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Expert elicitation on agricultural enhanced weathering reveals carbon dioxide removal potential and uncertainties in loss pathways

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Enhanced weathering in agriculture is a potential gigatonne-scale carbon dioxide removal (CDR) pathway, but its potential remains difficult to constrain. We used a formal expert elicitation process to estimate CDR potential and efficiency, uncertainties, and key data needs for six feedstocks. Expert opinion of global potential varied by feedstock, with estimates averaging 0.2-0.7 Gt CO2e/yr, but with a wide range (from a source to greater than 5 Gt CO2e/yr removal). When focusing on the American Midwest (pH 5.5-6), carbon dioxide removal efficiency, meaning the fraction of potential ultimately realized, ranged from 27-39%. Key uncertainties included feedstock availability, calcite saturation, and deep soil/freshwater emission pathways. There is a need for empirical data in key stages, with potential to leverage liming data where appropriate. Overall, there appears to be strong potential CDR at broad scales. However, continued research is necessary to build confidence when quantifying that potential and actual removals.

Slowing the pace of global climate change will require a combination of rapid emissions reductions and carbon dioxide (CO_2) removal (CDR) to limit future warming and reduce greenhouse gas (GHG) concentrations already in the atmosphere[1]. However, few CDR technologies can achieve durable carbon (C) sequestration (i.e., >100 years) at a sufficient scale and pace needed to meet projected CDR demands[2,3]. Enhanced weathering (EW) has the potential to be a broadly applicable CDR technology with long-term, durable storage. The EW approach focuses on accelerating the natural process of rock weathering, which is known to be an important control on long-term (ca million-year) atmospheric CO_2 levels. However, the ability to accelerate weathering rates at large scales remains an outstanding question, one that requires consideration of feedstock availability and energy inputs[4], land system response[5], efficiency of CDR across the land-to-sea continuum[6], and the potential for adverse environmental impacts[7].

Enhanced weathering exposes rock feedstock (finely ground cation-rich material) to environments conducive to rapid weathering processes, often agricultural soils[8–11]. In soil, the finely ground materials undergo chemical dissolution reactions, converting CO_2 in the soil into bicarbonate ions and releasing base cations, such as Ca^{2+} and Mg^{2+}. The bicarbonate may be precipitated as carbonates in situ or transported to the ocean for long-term storage (e.g., as alkalinity, or incorporated into shells as calcium carbonate).

While the process of EW is well established[12–16], it remains unclear the extent to which large-scale deployment could contribute meaningfully to the magnitude of additional carbon removal necessary to achieve climate targets under the Paris Agreement (e.g., well below 2°C warming). Uncertainties around weathering rates, feedstock supply, chemical processes post-weathering (such as carbonate precipitation) are large, as are questions about the potential scale of adoption and transport. Estimates of global weathering rates are typically divided between silicate weathering and carbonate weathering, with silicate weathering constrained to transfer between 0.33 and 0.51 Gt CO_2/yr from the atmosphere to the oceans, compared to carbonate weathering rates of 0.48–1.39 Gt CO_2/yr (16). The potential for EW is estimated to be significantly higher than natural rates, 0.5 to >4 Gt $CO_2e\ y^{-1}$ (using silicate rates[4,11,17–19]). Early incorporation of EW into

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integrated assessment models has assumed that enhanced weathering could contribute to removals of around 2–4 Gt CO2/yr by 2050[18,20–22]. Projections for 2100 span a much wider range with an average estimate of approximately 6 Gt CO_2e/yr due to variation across scenarios and underlying assumptions[21,23]. Thus far, however, these estimates are largely derived from models rather than empirical data, often assume maximum adoption and deployment, and do not always consider geochemical limits of EW. Weathering, especially with the aim of long-term CDR, is a complex process that requires a full system perspective to evaluate.

Many materials are under consideration for EW. Agricultural lime (aglime) is typically dominated by calcium carbonate, though other materials like dolomite are commonly used. Limestone addition to soils has been used for millennia to adjust pH in acidic soils. Interest in the C uptake potential of silicates like olivine, basalt, and wollastonite has recently increased[24,25]. Recycled materials, especially steel slag and cement waste[26], are also being explored for this purpose. Each material has unique properties that feed into its overall CDR potential. In particular, feedstocks differ in terms of their CO_2 capture efficiency, potential to form secondary minerals (e.g., secondary clay formation vs. carbonates), biological reactions, and side effects such as metal accumulation in vegetation, soils, or waterways[27].

