

1 **Supplementary Materials**

2 Enhanced Rock Weathering for Carbon Removal – Monitoring and Mitigating Potential Environmental  
3 Impacts on Agricultural Land

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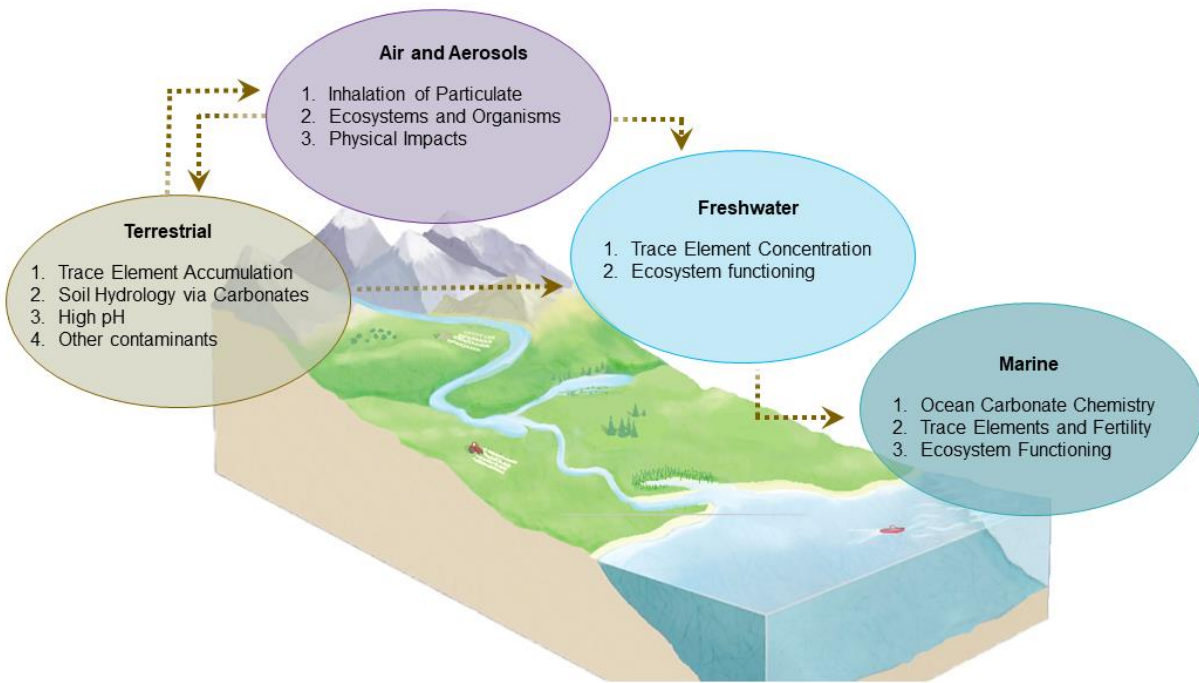
21 Nineteen pages

22 Four figures

23 Four tables

24 In this study, enhanced rock weathering (ERW) is defined as the application of pulverized silicate rock to  
25 terrestrial soils. Our focus is on application to agricultural cropland, with the primary intent of removing  
26 carbon dioxide from the atmosphere. Rangelands, waterways, and oceans are also candidates for the  
27 application of pulverized minerals, which may represent their own unique environmental questions to be  
28 examined.

29 In the context of agricultural application, the primary impact of ERW will take place at the site of  
30 application. Erosion by wind and water, and leaching from soils into freshwater, then distributes particles  
31 and indirect effects beyond the farm field. Finally, marine systems are impacted where upstream  
32 application reaches the coast and deeper waters.



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34 **Supplementary Figure 1.** A conceptual diagram showing the environmental impacts of enhanced rock  
 35 weathering as they disperse from the initial point of application. The highlighted sectors, terrestrial, air  
 36 and aerosols, freshwater, and marine map to the expected transport of enhanced rock weathering  
 37 feedstocks and impacts beyond the farm field. Arrows indicate the exchange between these sectors.

