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Enhanced Weathering as an Important Negative Emission Technology

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Climate change that is defined by high atmospheric carbon dioxide (CO_2) concentrations (≥more than 400 ppm); increasing air temperatures; significant and abrupt changes in daily, seasonal, and inter-annual temperature; changes in the wet &dry cycles; intensive rainfall and heavy storms; extended periods of drought; extreme frost; and heat waves and increased fire frequency, is expected to significantly impact terrestrial systems, soil properties, surface water and stream-flow; groundwater quality, water supplies and terrestrial hydrologic cycle; and, as a consequence, food security and environmental quality. Increased global CO_2 emissions, estimated at 8.4 Pg carbon (C) yr^{-1} in 2010, have accelerated from 1% yr^{-1} during 1990–1999 to 2.5% yr^{-1} during 2000– 2009, being the main driver of the global warming. Climate-change impacts, which already are being felt in agriculture, ecosystems, and forests, are expected to be diverse and complex.

The progressive release of anthropogenic carbon dioxide into the atmosphere has been estimated at 2,035 ± 205 Gt from 1870 to 2015 (Le Quéré *et al*., 2015). Today, an emission of CO_2 is about 40 Gt/yr (IPCC Special Report, 2018). Each year, roughly half of these emissions are removed BY natural uptake in the ocean and in the terrestrial biosphere, while the remaining part accumulates in the atmosphere and contributes to global warming. To avoid the worst impacts of global warming and subsequent climate change, the Paris agreement recommended limiting average warming of the atmosphere to < 2 ºC and importantly below 1.5ºC. (UNFCCC, 2015).

To achieve the 1.5 ºC goal, negative emission technologies(NET); which indicate more carbon absorption then emission by various technology, have to remove 10 Gt CO_2/ year (IPCC Special Report, 2018), in addition to reducing emissions and capturing CO_2 from point sources. Options for CO_2 removal from air (CDR) include an increase of carbon storage in soils and biomass, but also Direct Air Capture using synthetic sorbents (DACSS) and carbon mineralization via enhanced weathering (DACEW). All the available options operating in parallel, will be necessary to achieve the required level of global CO_2 removal, approximately 10 Gt/yr and 20 Gt/yr by 2050 and by 2100 respectively (United Nations Environment Programme (UNEP, 2017). So it is necessary to reduce CO_2 emission by negative emission strategy.

Common categories of negative emission strategies for CO_2 removal from atmosphere

1. Afforestation and reforestation: In these practices additional trees are planted/prevention of removal of trees, as they grow, will capture CO2 from the atmosphere. And then the CO2 is stored in living biomass.

2. Biochar and soil carbon sequestration (SCS): Biochar is produced by pyrolysis in controlled condition, which is resistant to decomposition or very slowly decomposed over the years. When biochar is added to soil it is become source of soil carbon. SCS is a technology in general which enhances soil carbon by reducing losses or increasing inputs.

3. Ocean fertilization: When nutrients like Iron or other are applied to the ocean, they increase CO2 absorption via stimulation of growth of phytoplanktons in ocean. Then they sink to the deep ocean and become source of permanent carbon as they die.

4. Bioenergy with carbon capture and sequestration: Plants turn CO_2 into biomass, which is then combusted inpower plants, a process that is ideally CO_2 neutral. If CCS is applied in addition, CO_2 is removed from the atmosphere

extensive modelling scenarios assessed by the Intergovernmental Panel on Climate Change that give us more than a 50% chance of limiting warming to less than 28°C assume substantial CO_2 extraction is achievable with bioenergy crops in combination with carbon capture and storage (BECCS) in the second half the 21^{st} Century [IPCC, 2014]

5. Direct Air Capture (DAC): DAC includes use of chemicals to absorb CO_2 directly from the atmosphere, which is then stored in geological reservoirs.

6. Enhanced weathering (EW): This technology includes natural absorption of atmospheric CO_2 by crushing and spreading of minerals on field or the ocean with increasing of surface area so that CO_2 absorbed more rapidly.

What is natural chemical weathering?