Multiple factors determine the real-world potential of EW. Feedstock availability is a critical question: to reach the gigatonne CDR scale, the quarrying and mining of EW feedstocks at a similar scale as the production of crushed stone (1.6 Gt), sand and gravel (1 Gt), and construction aggregate (2.5 Gt) in the United States[28] would be needed. The rate, completeness, and mode (e.g., carbonic acid vs. nitric acid weathering) of the feedstock weathering reaction are major drivers of overall efficiency[29–31]. Once the material weathers, there are multiple downstream loss processes that can reduce the efficacy of EW carbon removal potential. Foremost, precipitation of secondary minerals can reduce CDR efficiency by consuming base cations, resulting in the conversion of bicarbonate back to CO_2[32–34]. Carbon losses during river transport may also impact the net CDR potential of EW. Secondary carbonate formation in rivers, triggered by increased carbonate saturation states, could reduce efficiency[35]. Uncertainty in the magnitude of these loss pathways is still high. River transport may not significantly limit EW's CDR potential in most rivers in the US[36,37], though these estimates are chemistry-focused and do not always include the full suite of potentially relevant processes (e.g., biological carbon uptake[38]). There are limited estimates of the fate of weathering products in nearshore environments and the oceans[39,40], but agreement that there will be CO_2 evasion linked to the equilibration of the carbonic acid system. Overall, for EW to be a reliable means for quantifiable CDR, the entire system efficiency needs to be reliably evaluated.

In addition, potential interactions with the soil organic carbon (SOC) reservoir have not been well documented for many of the potential feedstocks. Enhanced weathering in any one site may reduce or enhance the land organic C sink, and these effects are site, feedstock, and time dependent[41,42]. Biological system interactions with the EW process are also highly variable, both positively and negatively[43–45]. The balance of these tradeoffs will determine both EW's viability as a CDR pathway and its sustainability if scaled.

Although substantial uncertainty of system-level CDR efficacy remains, commercial projects spreading cation-rich rocks in agricultural have begun being funded via the voluntary carbon market (carbon crediting). Further, liming is a critical part of industrial agricultural and is incorporated into the national determined contribution of several countries. Having confidence in the value of EW-based GHG offsets requires a critical evaluation of the robustness of EW as a real climate solution. Claims that fail to deliver on their system-level CDR promise—for example, if a large fraction of initially fixed C were lost during aquatic transport stages—will result in unintended and untracked emissions to the atmosphere.

The agronomic benefits of EW increase its scalability, further driving interest. As the weathering reaction progresses in frequently acidified agricultural soils, an EW-induced increase in soil pH can raise nutrient availability (at least up a pH of ~7)[46], improve crop yields[27,47], reduce soil N_2O production[48], and improves air quality[40]. Aglime is already added at rates above tens of millions of tons per year for agronomic benefits in the United States[49]. Potential challenges also exist, however, when exploring other feedstocks. For example, there are concerns that some EW feedstocks contain heavy metal elements (e.g., nickel, cadmium), which can accumulate in soils and impact crop health and food safety[7,50].

Given poorly constrained uncertainties about multiple aspects of the EW process, we pursued a formal expert elicitation[51] to identify the magnitude of potential CDR via EW in agriculture globally, and to highlight the most critical research gaps surrounding CDR efficiency along the soil to ocean continuum for a well-studied and intensively farmed region, the American Midwest. Expert elicitations are intended to incorporate both the full spectrum of available data, as well as expert opinion on that data. The process addressed multiple questions that are key to the scalability and climate value of EW in agriculture, including:

(1) What is the potential global climate impact of EW via inorganic C removal, considering supply chain emissions, feedstock type and availability, and emissions of other GHGs?
(2) What is the efficiency of C capture at the field scale, and of transport from the field to long-term ocean storage, both in total and by process stage (Fig. 1)? This question focuses on the American Midwest specifically, as a context is needed to explore efficiency considerations.
(3) What level of uncertainty is expected in quantifying capture and transport efficiency? How do the sources and magnitudes of error influence whether models or empirical data (or a mix) are most appropriate for monitoring?
(4) Are there substantial health or environmental impact concerns if EW is scaled, and for which feedstocks?

Because the responses are feedstock dependent, these questions were addressed independently for each of six feedstocks: lime, basalt, olivine-rich rock, wollastonite-rich rock, steel slag, and concrete waste.

Results

Overall, estimates from the experts based on available literature on the potential global annual CDR rate estimates via agricultural EW—which encompass constraints on feedstock production, land availability, as well as non-target GHG emissions associated with rock grinding, changes in soil biogeochemistry, and other factors—varied by feedstock. Throughout, note that positive values will refer to a CO_2 sink (e.g., removal from the atmosphere) and negative values to emissions into the atmosphere. Individual estimates of the most likely amount of CDR ranged substantially, from a net source of -0.1 Gt CO_2e yr^{-1} to a net sink of $+4.0$ Gt CO_2e yr^{-1} (Fig. 2a, circles). Estimates of the minimum possible amount of CDR ranged from a source of -2.0 Gt CO_2e yr^{-1} (the lowest option provided in the survey) to a sink of 1.0 Gt CO_2e yr^{-1}, while estimates for the maximum possible amount of CDR ranged from 0 Gt CO_2e yr^{-1} to >5.0 Gt CO_2e yr^{-1} (For individual responses, see full dataset). Note these estimates include lifecycle emissions including N_2O and other GHG impacts.