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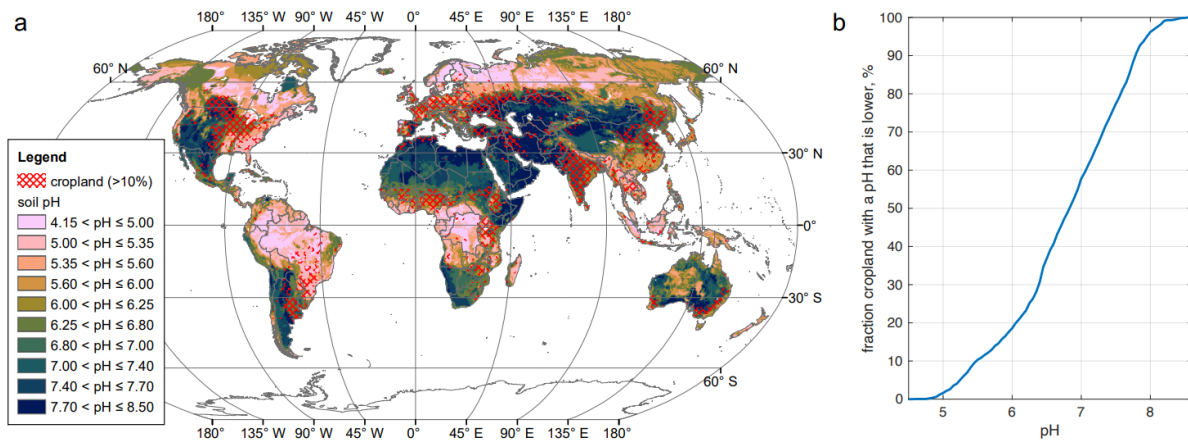
<b>Impact</b>	<b>Metric</b>	<b>Spatial Extent</b>	<b>Risk Level</b>	<b>Monitoring Entity</b>
Accumulation of Trace Elements in Soils and Biomass	Chromium VI concentration	Application Site	High	Landowner, ERW Supplier
	Nickel concentration	Application Site	Medium-high	Landowner, ERW Supplier
	Zinc concentration	Application Site	Medium	Landowner, ERW Supplier
	Copper concentration	Application Site	Medium	Landowner, ERW Supplier
Magnesium excess in soils	Ratio of magnesium to total magnesium and calcium	Application Site	Low-Medium	Landowner, ERW Supplier
	Exchangeable magnesium concentration	Application Site	Low-Medium	Landowner, ERW Supplier
Changes to soil hydrology due to carbonate accumulation in soils	Runoff/Ponding	Application Site	Medium	Landowner
	Salinity	Application Site	Medium	Landowner
	Porosity	Application Site	Medium	Landowner
Application increases pH excessively	Nutrient availability	Application Site	Medium	Landowner
	pH	Application Site	Low	Landowner
	Soil microbial activity	Application Site	Low	Landowner
Other contaminants to soils	Radiation	Application Site	Very low	Landowner, ERW Supplier
	Asbestos	Application Site	Very low	Landowner, ERW Supplier
Health impacts from mineral dust inhalation	Pneumoconiosis	Application site + 100 m	Medium Medium-High in dry, windy environments	National, Local Government
	PM 2.5	Application site + 100 m	Medium	National, Local Government
	PM 10	Application site + 100 m	Low	National, Local Government
Impact to sensitive ecosystems and organisms	Plant biodiversity	Application site + 20 m	Low	Landowner, ERW Supplier
	Community composition		Medium near sensitive habitat	
	Invertebrate biodiversity (aboveground)	Application site + 20 m	Low to medium	Landowner, ERW Supplier
	Invertebrate biodiversity (belowground)	Application site + 20 m	Low	Landowner, ERW Supplier
	Soil microbial biodiversity	Application site + 20 m	Low	Landowner, ERW Supplier
Physical damage to plants	Yield	Application site + 100 m	Low	Landowner, ERW Supplier
	Physical abrasion			

Alkalization of Freshwater Systems	pH	Drainage basins (e.g. lakes, streams, rivers, reservoirs)	Low where historically acidified or well-buffered, high where poorly buffered or sensitive	National Government
Increase in freshwater turbidity	Turbidity	Drainage basins (e.g. lakes, streams, rivers, reservoirs)	Low	National, Local Government
Freshwater bioavailability of trace metals	Concentration	Drainage basins (e.g. lakes, streams, rivers, reservoirs)	Low to high High for hexavalent chromium	National, Local Government
Loss of sensitive freshwater ecosystems and organisms	Biodiversity Community composition Fisheries health	Drainage basins (e.g. lakes, streams, rivers, reservoirs)	Low where historically acidified or well-buffered, high where poorly buffered or sensitive	National, Local Government
Photosynthetically driven eutrophication of freshwater ecosystems	Dissolved oxygen concentration	Drainage basins (e.g. lakes, streams, rivers, reservoirs)	Low in low order streams, medium in connected lakes and reservoirs	National Government
Alkalization of marine systems	pH Aragonite saturation	Regional coastal ocean	Low	National Government Local Government
Eutrophication of marine systems	Bioavailable nitrogen	Regional coastal ocean	Low	National, Local Government
Loss of sensitive marine ecosystems and organisms	Biodiversity Community composition Fisheries health	Regional coastal ocean	Low	National, Local Government

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40 **Supplementary Table 1.** An assessment of environmental risks associated with ERW, incorporating the geographic scale of the impact, the level of  
41 concern of the risk from low to high, and the political entity responsible for monitoring and mitigation.

