RESEARCH UPDATE

ENHANCED WEATHERING

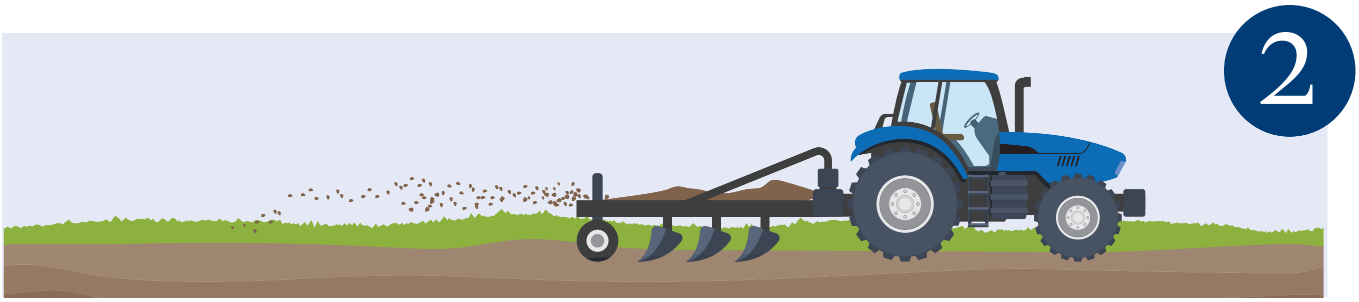
Photo provided by Dr. James Saiers, Yale School of the Environment

WHAT is Enhanced Weathering?

Enhanced weathering (EW) is a promising natural solution for durable carbon dioxide removal (CDR) that builds on the longstanding practice of applying crushed rock (such as limestone) to agricultural lands to mitigate soil acidification. EW uses the same method to accelerate the Earth's natural carbon cycle by spreading finely ground alkaline material (e.g. silicate rock such as basalt) over agricultural fields. In addition to reducing soil acidification, the crushed rock reacts with CO_2 in soils to form stable bicarbonate ions that are eventually stored in the ocean for millennia.

EW takes advantage of infrastructure and supply chains from mining and agriculture to offer great potential for deployability, scale, and low cost – along with the potential to deliver substantial co-benefits to farmers, agriculture, and ecosystems. Some open questions remain about EW's CDR efficacy across varying deployment contexts; monitoring, reporting, and verification (MRV); and potential negative impacts to food systems and ecosystems. Scientists at the Yale Center for Natural Carbon Capture (YCNCC) are actively advancing research to address these questions, as well as proactively engaging with the EW startup ecosystem, the mining and agriculture sectors, and corporate CDR buyers. EW remains a core YCNCC priority, wherein the Center is delivering substantial real-world climate impact.

Basalt is collected, crushed, and transported for application on fields.



Farmers spread the crushed rock on their fields, using existing machinery and tools.

The crushed rock absorbs carbon dioxide.

Opportunity for Impact:

- **SCALABILITY AND LOW COST.** EW has the potential to deliver billions of tons per year of durable CDR at a cost below $100 per ton.[1,2] EW employs Earth-abundant mineral feedstocks, and leverages logistical capabilities and supply chains from mining and agriculture – two massive global economic sectors. Relative to EW's CDR potential, energy requirements (extraction, processing, and transport of feedstock) are low. Initial EW deployments do not require new technology or infrastructure development.

- **DURABILITY.** EW delivers highly durable CDR with minimal risk of reversal. The carbon captured by EW travels through the soil and river systems to the ocean, where it is stored in stable bicarbonate form for at least ten thousand years. Long-duration CDR is increasingly valued by corporate buyers in the voluntary carbon market (VCM), as well as by government policymakers in the U.S., European Union, and other jurisdictions globally.

1 Beerling et. al., Potential for Large-Scale CO_2 Removal via Enhanced Rock Weathering with Croplands. Nature, July 2020.
2 Fuhrman et. al. Diverse Carbon Dioxide Removal Approaches Could Reduce Impacts on the Energy-Water-Land System. Nature Climate Change, March 2023.

- **CO-BENEFITS.** EW reduces soil acidification and increases the bioavailability of major crop nutrients such as nitrogen, phosphorus, and potassium. Many EW feedstocks contain additional phosphorus and potassium, as well as micronutrients that can also increase crop yields. These agronomic co-benefits can reduce farmers' reliance on polluting chemical fertilizers, lowering costs as well as the greenhouse gas intensity (CO_2 and nitrous oxide emissions) of farming. Additionally, EW is starting to become eligible for federal (e.g. U.S. Department of Agriculture) subsidies, providing a new and potentially meaningful income stream for U.S. farmers.