Mean and median values (presented as "mean/median" below) for group estimates of the maximum and most likely amount of CDR were greatest for basalt and smallest for wollastonite. For basalt, the maximum possible CDR was 2.1 (mean)/2.0 (median) Gt CO_2e yr^{-1}, while the most likely amount of CDR was 0.7/0.4 Gt CO_2e yr^{-1}. For wollastonite, the maximum possible CDR was 0.9/0.1 Gt CO_2e yr^{-1}, while the most likely amount of CDR was 0.2/0.01 Gt CO_2e yr^{-1}. Means and medians for aglime were close to basalt for the maximum and most likely amount of CDR, while those for the other feedstocks, the mean and median estimate for the minimum amount of CDR intersected zero (i.e., no C removal). Note that the estimates for aglime were inclusive of current application rates, not additional to current applications. Confidence, meaning the likelihood that the true value was within the estimated ranges, was generally low. It was, across the group, lowest for concrete waste (66%/60%) and highest for basalt (74%/75%), corresponding to roughly 2:1 to 3:1 odds that the real value is within the estimated ranges. We found little relationship between the

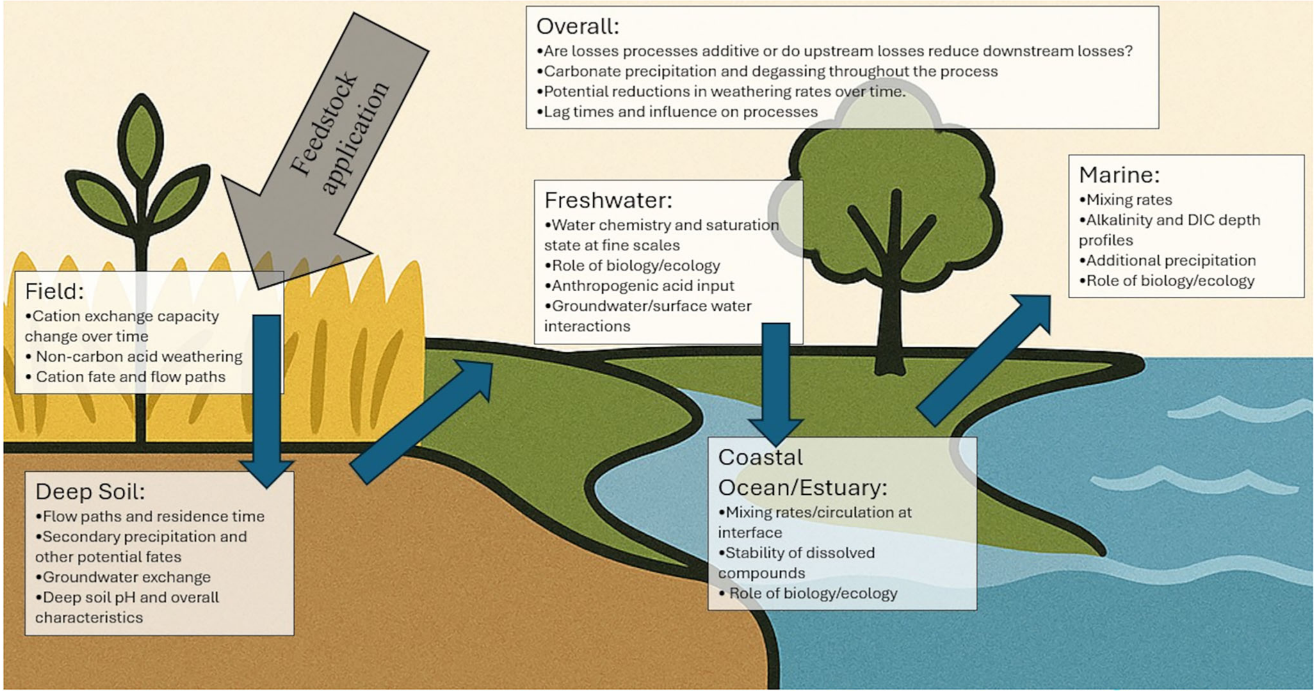

Fig. 1 | Conceptual flow of carbon fixed via enhanced rock weathering. Inset boxes show key processes at each stage highlighted by the review as ways to reduce uncertainty in estimates of CDR efficiency. All responses for uncertainties are in the complete response dataset (see "Data availability" for link).

magnitude of the estimate for the most likely amount of CDR and confidence in the overall range (Supplementary Fig. 1). For individual ranges with confidence, see Fig. 2. For individual feedstock global estimates, see Supplementary Table S1.