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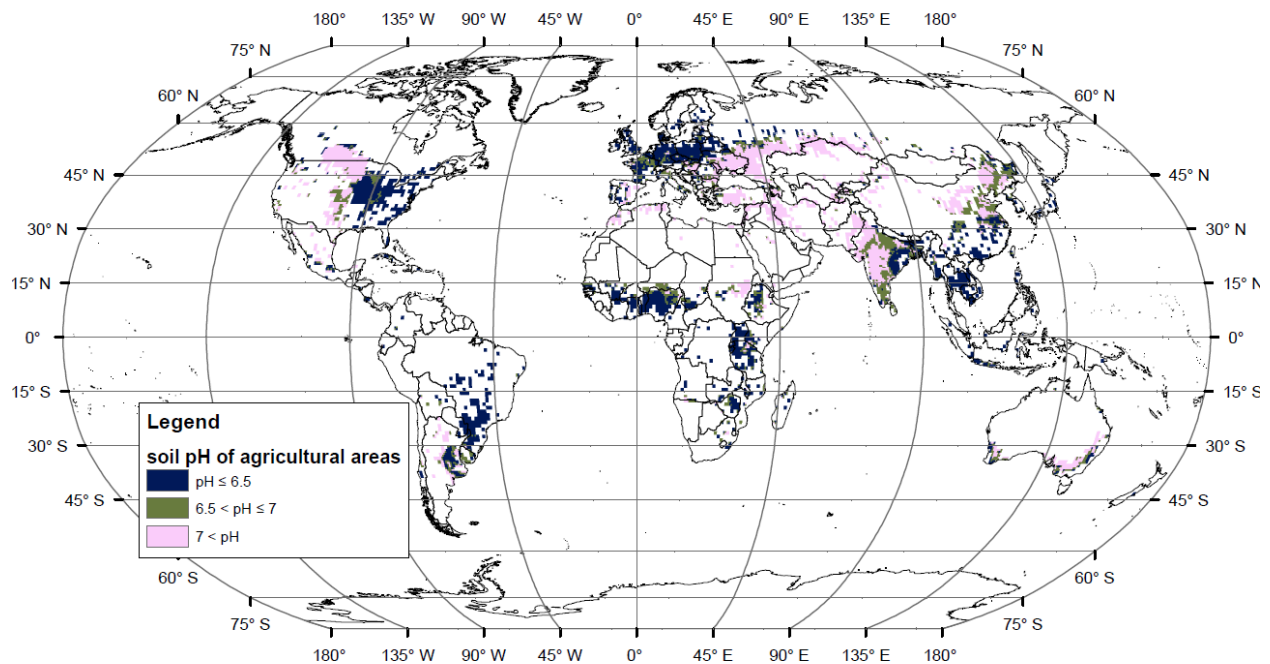
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44 **Supplementary Figure 2.** a. Map of global soil pH<sup>123</sup> and areas where croplands cover at least 10%  
 45 of the land surface<sup>124</sup>. b. The fraction of farmland area with a pH lower than that given on the x-axis, based  
 46 on these data.

47 *Analogues in and Application to Weathering of Carbonate Minerals*

48 Enhanced rock weathering for carbon removal can also incorporate reaction of pulverized carbonate  
 49 minerals. These minerals are able to remove a mol of CO<sub>2</sub> per mol of calcium dissolved with permanence  
 50 of 1,000 to 10,000 years. Carbonate weathering is more likely to be carbon neutral or even positive than  
 51 silicate weathering, due to the lower carbon removal efficiency and potential for precipitation back to  
 52 carbonate minerals, re-releasing carbon dioxide.

53 Some carbonate minerals, e.g. limestones, have been used in agriculture since antiquity – thus decades of  
 54 research is available to inform probable environmental risks and existing supply chains and practitioners  
 55 have developed best practices for use. Rather than recapitulate these here, we have instead explored  
 56 where carbonate weathering can serve as an analogue for the consequences of implementing enhanced  
 57 rock weathering with silicate minerals at scale.