Challenges to Enable Scale:

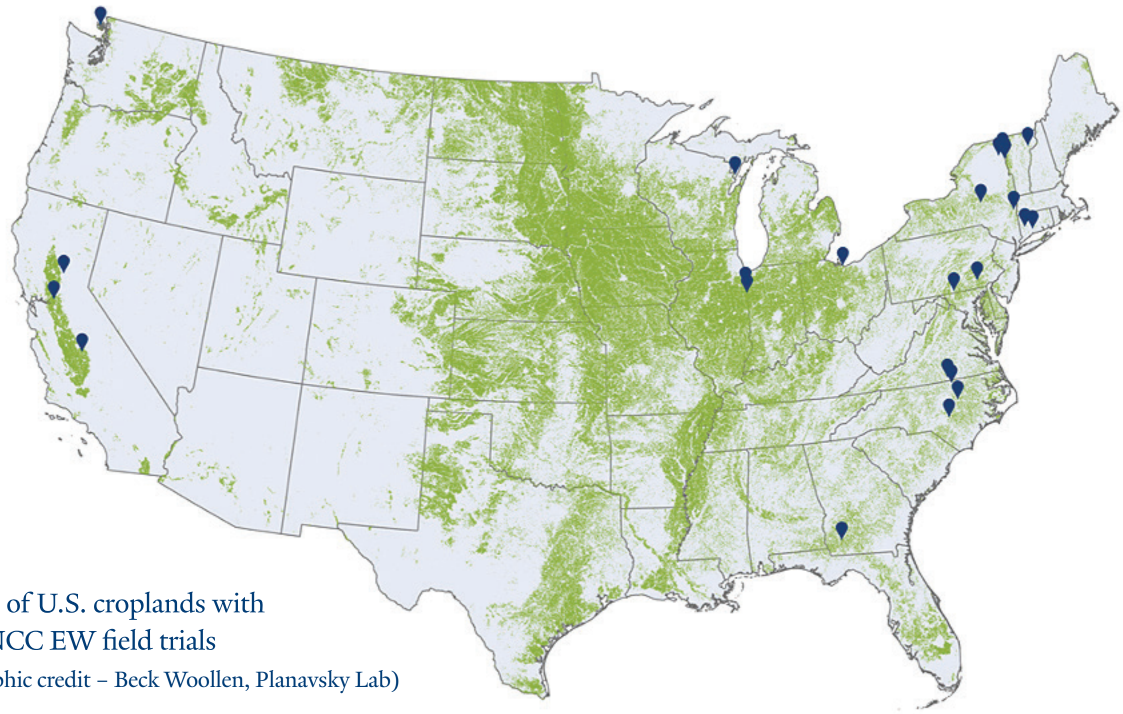
- **MRV.** High-quality monitoring, reporting, and verification (MRV) is essential for EW to fulfill its potential to deliver climate impact at scale. The core of MRV is quantification of a project's net removal of CO_2 from the atmosphere. This can be challenging for "open-system" CDR approaches, such as EW, which leverage large-scale Earth processes that lack clear system boundaries, cannot always be clearly or easily measured due to variations in ecosystems, and may occur over varying time intervals. Additional research is needed to reduce uncertainty (and cost) of EW MRV – to refine and operationalize in-field measurements necessary to quantify gross CDR, and accurately and economically model the transport of bicarbonate through river systems and its long-term storage in the ocean.

- **ECOSYSTEM AND COMMUNITY SAFETY.** Several potential risks can stem from improper EW project design and implementation. Certain EW feedstocks contain trace metals that can be potentially dangerous to food systems and ecosystems. This concern can be mitigated by choice of feedstock; detailed analysis of feedstock samples; careful management of application rates; and sustained in-field monitoring. Additionally, deployment of EW at significant localized scale can affect the alkaline chemistry of groundwater and river systems. Further research is required to better understand this potential effect, and eventual large-scale EW deployments should include biogeochemical monitoring of nearby groundwater and rivers.

- **EFFECTIVE PROJECT DESIGN.** While there is emergent scientific consensus as to the general potential efficacy of EW as high-quality, durable CDR, mineral weathering rates are subject to a range of factors, from feedstock characteristics (mineralogy and particle size) to soil type, pH, and water fluxes. More EW research is needed, including field trials in a range of deployment contexts, at increasing scale. Site selection and project design informed by the best available science will be critical to EW having the desired long-term climate impact.