Efficiency (transfer potential)

The fraction of a hypothetical 10 tons ha^{-1} of fixed carbon moving from the field to the ocean over 20 years (and with 100 year minimum retention time in the ocean) was broadly similar among feedstocks—approximately 1/3—but with high variability in individual estimates (Fig. 2b). On average, estimates for the most likely amount of C removed as durable CDR given a theoretical potential of 10 tons C fixed ha^{-1} ranged from 2.7 ton ha^{-1} for lime (e.g., 27%) to 3.9 ton ha^{-1} for wollastonite (e.g., 39%). Low range estimates were around 1 ton ha^{-1} (lowest for lime with 0.6 tons ha^{-1}, or a 6% efficiency); high range estimates spanned from 5.6 ton ha^{-1} (lime) to 7 ton ha^{-1} for wollastonite. Some individual responses were lower and higher, reflecting disagreement across respondents. Confidence in those ranges was approximately 70%, regardless of feedstock (approximately 2:1 odds that the true value is actually within those ranges). For responses on all feedstocks, including confidence estimates, see Supplementary Table S2.

At the stage level, efficiency estimates were lowest (i.e., most fixed C lost) in earlier stages and highest in latter stages, regardless of feedstock (Fig. 3 and Table 1). The field stage had the widest range of estimates, spanning 60% for aglime. The 5th–95th estimates of C fixed and moving through the field averaged (across all feedstocks) from 21–76%, with a mean of 46%. For the distribution in individual estimates across feedstocks, see Supplementary Table S3.

Other

Measurement error associated with CDR was consistently estimated as approximately 100% regardless of feedstock or stage (meaning that the uncertainty equals the magnitude of potential carbon removal). This response encompassed both empirical and current modeling uncertainties, though the deep soil and coastal ocean stages were frequently estimated to have >100% error in measurement. This pattern was independent of feedstock (Supplementary Fig. 2).

The potential for substantial health or environmental damage if deployed at scale varied substantially by feedstock, though generally declined when moving downstream from the field. Aglime had the lowest estimated potential for damage regardless of stage in part because it is already extensively deployed (though experts expressed slightly higher concerns for freshwater systems, specifically). In contrast, steel slag and olivine had higher values across the stages, with the highest concerns for both at the field scale (Fig. 4). Experts noted that there was little research on long-term health/toxicity implications of large-scale ERW deployment downstream of fields, though generally did not identify any mechanisms by which this would occur in one feedstock over another.

Experts were split on the level of empirical monitoring or modeling needed for monitoring, measurement, reporting, and validation for the voluntary carbon market. At the field scale, nearly half suggested that modeling would be sufficient, though another third thought empirical measurements should be required. Overall, the trend was a preference for more empirical measures at the field and soil stage, moving towards a greater modeling emphasis at later stages.

To better constrain the global CDR potential of EW, experts cited the need for a better understanding of soil organic carbon and microbial responses in various geographic settings, more information about feedstock availability, and additional focus on poorly studied loss pathways beyond field application: secondary clay formation, carbonate precipitation rates, biological pathways, and downstream degassing were identified as unknowns that would tighten uncertainty bands if they could be resolved. For all qualitative responses on datasets to resolve uncertainties, see the individual responses.

Discussion

The expert elicitation estimated that the global potential for CDR from agricultural EW ranged from 0.2 to 0.7 Gt (median 0.01–0.4) CO$_2$e yr^{-1}, depending on feedstock and inclusive of upstream (e.g., supply chain) emissions. Basalt and lime had the highest average estimated potential globally. However, experts also identified the potential for lime, basalt, and olivine to be a source of C emissions, depending on lifecycle