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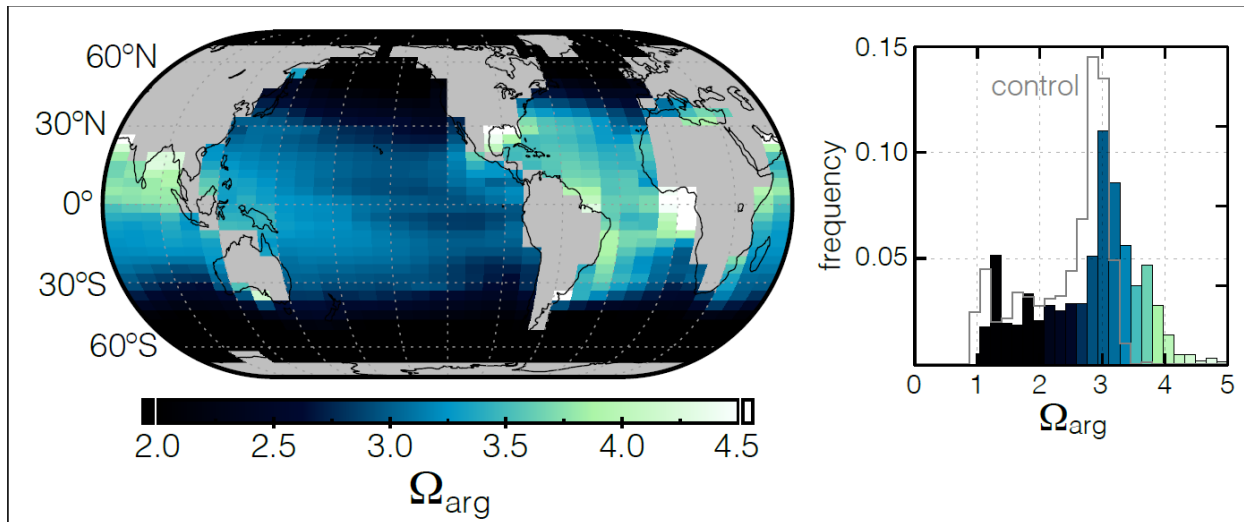
59 **Supplementary Figure 3.** Map of global agricultural areas as delimited by relevant pH thresholds.  
 60 Thresholds are set as where soil pH<sup>123</sup> is below 6.5, between 6.5 and 7, and above 7. The extent of  
 61 agricultural area is defined as areas where croplands cover at least 10 % of the land surface<sup>124</sup>.

62 Shifts in marine carbonate systems will be driven by the balance between alkalinity and dissolved  
 63 inorganic carbon (DIC) in integrated outflow from terrestrial systems. In an idealized transfer of carbon  
 64 and alkalinity from the farm field to the ocean, outflow is in balance with an alkalinity to DIC ratio of 1.0.  
 65 There would be a slight increase in the partial pressure of dissolved carbon dioxide, driving it to outgas  
 66 from the surface ocean.<sup>3, 112, 125</sup> Overall carbonate ion abundance and state in surface waters would  
 67 increase except at extremely high saturation states.

68

69 In real world scenarios, this ratio is modified upstream of the coastal ocean. For instance, during  
 70 freshwater transport, outgassing of carbon dioxide drives down DIC concentration without changing  
 71 alkalinity. When these waters reach the coastal ocean they drive down the partial pressure of dissolved  
 72 carbon dioxide, resulting in ingassing from the atmosphere as the carbonate system re-equilibrates. This  
 73 dynamic represents a key difference between ERW and ocean alkalinity enhancement (OAE) — even  
 74 with an identical alkalinity flux, most or all of the carbon removal of ERW takes place in the soil, while  
 75 with OAE carbon removal will depend on local gas exchange equilibrium between the surface ocean and  
 76 atmosphere.

77



78  
 79 **Supplementary Figure 4.** Visualization of aragonite saturation state ( $\Omega_{\text{arg}}$ ) in an intermediate-complexity  
 80 Earth system model<sup>112</sup>. The model assumes ERW at scale ( $10 \text{ Gt CO}_2 \text{ yr}^{-1}$ ) against a moderate  
 81 anthropogenic emissions pathway (RCP 4.5). Shown at left are surface aragonite saturation states, while  
 82 at right the statistical distribution of  $\Omega_{\text{arg}}$  values is compared to a control simulation without ERW.  
 83 Aragonite saturation states below 3 are anticipated to be harmful to calcifying organisms. However, the  
 84 resolution of this model is insufficient to effectively resolve transient coastal impacts. We recommend  
 85 development of high-resolution simulations of coastal ERW impacts on key ecologically relevant  
 86 carbonate system parameters and macronutrients.

