Removing Carbon (with) Rocks

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1. Introduction

Most leading climatologists have told us that we need to do more than just evolve all processes that currently emit greenhouse gasses (GHG) to no longer emit these, but also directly remove GHG from the atmosphere, especially carbon dioxide (CO_2). I agree with this for two big reasons: (1) evolving energy production to 100% renewables and zero carbon processes will require several decades, and (2) evolving all of our mobility to processes that do not burn carbon-emitting fuel will take even longer. Also, I'm not even considering the many industrial processes that need to be so converted. As long as we are still emitting substantial GHGs, climate change / global warming will worsen, and in order to prevent this we need to directly pull GHGs from the atmosphere to get to net-zero (removing GHG from the atmosphere at the same rate we are emitting them).

There are many processes for pulling CO_2 from the atmosphere, but most are very energy-intensive, and as long as we get most of our energy from GHG-emitting processes, these would not be very productive. There are at least a couple that are not so energy intensive. I wrote about one a few months ago:

Long-Term Sequestration of Woody Biomass: *A recent discovery may give us a short-cut to isolate biomass from the biosphere for a very long time without extensive processing.*

Limiting climate change requires achieving net-zero carbon dioxide emissions. Although substantial reduction in fossil fuel emissions is essential, it is insufficient for achieving the international goal of restricting global warming to 1.5° or 2°C above preindustrial levels. Achieving net-zero necessitates approaches that remove carbon dioxide from the atmosphere, known as carbon dioxide removal (CDR).

Engineering CDR methods, such as direct air capture, are expensive and energy-intensive. Nature-based CDR, such as reforestation and afforestation, are cheaper but face land-use competition, scalability, and carbon leakage risks.

Forests are central to climate change discussions because of their critical role as a dominant land carbon sink in natural carbon cycles. They sequester carbon from the atmosphere through photosynthesis. This carbon is stored in wood with ~50% carbon content that varies by species. The carbon is released back to the atmosphere through burning (forest fires or prescribed burning for fire risk management) or decomposition of woody biomass.

This paper describes a pathway to making long-term deadwood carbon storage a reality. The authors present a CDR approach involving the burial of sustainable wood in an underground engineered structure called a "wood vault" to prevent wood decomposition.

https://energycentral.com/c/ec/long-term-sequestration-woody-biomass

Guess what? Another low energy method to directly remove carbon dioxide from the atmosphere just popped up thanks to the main reference for this paper.

2. Rocks

The scene that unfolded on a cold November day in central Illinois might seem commonplace, but it was part of a bold plan to pull billions of tons of carbon dioxide from the atmosphere and stuff it into the ocean.[1]

A few miles south of Urbana a dump truck trundled past bare fields of dirt before turning into an adjacent lot. It deposited a cottage-size mound of grayish blue sand–190 metric tons of a crushed volcanic rock called basalt. Farmers spread the pulverized basalt across several fields that they sowed with corn months later. This was the fourth year of an ambitious study to test whether the world's farmlands can be harnessed to simultaneously address three global crises: the ever-rising concentration of planet-warming CO_2 in the atmosphere, the acidification of the oceans and the shortfall in humanity's food supply.

The trial results, published in February 2024, were stunning. David Beerling, a biogeochemist at the University of Sheffield in England, and Evan DeLucia, a plant physiologist at the University of Illinois Urbana-Champaign, led the study. They found that over four years, fields treated with crushed basalt and planted with alternating crops of corn and soy pulled 10 metric tons more CO_2 per hectare (4 metric tons per acre) out of the air than untreated plots. And crop yields were 12 to 16 percent higher. In other research, they found that adding crushed basalts to soils improved the harvest of miscanthus, a tall grass that is used to make biofuels, by 29 to 42 percent, and the fields captured an estimated. 8.6 metric tons of CO_2 per hectare (3.4 metric tons per acre) of land each year, compared with untreated fields. "It was exciting," Beerling says. "We were pleasantly surprised."