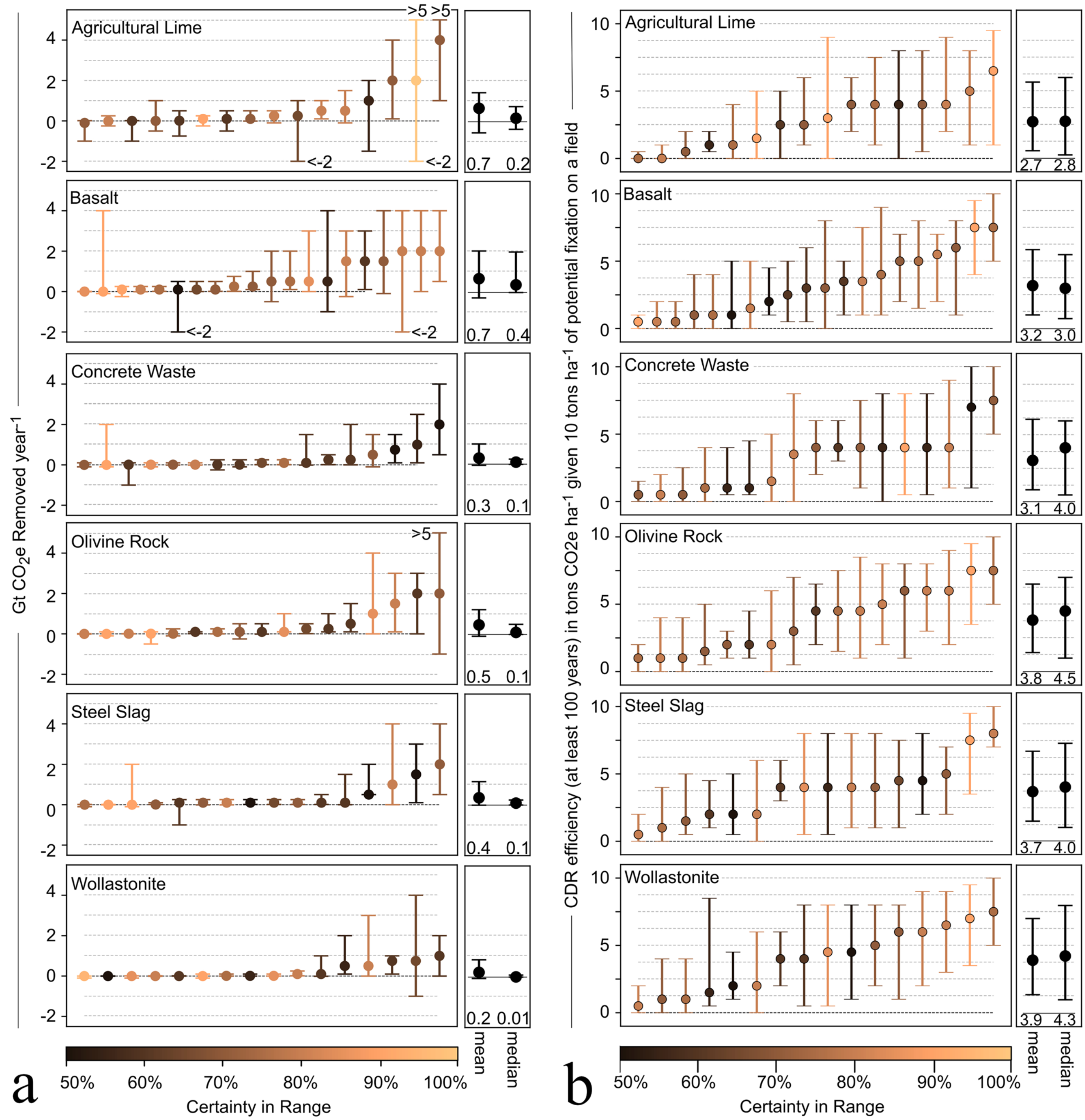

Fig. 2 | Estimates and certainty in estimated ranges for total CDR potential. **a** Total global CDR potential by feedstock, including upstream/production emissions, impact on N_2O and other greenhouse gases, supply limitations, and other system-level factors. Estimates are for maximum deployment of each feedstock independently (e.g., individual estimates should not be added together). Circles are the estimated most likely amount of system-wide, annual CO_2 removal given widespread adoption, bars mark 5th percentile and 95th percentile plausible estimate. **b** Estimates of total CDR efficiency of the process starting from field application and ending with long-term storage, assuming enough material is applied to potentially fix 10 tons of carbon ha^{-1}, with a maximum 20-year residence time within each stage with the exception of the marine stage, where the time was defined as lasting at least 100 years. Estimates in **b** excluded potential organic C cycle feedbacks (i.e., losses or gains of SOC). Circles and bars same as in (**a**). In both **a** and **b**, the darker the shading, the lower the confidence that the defined range contains the true probability.

emissions and CDR efficacy. We note this is an expert judgment; there was marked uncertainty and substantial variation in estimates (Fig. 2). In general, however, the preponderance of experts indicated a net positive CDR potential for all feedstocks over the particularly well-described region of the American Midwest. This result aligns with the estimates of overall transport efficiency from field to long-term storage, which averaged from ~27–39%.