When some special minerals (silicate and carbonate) come in contact with rainwater and carbon dioxide (CO_2), they dissolve in the rainwater, remove CO_2 from the atmosphere and create bicarbonate ions,ending up in the ocean with the rainwater. They are then formed back into carbonate minerals by calcifying organisms (often to make their shells) in time periods of 1000s of years. An increase in this kind of weathering will therefore result in a build up of bicarbonate ions and with it the alkalinity in the ocean (this counters the effects of ocean acidification) and removes carbon dioxide from the atmosphere storing it in solid carbonate minerals. Over geological time periods - hundreds of thousands to millions of years - these natural processes act as a thermostat stabilising Earth's climate: Volcanoes emit CO_2, which would heat our planet if natural chemical weathering would not sequester the emitted CO_2 and stabilise Earth's temperature. Unfortunately this cycle happens in a time frame much larger than the human one and can thus not regulate our current excess of CO_2 which has accumulated since the industrial revolution. So to increase rate of CO_2 absorption an enhanced weathering is the best option.

During weathering , silicate rocks rich in Ca or Mg are chemically broken down into base cation and generate biocaronate, which is ultimately transferred to the oceans leading to carbonate precipitation on the seafloor. The best source of Ca and Mg are mafic and ultra mafic rocks, mine tailings and industrial byproducts. The rate of these processes can be increased by amending soils with crushed calcium and magnesium bearing silicate rocks with a large surface area. Enhanced weathering can also be used with forestry and crops used in BECCS (Bio-energy crops in combination with carbon capture and storage), intensifing its carbon sequestration potential and reducing costs. Production of soluble alkalinity from weatherd rocks, could help to reduce ocean acidification to protect coral reefs and marine fisheries

Process of weathering and carbon capture

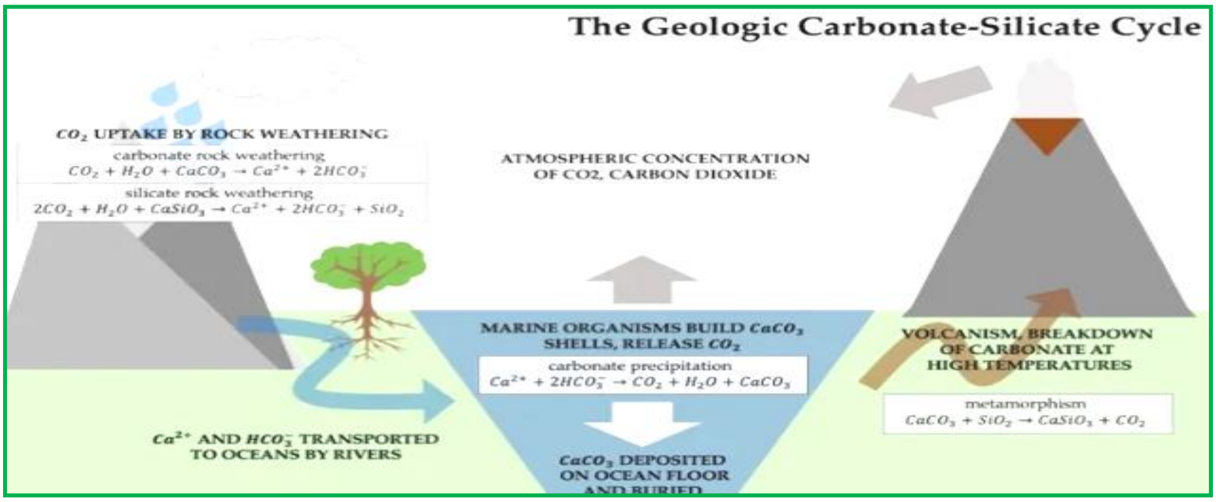
- Silicate mineral dissolution consumes CO_2 using Wollastonite ($CaSiO_3$):
  $CaSiO_3 + 2CO_2 + H_2O = Ca^{2+} + 2HCO_3^- + SiO_2$

- Bicarbonate (HCO_3^-) and calcium (Ca^{2+}) ions produced by this reaction are transported to the oceans where they ultimately are precipitated as calcium carbonate minerals ($CaCO_3$):
  $$Ca^{2+} + 2HCO_3^- = CaCO_3 + H_2O + CO_2$$
- Overall process involves one mole of CO_2 for each mole of $CaCO_3$ produced
  $$CaSiO_3 + CO_2 = CaCO_3 + SiO_2$$

Utilizing these same principles, applications of enhanced weathering aim to increase the rate of chemical weathering by applying fine-grained silicate rock powders to agricultural soils. On human timescales ($<10^3$ years) HCO_3^- drainage to local watersheds and $CaCO_3$ precipitation in soil (as opposed to the oceans) represent long-term sinks for carbon sequestration