Their findings added to positive results elsewhere. In 2020 researchers in Canada reported that adding the mineral wollastonite[2] *to fields growing lettuce, kale, potatoes and soy sequestered CO_2 in the soil at rates as high as two metric tons per hectare per year. And last spring Kirstine Skov, a natural geographer at the start-up company UNDO Carbon in London, showed that crushed basalts improved the yields of spring oats by 9 to 20 percent while reducing soil acidity in several fields in England.*

Scientists, start-up companies and large corporations are experimenting with elaborate technologies to slow global warming: High-altitude planes that release sulfur dioxide into the stratosphere to block some incoming sunlight. Machines on Earth's surface that pull CO_2 out of the atmosphere. Iron sprinkled across the sea that enhances the growth of algae that absorb CO_2. These deployments could buy humanity some extra time to transition from fossil fuels to clean energy while preventing the climate from crossing dangerous thresholds in a permanent way. But the exotic approaches require gobs of money and energy or could threaten ecosystems. Simply spreading crushed rock on fields- as farmers have done for centuries with lime- seems refreshingly low tech. "That's part of its elegance," Beerling says.

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[1] Douglas Fox, "Rocks, Crops and Climate," February 2025 Issue of Scientific American, Page 36, to Order a Copy of a Scientific American Issue: Call (800) 333-1199, https://www.scientificamerican.com/article/could-seeding-farm-fields-with-crushed-rock-slow-climate-change/

[2] Wollastonite is a calcium inosilicate mineral ($CaSiO_3$) that may contain small amounts of iron, magnesium, and manganese substituting for calcium. It is usually white. Wikipedia article on Wollastonite.

The basalt in Illinois came from a quarry in southern Pennsylvania, where it is mined for roofing and building materials. Basalt is the most abundant rock in Earth's crust. As it naturally weathers-gradually dissolving in rain- and ground-water- it captures CO_2, converting it into bicarbonate ions in the water, which cannot easily reenter the atmosphere. The reaction also releases into the soil nutrients that are important for plant health, including calcium, magnesium and silicon. Grinding and spreading basalt-an approach known as enhanced rock weathering (ERW)-speeds up those processes greatly. It could help cash-strapped farmers around the world by increasing crop yields, reducing fertilizer use and potentially allowing them to sell carbon credits.

If ERW were to be scaled up globally, it could remove up to two billion metric tons of CO_2 from the air every year, according to Beerling. That would cover a significant share of the atmospheric carbon humanity must draw down to keep temperature rise to 1.5 degrees C, widely acknowledged as the necessary goal to prevent widespread catastrophe. But ERW would require mining and crushing billions of tons of rock every year–enough to build a mountain–and transporting it to farms, all of which would release CO_2. Still, calculations suggest that those emissions would pale in comparison to the amount of CO_2 that the rock stores away for centuries or longer-sequestered more permanently than it could have been in a forest of trees.

ERW is newer than the other so-called negative emissions strategies, and so far, only a few trials have been fielded. Yet companies are already looking to sell carbon credits tied to the technique. Noah Planavsky, a biogeochemist studying enhanced weathering at Yale University, sees promise in these unsettled circumstances. But he worries that if ERW expands too quickly, before the technique is refined, it could produce disappointing results and generate a backlash. "This has the potential to be something truly impactful," he says. "But there are so many ways you can imagine it going poorly."

The idea of ERW is based on a fundamental insight about how Earth naturally functions. Across geological time, lava eruptions spewed huge amounts of CO_2 into the atmosphere, heating the planet. Subsequent weathering of the erupted rock over ~ millions of years pulled the gas out of the atmosphere, cooling the planet back down. Basalts are effective in capturing CO_2 because they are high in calcium and magnesium from deep in the planet. Today vast swaths of North and South America, Africa, Asia, and other areas are covered in these solidified lavas.

Scientists have long wondered whether humans could accelerate CO_2 removal by speeding up rock weathering. In 1995 Klaus Lackner, a physicist then at Los Alamos National Laboratory in New Mexico, proposed heating basalts to absorb CO_2 more quickly. Over time this basic idea fermented into other forms: injecting concentrated CO_2 into hot layers of basalt underground where they would form carbonate minerals, or spreading powdered basalt across the ocean, which would absorb CO_2, sinking the carbon.

In the late 2000s Phil Renforth, a Ph.D. candidate at Newcastle University in England, noticed that the demolished remnants of steel mills in his area accumulated white crusts of carbonate minerals on the ground. Fragments of steel slag and concrete, both high in calcium, were reacting with CO_2. In 2013 he and Jens Hartmann, a geochemist then at the University of Hamburg in Germany, published a paper suggesting that calcium-rich rocks could be crushed and spread on farmland to capture CO_2 while also improving soils.