Global CDR potential estimates were generally lower than the prevailing literature estimates (e.g., 0.5–3.6 Gt yr^{-1})[11,17,52,53]. The lower estimates in this study may reflect recent field studies that demonstrate strong constraints on the export of weathering products from soils, as well as potential downstream (post-field) loss processes not yet incorporated (or simplified) into transport models[36,38,54]. Lower estimates were, in some cases, guided by the low efficiencies implied by the global rate of natural CO_2 consumption

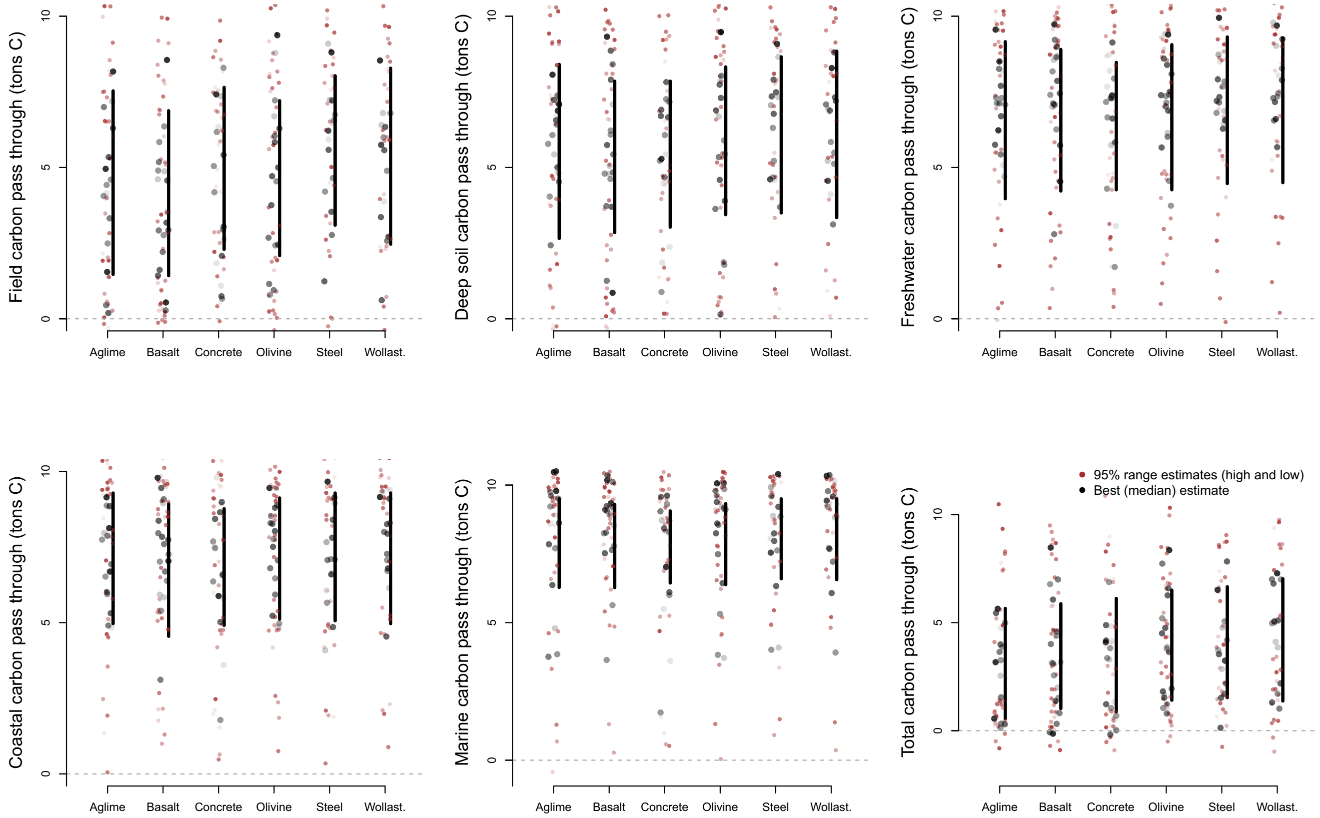

Fig. 3 | Efficiency estimates for the transfer of a fixed amount of C. Units in tons of C, assuming 10 tons added to each stage (see text). Red dots show upper and lower range estimates, and black dots show best estimates. Bars show the mean of the high to the mean of the low-end estimates. Overall efficiency was estimated separately from the individual stages. Points jittered and partially transparent for clarity. See methods for the definition of stages. For numerical results overall, see Supplementary Table S2; for individual stages, see Supplementary Table S3.

by silicate weathering (~0.5 CO_2e yr^{-1})[13] and by the fraction of total silicate weathering associated with weathering of basaltic rocks on Earth today (0.04 to 0.07 Gt CO_2/yr)[55,56].

Feedstock supply constraints, which were considered for the global estimates (Fig. 2a), are also not always incorporated in global modeling studies. The supplies of lime, basalt, and olivine are effectively unlimited (even if production would need to increase)[57,58]. Concrete waste is substantial, and towards 600 million tons in the US alone (however, estimates include all construction waste, so the true number is likely lower)[59]. Steel slag is more constrained[60], estimated at an annual production of 120 Mt in China, and industry estimates more than 400 Mt per year globally[61]. In contrast, current production of wollastonite is approximately 1 Mt per year, though unsurveyed reserves potentially exploited in the future may exceed 100 Mt[28]. Upstream, supply-chain emissions were considered in the global potential estimate. Emissions from rock sourcing, grinding, transport, calcination (if applicable), and other upstream processes can impact net climate benefit[4] and, if those emissions are high and the CDR efficiency is low, potentially make the system net climate negative if not well managed. However, we note the impact of those factors varies between locations (with transportation of feedstock often the highest proportion of upstream emissions[62]) and must be analyzed on a regional scale.

