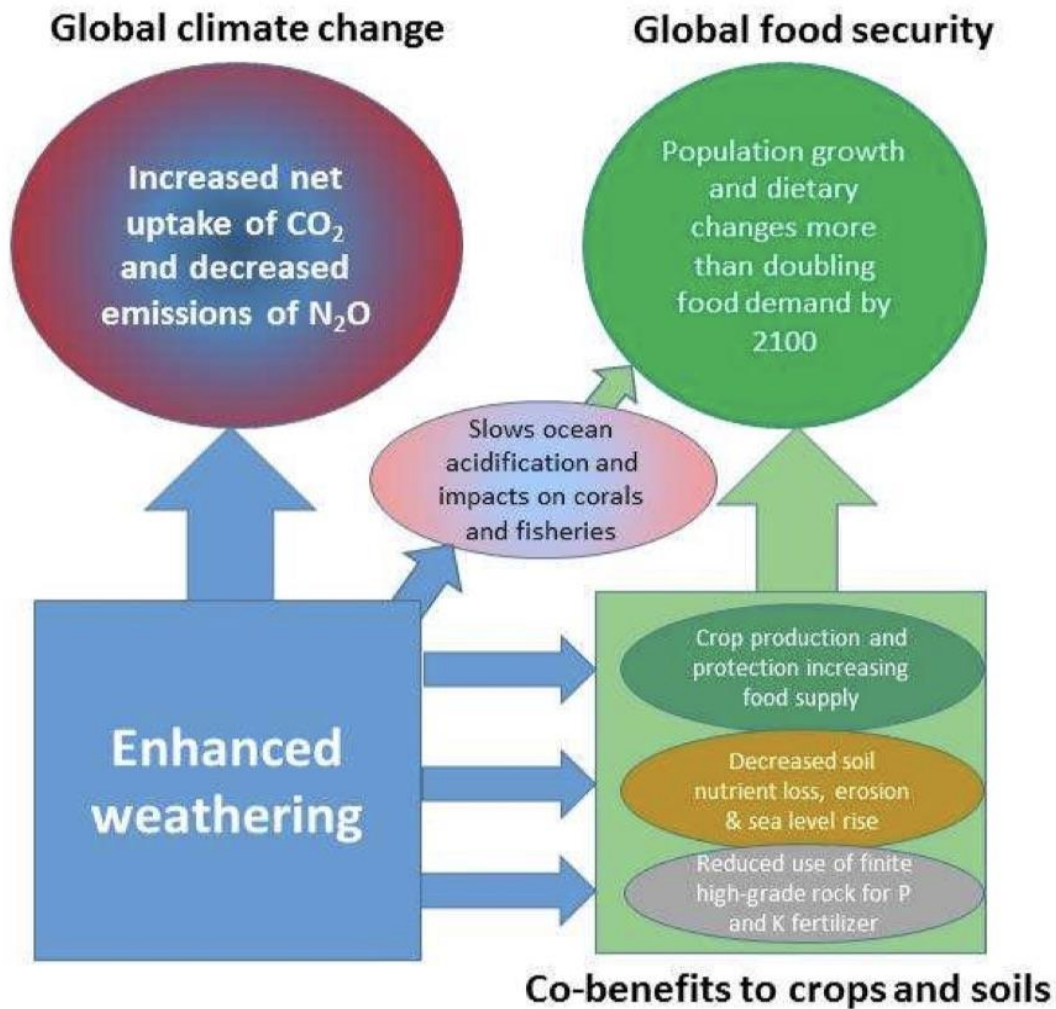
during nitrification and nitrification rates are probably uncoupled. Collectively, these results suggest that if seawater pH continues to decline at the same rate, **ocean acidification could increase marine N₂O production during nitrification in the subarctic North Pacific by 185 to 491% by the end 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.