At about that time, Beerling was studying how grasslands influence the weathering of bedrock and the natural capture of CO_2. When he read Renforth and Hartmann's paper, he realized he could use his model to predict how basalt weathering would unfold on farmlands. In 2016 Beerling published calculations predicting that a millimeter or two of basalt dust spread annually over the world's tropical lands could reduce CO_2 levels by 30 to 300 parts per million (ppm) by 2100. Atmospheric carbon dioxide is currently around 425 ppm-up from 280 ppm before the industrial revolution-and is expected to hit 500 to 1,200 ppm by 2100. The modeling suggested that ERW could prevent 0.2 to 2.2 degrees C of warming by that date.

Common climate scenarios predict that if humans are going to limit warming to two degrees C, we need to remove five to 10 gigatons of CO_2 from the atmosphere annually by 2050. In 2018 Beerling's team published updated calculations predicting that if crushed basalt were spread yearly across 700,000 square kilometers of corn and soy croplands in the U.S., it could remove 0.2 to 1.1 gigatons of CO_2 from the atmosphere annually.

In 2020 Beerling and his collaborators, joined by Renforth, published a refined analysis in Nature. They estimated that if two gigatons of CO_2 a year had to be captured worldwide through ERW, China, India, the U.S. and Brazil could cover 80 percent of that amount, even after accounting for the CO_2 emitted while mining, crushing and transporting the rock. Obviously, a combination of carbon capture methods would be needed to reach 10 gigatons a year. But, Beerling says, "If you can do two [gigatons] of it with enhanced weathering and improve food security and soil health, that's 20 percent of the way there."

The Illinois trial provided strong validation. Farming of corn and soy typically releases CO_2 through the respiration of roots and soil microbes, but the basalt- treated corn-soy fields released 23 to 42 percent less CO_2. Multiplied across the U.S., that's 260 million tons of CO_2 potentially avoided each year.

Unlike geoengineering approaches such as hoisting sulfur into the sky or scattering iron across the sea, which people often view as risky tinkering with nature, ERW was well received when papers were published, Beerling says. "It was important to see how this landed with the public and the press," he says. The reactions "strengthened our belief that this was the right way to go."

ERW is fundamentally different from two other soil-based carbon strategies that have been around longer. In a method called biochar, farmers partially burn leftover plant matter, turning it to charcoal nearly pure carbon-which is plowed into the dirt for long-term storage. In the second method, leftover plant material is plowed back into the soil without being charcoaled; this stores carbon as organic molecules that can nourish crops, although the molecules can also return to the atmosphere.

ERW traps CO_2 as dissolved bicarbonate in soil water, which eventually runs off farm fields into streams that ultimately lead to the sea, storing CO_2 in the ocean water as bicarbonate or as solid carbonate minerals on the seafloor. Studies predict that ERW would reliably store bicarbonate in the ocean for 100 to 1,000 years, which could also help reduce climate-related ocean acidification. What's more, ERW could alleviate another major problem, not addressed by the two other methods, that plagues farmers around the world.

One of the most striking examples of how rock weathering has regulated atmospheric CO_2 levels over the eons can be found along the western coast of India-one reason some of the earliest efforts to roll out ERW by start-up companies are happening in this country. India's coastal plain, dotted with rice paddies and villages, abruptly rises 1,000 meters through a chaotic maze of sharp ridges, V-shaped canyons, rushing rivers and waterfalls to a high plateau. The canyon walls are striped in alternating layers of yellow and brown basalt, marking the edge of the Deccan basalts, formed from a massive series of lava flows that started around 66 million years ago. By 50 million years ago Earth was unusually warm, with CO_2 levels nearly four times what they are today. Around that time, the Deccan basalts began altering the planet's climate in a slow but potent way. Continental drift carried them into the equatorial belt, where abundant rainfall and warm temperatures caused the rocks to weather more quickly. The weathering minerals pulled CO_2 from the air and washed it down rivers to the sea, trapping it there.

Over the next 30 million years, estimates indicate, weathering basalts drew more than one million gigatons of CO_2 from the atmosphere, some of it becoming buried as carbonate on the seafloor. Atmospheric CO_2 declined, temperatures cooled, and an ice sheet began growing across Antarctica.