Once applied, the CDR potential of EW is influenced by the weathering rate and subsequent efficiency of carbon transport at each stage from the field to the ocean. In the Midwestern U.S. context provided, the largest estimated post-weathering losses (lowest efficiency) were expected in the earlier stages of the process, for example, by non-carbonic acid weathering during feedstock dissolution, secondary mineral formation, or retarded movement of weathering products through the deeper soils. Estimates of efficiency rose as the inorganic carbon moved into freshwater, coastal ocean, and marine systems. Unsurprisingly, efficiency estimates by feedstock also converged, reflecting the general bicarbonate identity of the fixed carbon (though some noted that cations from feedstocks would also be transported and potentially have secondary effects, thereby altering their estimates). We note that these specific efficiency estimates may not be as applicable beyond the Midwest context used here, given regional differences in soil texture, water residence time, pH, and other salient factors.

Overall estimated transfer efficiency was >0. This implies that the fundamental EW process itself is an effective CDR strategy (if upstream emissions are balanced against the CDR gains). As upstream emissions are more straightforward to estimate, reducing uncertainty in the CDR process becomes key to correctly estimating the net value of EW as a CDR opportunity. Core uncertainties included soil characteristics at both the field surface and in the deep soils, particularly around flow paths and cation fates, biology and water chemistry in freshwater and near coastal/estuarine systems, and unknowns in the ocean, such as alkalinity and DIC profiles with depth (Fig. 1, see also full data set). The experts recognized these uncertainties, though their relative weighting of importance (e.g., how likely these factors are to lower CDR potential or transfer efficiency to a low value) differed greatly (Figs. 2 and 3).

The context for the efficiency estimation is not a specific location—it was designed to be representative of intermediate risk for carbon loss in a region with extensive agriculture. Within the American Midwest focusing on soils with different chemistries—lower cation exchange capacities and lower high levels of residual acidity—would decrease the potential for secondary mineral phase formation. Focusing on fields that shunt soil waters into surface waters (e.g., fields with tile drainage) is also likely to decrease

Table 1 | Efficiency estimates for the transfer of a fixed amount of C

Feedstock	Field	Deep soils	Freshwater	Coastal ocean	Marine	Overall
AgLime	41% (15–75)	59% (27–84)	71% (40–92)	72% (50–93)	80% (63–95)	27% (6–57)
Basalt	39% (14–69)	55% (29–79)	70% (42–89)	69% (46–89)	79% (63–93)	32% (10–59)
Concrete	43% (23–77)	55% (30–79)	68% (43–86)	70% (49–88)	78% (64–91)	31% (9–61)
Olivine	47% (21–72)	57% (34–83)	72% (43–91)	74% (51–91)	82% (64–93)	38% (14–65)
Steel slag	53% (31–80)	63% (35–87)	75% (45–93)	74% (51–93)	82% (66–95)	36% (15–67)
Wollastonite	53% (25–83)	62% (33–88)	76% (45–93)	73% (50–93)	82% (66–95)	39% (14–70)

Overall efficiency was estimated separately from the individual stages. Numerical values are the mean of the best estimates for all responses (parentheses: mean of the 5th and 95th percentile). See methods for the definition of stages. For individual responses, see Fig. S3, for confidence in individual stages, see Supplementary Table S2.