87  
 88 We identified as low-risk changes to soil pH, changes to soil microbial diversity. As described above, few  
 89 cropland soils are too alkaline – excess increase to pH can thus be avoided by prioritizing more acidic and  
 90 acidifying soils. Monitoring of soil pH should face minimal technical and financial barriers, and can be  
 91 done at the level of the landowner – routine soil pH measurements are also part of the current practice in  
 92 many agricultural settings. Similarly, microbial diversity on croplands is unlikely to be impacted by ERW  
 93 at most rates of application and on most cropland soils. Monitoring for microbial diversity is more costly  
 94 and technical than pH, however monitoring will likely only be required where other soil health indicators  
 95 (such as pH or trace element content) raise concerns. Finally, radiation and asbestos are low-probability  
 96 concerns provided sourcing guidance to protect against trace element exposure is followed. As with trace  
 97 elements, mineral dust sources to be low risk, individual feedstocks should be tested on sourcing, and  
 98 regulation should provide overall guidance on safe exposure thresholds.

99 We also identified low-risk environmental harms due to wind transport of ERW minerals. Wind transport  
 100 of ERW minerals to sensitive proximate ecosystems was considered low risk except in unusually dry and  
 101 windy environments. Biodiversity of plants, macroinvertebrates, and soil biota may be impacted if ERW  
 102 minerals are transported into a pH sensitive environment e.g. bogs and wetlands. The mitigation strategies  
 103 employed above to prevent regional dust transport will also be effective here. However, there is not  
 104 currently a clear mechanism for enforcement should dust reach a sensitive ecosystem in high quantities.  
 105 Conservation groups and regional governments may need to develop new regulatory strategies to protect  
 106 wetlands and unique habitat proximal to cropland. Additional research effort may be warranted to  
 107 determine how widely dust is likely to be transported, in quantities that can impact sensitive ecosystems.

<b>Impact</b>	<b>Metric</b>	<b>Safe range or threshold</b>
Accumulation of Trace Elements in Soils and Biomass	Chromium VI concentration	Global soil average threshold 113 ppm (30-250 ppm, n=11). Global average biomass threshold 30 ppm (26-24 ppm, n=2).
	Nickel concentration	Global soil average threshold 59 ppm (15-190 ppm, n=15). Global average biomass threshold 133 ppm (38-280 ppm, n=8).
	Zinc concentration	Global soil average threshold 179 ppm (55-300 ppm, n=14). Global average biomass threshold 101 ppm (46-160 ppm, n=4).
	Copper concentration	Global soil average threshold 62 ppm (20-132 ppm, n=14). Global average biomass threshold 57 ppm (28-80 ppm, n=4)
Magnesium excess in soils	Ratio of magnesium to total magnesium and calcium	magnesium/(calcium +magnesium) < 65% to prevent decrease in wheat yield, magnesium/(calcium +magnesium) < 90% to prevent severe calcium deficiency for wheat - may depend on crop type
	Exchangeable magnesium concentration	Exchangeable magnesium concentrations of 300 ppm or 2.5 meq/100g soil
Changes to soil hydrology due to carbonate accumulation in soils	Ponding	Increase in frequency (number of incidents in 100 years), depth (average representative depth), and duration (estimated average time per ponding event)v
	Salinity	Most crops: Electrical Conductivity > 4 mmho per cm Defer to crop specific guidance as appropriate
	Porosity	Most crops: $1.0 \text{ g cm}^{-3} < \text{Bulk density} < 1.7 \text{ g cm}^{-3}$
Application increases pH excessively	Nutrient availability	3.5 ppm > Extractable phosphorus > 21.5 ppm 25 ppm > Extractable potassium 33 ppm > magnesium` 25 ppm > Iron 50 ppm > Manganese
	pH	Most crops: $6.2 < \text{pH} < 6.8$ Acidophilic Crops (including oats, rye, rice, blueberries): $5.0 < \text{pH} < 7.5$ Defer to crop specific guidance as appropriate
	Soil microbial activity	Respiration >0.5 mg CO <sub>2</sub> per g dry weight
Other contaminants to soils	Radiation	Soil screening levels for ingestion of soil and for inhalation of fugitive dusts adjusted by project area, climate, and vegetation cover.
	Asbestos	Feedstock < 1% chrysotile, cummingtonite-grunerite asbestos (amosite), crocidolite, anthophyllite asbestos, tremolite asbestos, and actinolite asbestos
Health impacts from mineral dust inhalation	Pneumoconiosis	Detected cases in individuals with high occupation risk
	PM 2.5	PM 2.5 <= $35 \mu\text{g m}^{-3}$ within a 24 hour period
	PM 10	PM 10 <= $150 \mu\text{g m}^{-3}$ within a 24 hour period
Impact to sensitive ecosystems and organisms	Plant biodiversity and community composition changes	Loss thresholds to be set within the context of target species, organisms, and ecosystem services
	Invertebrate biodiversity, aboveground	