YCNCC Scientists – Advancing EW Through Research:

- YCNCC scientists are evaluating geochemical responses in soils, groundwater, and streamwater to a whole-watershed application of crushed silicates in Vermont and Virginia. YCNCC has launched more than 25 additional field trials across 8 U.S. states to provide further data about EW performance in a range of deployment contexts.



Map of U.S. croplands with
YCNCC EW field trials
(Graphic credit – Beck Woollen, Planavsky Lab)

- YCNCC research teams continue to develop novel methods and instrumentation for tracking EW in soils, sampling EW dissolution products in soil waters, and measuring EW-generated alkalinity at high resolution in stream waters. These tools have the potential to greatly amplify the impact of YCNCC research as they become more broadly accepted.

- YCNCC scientists are developing novel modeling frameworks to simulate initial CDR in soils; export of alkalinity and other EW products from watersheds; CO_2 evasion (loss) as alkalinity is transported through river systems; and the durability of bicarbonate storage in the ocean. These frameworks are essential for quantifying net CDR at scale and the overall climate benefit of EW deployments.

- YCNCC researchers are exploring how traditional liming practices can be modified to deliver CDR and potentially even lower-cost CDR credits. This work is ongoing and YCNCC scientists plan to publish the results of this research in the coming year.

- YCNCC scientists advise leading agricultural EW project developers including Lithos, Silica, and Mati Carbon, as well as CREW Carbon, which integrates EW with wastewater treatment systems. YCNCC scientists continue to research the opportunity to integrate EW into large-scale industrial and agricultural processes including wastewater treatment and irrigation systems.

- YCNCC is training the next generation of EW scientists. Yale graduates are already serving important roles at EW startups, CDR registries, government agencies, environmental nongovernmental organizations, and other research institutions. In the Spring of 2025, YCNCC researchers convened a public online seminar (in conjunction with a Yale School of the Environment course) that has drawn thousands of viewers to learn more about EW.

Select YCNCC EW Publications for Reference:

Baek et. al. Impact of Climate on the Global Capacity for Enhanced Rock Weathering on Croplands, AGU Earth's Future, August 2023.

Beerling et. al. Transforming U.S. agriculture for carbon removal with enhanced weathering. Nature, February 2025.

Beerling et. al. Enhanced weathering in the US Corn Belt delivers carbon removal with agronomic benefits, Proceedings of the National Academy of Sciences (PNAS), February 2024.

Chiaravallotti et. al. Mitigation of Soil Nitrous Oxide Emissions During Maize Production with Basalt Amendments. Frontiers in Climate, June 2023.

Driscoll et. al. Hotspots of irrigation-related US greenhouse gas emissions from multiple sources. Nature Water, August 2024.

Fung et. al. Improving nitrogen cycling in a land surface model (CLM5) to quantify soil N2O, NO, and NH3 emissions from enhanced rock weathering with croplands. Geoscientific Model Development, October 2024.

Kanzaki et al. Soil Cycles of Elements Simulator for Predicting Terrestrial Regulation of Greenhouse Gases: SCEPTER v0.9. Geoscientific Model Development, June 2022

Kanzaki et al. In silico calculation of soil pH by SCEPTER v1.0. Geoscientific Model Development, May 2024.

Levy et. al. Enhanced Rock Weathering for Carbon Removal–Monitoring and Mitigating Potential Environmental Impacts on Agricultural Land. Environmental Science & Technology, September 2024.

Li et. al. Geospatial assessment of the cost and energy demand of feedstock grinding for enhanced rock weathering in the coterminous United States. Frontiers in Climate, August 2024.

Martin et. al. Improving nitrogen cycling in a land surface model (CLM5) to quantify soil N2O, NO, and NH3 emissions from enhanced rock weathering with croplands. Geoscientific Model Development, October 2023.

Reershemius et al. Initial Validation of a Soil-Based Mass-Balance Approach for Empirical Monitoring of Enhanced Rock Weathering Rates. Environmental Science & Technology, November 2023.

Sun et al. Long-Term Trends of Streamwater Chemistry in a Headwater Watershed: Impacts from Anthropogenic and Climate Factors. Science of the Total Environment, in review.

Suhrhoff et. al. A tool for assessing the sensitivity of soil-based approaches for quantifying enhanced weathering: a US case study. Frontiers in Climate, April 2024.

Zhang et. al. River Chemistry Constraints for Carbon Capture Potential of Surficial Enhanced Weathering. Limnology and Oceanography, October 2022.

Zhang et. al. Techno-Economic and Life Cycle Assessment of Enhanced Rock Weathering: A Case Study from the Midwestern United States. Environmental Science & Technology, September 2023.