Enhanced weathering in farm land

The biggest limit on weathering is the amount of silicate minerals exposed at any given time. Grinding up volcanic silicate rocks into a fine powder increases the surface area available for reactions. Further, adding this rock dust to the soil exposes it to plant roots and soil microbes. Both roots and microbes produce carbon dioxide as they decompose organic matter in the soil. In turn, this increases carbonic acid concentrations that accelerate weathering. One recent study by British and Americans scientists suggests that adding finely crushed silicate rock, such as basalt, to all cropland soil in China, India, the U.S. and Brazil could trigger weathering that would remove more than 2 billion tons of carbon dioxide from the atmosphere each year. Deployment of Enhanced weathering across over 680 million hectares of tropical agriculture with warm climate could offer an opportunity to employ these soils to sequester atmospheric carbon at a less time scale.



Factors affecting CO_2 Sequestration Rate and mineral weathering

The speed in which the minerals sequester CO_2 depends on the type of mineral, basalts are the most susceptible silicate rocks to weathering; sequestration rate increases with finer grinding grades due to higher surface area; increases with higher CO_2 concentrations; and is dependent on the saturation of the dissolving mineral in the solution - if there is not enough rain water this could slow down the sequestration rate. Silicate weathering depends on temperature, runoff and rate of physical erosion. Some studies indicate that vegetation can increase weathering rates by fivefold as compared to barren land. For the enhanced weathering tropical land is ideal.

Potential Benefits of enhanced weathering

1. **Improved productivity and reduced CO_2 emission from agriculture**:

➢ silicate containing various mineral like P, K, Mg & Ca, which are limiting nutrients for plant growth , they release via EW can fertilize crops.

- Releases of silica by EW which increase resistance to draught and insect pest in the crops such as rice, sugarcane, maize, sorghum.
- Application of basalt which increase pH of highly weatherd soils and helps mitigate soil acidification and other production constraint such as heavy metal toxicity in plants.
- substituting silicate EW for liming averts CO_2 emitted when lime reacts with soil water and during its production.
- if application of silicates rocks improves crop yields, food demand might be met on reduced land area of tropical agricultural land which continuously expanding via deforestation.

2. Reduced risk of phytoplankton bloom in rivers and reef:

Cultural eutropication could be prevented by high Si:N and Si:P ratios generated by EW of silicate minerals, increasing diatoms that remove nutrients from water, supporting diverse food webs. This could be a significant benefit for polluted riverine, reefs and oceanic ecosystems which is at downstream of major areas of tropical agriculture, while increased diatom could increase CO_2 sequestration in the ocean.

3. Counter Ocean acidification:

Due to the current excess of CO_2 in the atmosphere, Earth's oceans absorb a larger amount than they would naturally. This results in ocean acidification - the ongoing decrease of the ocean's pH - which has a range of harmful consequences for marine life, such as coral bleaching. Enhanced weathering counters ocean acidification as it increases the amount of bicarbonate (HCO_3^-) which increases ocean alkalinity.

Potential pitfalls

1. **Yield quality:** some silicate minerals containing toxic elements such as olivine, content high Ni and Cr would be problematic for agriculture. EW with basalt appears good choice by ancillary benefits of crop production and soil improvements and lack of heavy metal toxicity.
2. **Greenhouse gas emission from grinding and transport:** CO_2 emission associated with mining, grinding and spreading of rock dust could it's efficiency by 10-25%. Transportation of crushed rocks would increase NOx emission.
3. **Biodiversity impacts:** in particular increasing pH could have negative impacts for species adapted to low pH, widespread in tropical regieon especially in peatland.
4. **Reduce water quality in rivers and reefs:** if unweatherd silicate are washed into rivers, which increase inorganic turbidity and sedimentation, reducing reproduction and recruitment in river fish populations. Increased water pH might also negatively impact lives of naturally drainage.
5. **Mining and infrastructure expansion:** although silicates are a waste products from mining and steel and iron industry, more the requirement of silicate would increase mining activity and road construction, which combined with land cleaning and ultimately destructive to environment.

Conclusion

EW is a promising NET (negative emission technology) option that could be co-beneficial to tropical agriculture and coastal ocean ecosystem. However, one should emphasize that many issues related to weathering rates in different soils and conditions and impacts to soils and water resources are not fully understood, and further investigation in this area is required to reduce the many uncertainties associated with this method.