	Invertebrate biodiversity, belowground	
	Soil microbial biodiversity	
Physical damage to plants	Yield	Decrease in yield above expected variation and attributable to loss of young plants
	Physical abrasion	Physical abrasion sufficient to impact the success or survival of young plants
Alkalinization of Freshwater Systems	pH	pH > 9 in watersheds with historically lower pH
Increase in freshwater turbidity	Turbidity	Criterion maximum turbidity < 1 NTU
		Criterion chronic turbidity < 0.3 NTU
Freshwater bioavailability of trace metals	Chromium VI concentration	Criterion maximum concentration < 16 µg L <sup>-1</sup> Criterion chronic concentration < 11 µg L <sup>-1</sup>
	Nickel concentration	Criterion maximum concentration < 470 µg L <sup>-1</sup> Criterion chronic concentration < 52 µg L <sup>-1</sup>
	Zinc concentration	Criterion maximum concentration < 120 µg L <sup>-1</sup> Criterion chronic concentration < 120 µg L <sup>-1</sup>
Loss of sensitive freshwater ecosystems and organisms	Biodiversity	Loss thresholds to be set within the context of target species, organisms, and ecosystem services
	Community composition	
	Fisheries health	
Photosynthetically driven eutrophication of freshwater ecosystems	Dissolved oxygen concentration (DOC)	DOC > 8 mg per L daily measure for early-life stages in coldwater systems DOC > 5 mg per L daily measure for early-life stages in warmwater systems
Alkalinization of marine systems	pH	pH < 8.5 either chronic or acute
	Aragonite saturation ( $W_{arg}$ )	$W_{arg} > 3$
Marine bioavailability of trace metals	Chromium VI concentration	Criterion maximum concentration < 1100 µg L <sup>-1</sup> Criterion chronic concentration < 50 µg L <sup>-1</sup>
	Nickel concentration	Criterion maximum concentration < 74 µg L <sup>-1</sup> Criterion chronic concentration < 8.2 µg L <sup>-1</sup>
	Zinc concentration	Criterion maximum concentration < 90 µg L <sup>-1</sup> Criterion chronic concentration < 81 µg L <sup>-1</sup>
	Copper concentration	Criterion maximum concentration < 4.8 µg L <sup>-1</sup> Criterion chronic concentration < 3.1 µg L <sup>-1</sup>
Eutrophication and nitrogen availability in marine systems	Bioavailable nitrogen	Requirements in keeping with EPA state-specific water quality guidance
Loss of sensitive marine ecosystems and organisms	Biodiversity	Loss thresholds to be set within the context of target species, organisms, and ecosystem services
	Community composition	
	Fisheries health	

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109 **Supplementary Table 2.** Suggested monitoring thresholds to assess the metrics of environmental risk identified for enhanced rock weathering.