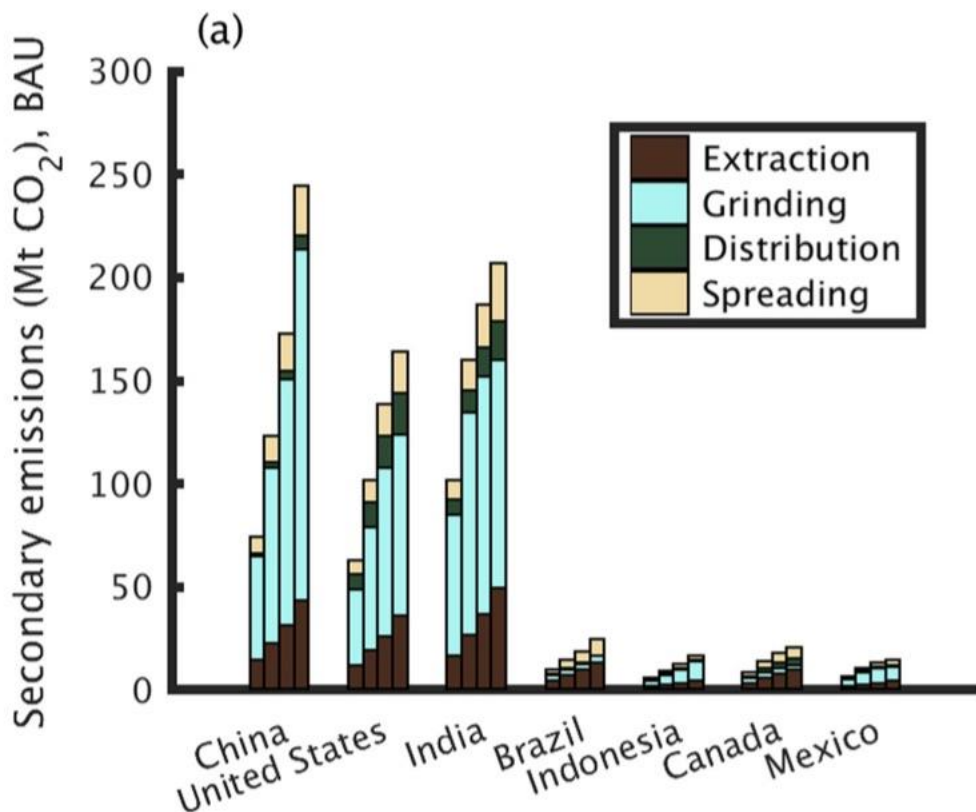


From Beerling, et al (2018)

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)

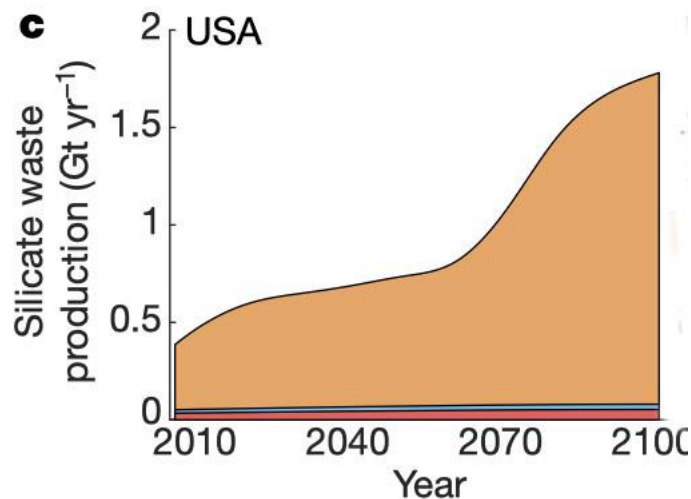
After the above review was completed it led us to conclude that enhanced weathering on cropland was one of the best NETs. After this, two articles appeared in the July 9, 2020 issue *Nature*. The primary article was again by Beerling et al, (2020) entitled “Potential for large-scale CO₂ removal via enhanced 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 or micro-nuclear reactors could significantly reduce the cost of this NET. It is of interest that Terrestrial Energy anticipates that their **Integrated Molten Salt Reactor** will be approved in Canada by 2025 and in the US by 2030. These are super-safe reactors.

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.

Increasing **soil pH** alone by adding mafic rocks, 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.**

What About Methane?

We stated in the introduction that one of the advantages of Enhanced Weathering was its potential to remove N₂O and methane as well as CO₂. The effect on N₂O was covered above. So where does the removal of methane come in?”