2.1. Much Rock

As promising as early trials have been, a large-scale rollout of ERW would have to overcome some stark realities, starting with the staggering amount of rock it would require. Beerling's calculations suggest that if ERW were used to capture two gigatons of CO_2 a year, it would consume 13 gigatons of basalt annually-about 4.5 cubic kilometers of rock, roughly equal to the volume of the Matterhorn. That would require 30 percent more mining than the 40 gigatons or so of sand, gravel and crushed rock that are now quarried worldwide annually for industry. Such an increase might not be possible for some kinds of rock, but the world's reserves of basalt are truly vast and distributed widely across the planet.

Crushed basalt that's already produced in quarries as an unused byproduct could pick up some of that slack. So could calcium-rich industrial biproducts, such as crushed concrete, mine tailings, ash from sugarcane milling and coal burning, and wastes from cement, aluminum and steel production. But many of these byproducts contain chromium, nickel, cadmium, and other toxic elements, so they could maybe be used to capture CO_2 in factory yards or tailings piles at mines but not on croplands. When additional basalt mining and crushing is needed, it will cost about \$10 and emit around 30 kilograms of CO_2 per ton. Beerling's team considered these factors when it estimated that ERW would cost \$80 to \$180 per ton of CO_2 captured, after emissions are subtracted.

2.2. Potentially Poor Targets

A 2022 trial that Beerling's group supported in Malaysia, where basalt dust was spread across parts of a palm oil plantation, produced inconclusive results. Beerling suspects that the benefits are being temporarily masked by local conditions. The dark, pungent soils contain more decaying organic matter and more clay than the soils in Illinois; those charged materials can latch on to the breakdown products of basalt, keeping them from converting CO_2 into bicarbonate. "There's a delay in capturing carbon dioxide," Beerling says. It doesn't happen until the soil's capacity to bind the dissolving minerals has been saturated, "which may take a year or take five years," he says. This remains to be seen.

Acidity is the other complicating factor, according to a trial on tropical sugarcane fields in northeastern Australia. The soil there is acidic, so it can potentially consume the basalt before it has a chance to react with CO_2. Initial results, published last October, show that CO_2 capture rates are only about 1 percent of those in Illinois. Paul Nelson, a soil scientist at James Cook University in Cairns who helped lead the study, says it may be hard to fix the problem just by neutralizing acidic soils before adding basalt because in wet tropical areas the acidity may extend many meters down, to the bedrock.

2.3. Financial Upsides and Downsides

Despite the uncertainties, some two dozen companies have emerged to try to exploit ERW. Many are selling anticipated carbon-capture credits, in some cases to companies such as Microsoft and Stripe that hope to zero out their carbon footprint. This activity makes Planavsky, the Yale biogeochemist, uneasy. He's aware of lessons learned in another carbon market that grew too quickly. In recent years companies have sold more and more "voluntary carbon offsets" for protecting forests, but some of the projects have subsequently been revealed as worthless. ERW is "a potentially really valuable opportunity" to remove CO_2, Planavsky says, "but it's not going to work everywhere." If companies cut corners, he says, ERW could "blow up on the launch pad."

Yet for ERW to have a large impact by 2050, it will need to expand quickly, says Gregory Nemet, an energy scientist at the University of Wisconsin-Madison. Last May he and his colleagues published a study analyzing the combined potential of novel CO_2 removal methods such as ERW, direct air-capture machines and the use of biofuels with CO_2 captured from smokestacks. Between now and 2050 these methods need to grow "by something like 40 percent per year, every year," Nemet says. That sounds extreme, although he says that electric cars and solar energy have expanded even more rapidly for 10 or 20 years. And if enhanced weathering ends up costing \$80 to \$180 per ton of CO_2, as Beerling's group predicted, it may be cheaper than direct air capture (\$400 to \$1,000 per ton right now), and similar to biofuels with smokestack capture (\$100 to \$300 per ton today).

If ERW does pan out on a large scale, Planavsky whose family farms-sees potential societal benefits that go beyond CO_2 removal. Building machines that capture CO_2 from the air or from smokestacks will generate profits for big companies. But with a low-tech approach like ERW, even small farmers could sell carbon credits. "Imagine the farm of the future," he says. "Part of the farmer's view of their mandate is carbon dioxide removal."