<b>Impact</b>	<b>Metric</b>	<b>Suggested sampling needed for quantification</b>	<b>Suggested laboratory/analytical procedures</b>
Accumulation of Trace Elements in Soils and Biomass	Chromium VI concentration	Soil/biomass product tests starting prior to treatment and thence annually, at harvest time	Bulk digests of soil or biomass followed by measurement of bioavailable heavy metal concentrations based on exchangeable pool leaching, e.g., using NH <sub>4</sub> -Ac, ICP-MS
	Nickel concentration		
	Zinc concentration		
	Copper concentration		
Magnesium excess in soils	Ratio of magnesium to total magnesium and calcium	Soil pore waters or effluent water	Measurement of aqueous concentrations, e.g. by ICP-MS
	Exchangeable magnesium concentration	Exchangeable magnesium concentrations	Soil extracts with NH <sub>4</sub> <sup>-Ac</sup> or NaHCO <sub>3</sub> and measurement by ICP-MS
Changes to soil hydrology due to carbonate accumulation in soils	Runoff/Ponding	Divide field into sampling units, collecting a sample per area of uniform soil type, management practice, crop growth, yield, and ERW application. At each site, collect two soil sub-samples at least fifteen feet apart. Core collection should be at least 30 cm depth and take place prior to field operations starting prior to treatment and thence annually	Ponding/Infiltration Test, Hydraulic Conductivity
	Salinity	Divide field into sampling units, collecting a sample per area of uniform soil type, management practice, crop growth, yield, and ERW application. At each site, collect two soil sub-samples at least fifteen feet apart. Core collection should be at least 30 cm depth and take place prior to field operations starting prior to treatment and thence annually	Electrical conductivity
	Porosity	Bulk density from soil cores starting prior to treatment and thence every few years accounting for any spatial heterogeneity	Calculated from in-situ soil bulk density measurements and soil particle density measure or estimate
Application increases pH excessively	Nutrient availability	Divide field into sampling units, collecting a sample per area of uniform soil type, management practice, crop growth, yield, and ERW application. At each site, collect two soil sub-samples at least fifteen feet apart. Core collection should be at least 30 cm depth and take place prior to field operations starting prior to treatment and thence annually	Filtration and inductively coupled plasma emission spectrometer
	pH	Check soil pH every 2 - 3 years, ideally sampling should take place in the fall starting prior to treatment and thence annually	Soil to water pH test in lab or with meter
	Soil microbial activity	Divide field into sampling units, collecting a sample per area of uniform soil type, management practice, crop growth, yield, and ERW application. At each site, collect two soil sub-samples at least fifteen feet apart. Core collection should be at least 30 cm depth and take place prior to field operations starting prior to treatment and thence annually	Soil Respiration Test using Draeger tubes or Solvita soil life kit

Other contaminants to soils	Radiation	In potentially contaminated soils, 2-3 soil cores collected from the ground surface to the point of no contamination or water table, whichever is shallower, starting prior to treatment and thence annually	Gamma scintillation detector Radionuclide-specific analyses (e.g., liquid scintillation, gamma spectrometry, and alpha spectrometry)
	Asbestos	Sampling of each feedstock prior to treatment sufficient to account for variability within the mineral source.	X-ray diffraction analysis, phase contrast microscopy, transmission electron microscopy, and/or other microscopy methods capable of OSHA's asbestos standard found in 29 CFR 1910.1001, Appendix A
Health impacts from mineral dust inhalation	Pneumoconiosis	Participatory health surveillance for workers in high exposure occupations starting prior to treatment and thence annually	Chest radiography assessment in accordance with the International Labour Office International Classification of Radiographs of Pneumoconioses
	PM 2.5	24 hour concentration during and following each application	Extract a sample of gas at constant flow rate through an in-stack sizing device. The particle-sizing device separates particles with nominal aerodynamic diameters
	PM 10	24 hour concentration during and following each application	Extract a sample of gas at constant flow rate through an in-stack sizing device. The particle-sizing device separates particles with nominal aerodynamic diameters
Impact to sensitive ecosystems and organisms	Plant biodiversity and community composition changes	Conduct surveys targeting high-risk systems starting prior to treatment and thence annually	Transect and quadrant surveys for presence, abundance, and biomass
	Invertebrate biodiversity, aboveground	Conduct surveys targeting high-risk systems starting prior to treatment and thence annually	Trapping, direct searches, and leaf-litter extraction as appropriate
	Invertebrate biodiversity, belowground	Conduct surveys targeting high-risk systems starting prior to treatment and thence annually	Soil invertebrate extraction, earthworm field surveys
	Soil microbial biodiversity	Conduct surveys targeting high-risk systems starting prior to treatment and thence annually	Phospholipid fatty acid extractions or quantitative PCR to determine fungal and bacterial loads
Physical damage to plants	Yield	Annual yield over area planted, measured at the time of harvest starting prior to treatment and thence annually	Standardized weight of commercial product
	Physical abrasion	Annual transects at time of peak biomass extending to 7–100 m in downwind direction from deployment site. Longer	Visual burial or damage to seedlings and low-stature plants, shifts in community composition toward taller or woodier species