Even if humans stop combusting fossil fuels and discharging CO₂ into the atmosphere, the average global temperature of the earth will continue to increase for the rest of the century for several reasons.

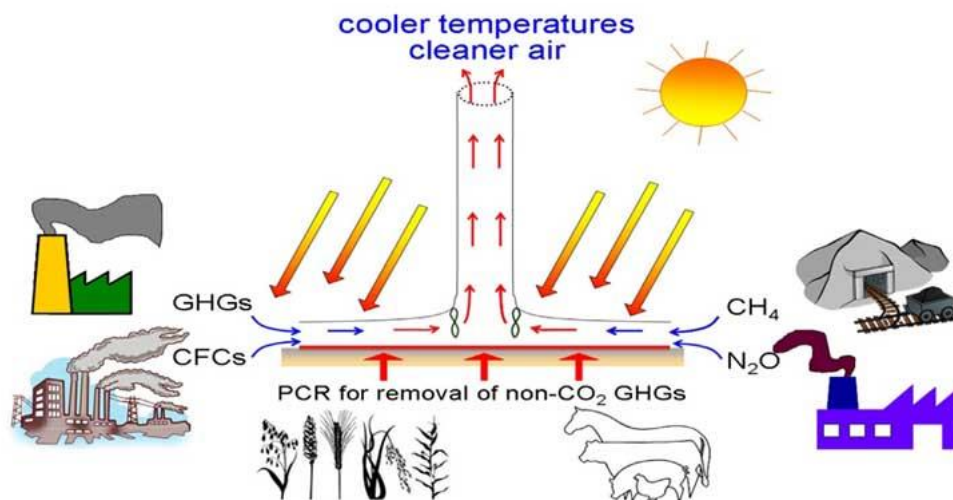
First, the long lifetime of CO₂ (estimated in the 100,000-year range) means that the excess atmospheric stocks (515 Gt Carbon) would continue to drive radiative forcing and global warming for many decades.

Second, even if atmospheric concentrations were to decrease, CO₂ would out gas from the oceans and offset this decrease, because of the dynamic equilibrium between the CO₂ in the atmosphere and the carbonates HCO₃⁻/CO₃²⁻ dissolved in the oceans.

Third, there is the contribution of other GHGs, besides CO₂, which together account for about 34% of radiative forcing. Even if all excess anthropogenic atmospheric CO₂ were removed, radiative forcing would only be reduced by half. The following is a proposal on how to remove the other half, especially methane.

The Removal of Methane from the Atmosphere with Solar Chimneys

A hybrid of a **Solar Chimney Power Plant (SCPP)** and a **Photo-Catalytic Reactor (PCR)** has been proposed as a method of removing non-CO₂ greenhouse gases. The concept is shown here (deRichter et al. 2017; Schlaich, 1995; Schlaich, et. al.2005).



The SCPP is an established concept that generates electricity in a solar updraft tower incorporating axial-flow turbines. Hot air is supplied to the tower by a large solar hot air collector. A conventional SCPP-PCR is composed of 4 principal components:

1. A very large collector for the greenhouse effect.
2. A tall chimney for the stack effect.

3. A thermal energy storage layer (water) to store the solar radiation for night-time operation.
4. Several turbines to generate renewable electricity which is carbon free.

PCR can be incorporated in the SCPP by coating its collector with a photo catalyst, such as TiO₂, which is able to transform methane and other non-CO₂ GHGs into less harmful products. Transformation of 1 kg of methane into 2.75 kg of CO₂ reduces its climate change effect by 90% and is equivalent to removal of 25.25 kg of CO₂ from the atmosphere.

The SCPP component could produce sustainable decarbonized renewable energy for grinding the rocks.

World-wide installation of 50,000 SCPPs, each of capacity 200 MW, would generate a cumulative 34 PWh of renewable electricity by 2050. These SCPP-PCR devices would **reduce or stop the atmospheric growth rate of the non-CO₂ GHGs and progressively reduce their atmospheric concentrations.**

One of the research projects the Comings Foundation could support was determining if SCPP-PCR works as proposed above.