transects recommended for drier/windier sites without windbreak

Alkalization of Freshwater Systems	pH	Sampling continuous or at intervals suitable to capture high and low discharge events. Sampling sites must be sufficient to capture inflow points from ERW sites and downstream effects.	Test in field or in lab using electrode probe or colorimetric
Increase in freshwater turbidity	Turbidity	Sampling continuous or at intervals suitable to capture high and low discharge events. Sampling sites must be sufficient to capture inflow points from ERW sites and downstream effects.	Visual assessment by secchi disk or transparent tube, or instrument assessment by nephelometer or spectrophotometer.
Freshwater bioavailability of trace metals	<u>Chromium VI concentration</u> <u>Nickel concentration</u> <u>Zinc concentration</u>	Sampling continuous or at intervals suitable to capture high and low discharge events. Sampling sites must be sufficient to capture inflow points from ERW sites and downstream effects.	Mass spectrometry
Loss of sensitive freshwater ecosystems and organisms	<u>Biodiversity</u> <u>Community composition</u> Fisheries health	Sampling within at least three reaches representative of the biological and habitat variability of the waterbody.	Biological sampling of benthic algae, invertebrate, and fish. Habitat assessment for key species and communities.
Photosynthetic eutrophication of freshwater ecosystems	Dissolved oxygen concentration	Sampling continuous or at intervals suitable to capture high and low discharge events. Sampling sites must be sufficient to capture inflow points from ERW sites and downstream effects.	Electroanalytical or optical probe, colorimetric or trimetric chemical analysis
Alkalization of marine systems	pH <u>Aragonite saturation</u>	Grab samples from near surface waters in coastal waters at intervals representative of seasonal flow	Test in field or in lab using electrode probe or chemical analysis Calculated from measured dissolved inorganic carbon and total alkalinity
Marine bioavailability of trace metals	<u>Chromium VI concentration</u> <u>Nickel concentration</u> <u>Zinc concentration</u> Copper concentration	Grab samples from near surface waters in coastal waters at intervals representative of seasonal flow	Mass spectrometry
Eutrophication of marine systems	Bioavailable nitrogen	Grab samples from near surface waters in coastal waters at intervals representative of seasonal flow	Bioassay
Loss of sensitive marine ecosystems and organisms	<u>Biodiversity</u> <u>Community composition</u> Fisheries health	Fisheries management sampling annually	Vessel-based, dockside, and logbook monitoring

110 **Supplementary Table 3.** Suggested monitoring guidance for sampling procedure and techniques, to assess the metrics of environmental risk identified for  
 111 enhanced rock weathering.

<b>Impact</b>	<b>Metric</b>	<b>Citations</b>
Accumulation of Trace Elements in Soils and Biomass	Chromium VI concentration	1,2
	Nickel concentration	1–3
	Zinc concentration	1,2
	Copper concentration	1,2
Magnesium excess in soils	Ratio of magnesium to total magnesium and calcium	4
	Exchangeable magnesium concentration	5
Changes to soil hydrology due to carbonate accumulation in soils	Ponding	6
	Salinity	7
	Porosity	8–10
Application increases pH excessively	Nutrient availability	11
	pH	10,12
	Soil microbial activity	13
Other contaminants to soils	Radiation	14
	Asbestos	15
Health impacts from mineral dust inhalation	Pneumoconiosis	16
	PM 2.5	17,18
	PM 10	17,18
Impact to sensitive ecosystems and organisms	Plant biodiversity and community composition changes	19–21
	Invertebrate biodiversity, aboveground	
	Invertebrate biodiversity, belowground	
	Soil microbial biodiversity	
Physical damage to plants	Yield	12
	Physical abrasion	
Alkalization of Freshwater Systems	pH	22,23
Increase in freshwater turbidity	Turbidity	24
Freshwater bioavailability of trace metals	Chromium VI concentration	22,23
	Nickel concentration	
	Zinc concentration	
Loss of sensitive freshwater ecosystems and organisms	Biodiversity	25
	Community composition	
	Fisheries health	
Photosynthetically driven eutrophication of freshwater ecosystems	Dissolved oxygen concentration	22,23
Alkalization of marine systems	pH	22,23
	Aragonite saturation	26
Marine bioavailability of trace metals	Chromium VI concentration	26,27
	Nickel concentration	
	Zinc concentration	
	Copper concentration	
Eutrophication of marine systems	Bioavailable nitrogen	26
Loss of sensitive marine ecosystems and organisms	Biodiversity	28
	Community composition	
	Fisheries health	

112 **Supplementary Table 4.** References for provided impact and metric monitoring and mitigation context

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