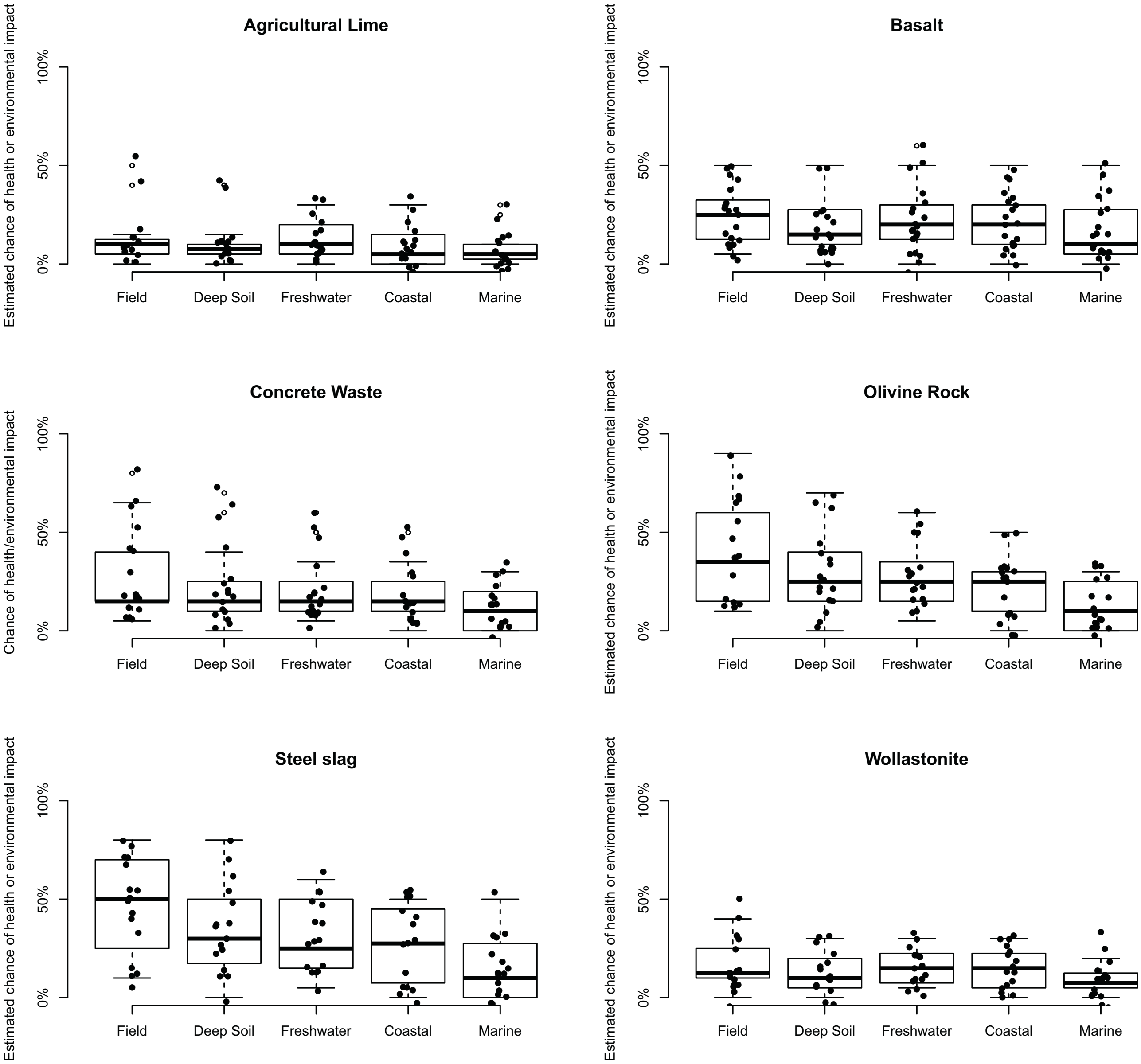

Fig. 4 | Estimated probability of substantial health or environmental impacts. Considers the case where a feedstock is applied at commercially and climatically relevant amounts and scales. Each feedstock was considered independently.

secondary mineral formation. Moving to a global context, most temperate soils are going to have a higher risk of inefficiencies from secondary mineral formation within the soil column than depleted tropical and sub-tropical soils. Although weathering rates of added EW feedstock in tropical soils are likely to be higher[63], the saturation states of common secondary mineral products in soil waters are likely to be lower in tropical soils, which commonly have low background dissolved cation concentrations. This is in strong contrast to arid and semiarid settings, where secondary mineral formation is ubiquitous and shapes basic aspects of the soil properties. The highlighted potential for high EW inefficiencies even in an intermediate risk, Midwestern soil, indicates the need to better chart where weathering products can be effectively transferred to deep groundwaters or the oceans for durable long-term storage if the goal of EW is cost-effective, robust carbon removals (instead of being predominantly for agronomic benefits).

One challenge for resolving these uncertainties is the process measurement itself. Estimates of measurement error clustered around 100%, meaning the magnitude of the measurement error was anticipated to be approximately equivalent to the magnitude of the CDR. This reflects the challenge of measuring weathering processes directly; many respondents indicate the need for either improved and well-validated models or further empirical study, especially in-field trials that encompass deep soils. Validation of models, especially for processes occurring in deep soils and the aquatic system, was considered to be relatively poor. As a result, balancing CDR gains in the weathering process against emissions associated with the system process is a challenge for programs that incentivize CDR with carbon credits, for example, as the effect of an individual effort is difficult to anticipate or assess. Spatial aggregation may partially alleviate this challenge, as has been shown in soil organic carbon quantification, where estimates are also highly variable[64]. There is an obvious need to develop frameworks that incorporate how uncertainty can change with project size.

Human and ecosystem health concerns were elevated for olivine, steel slag, and concrete waste at the field stage. This corresponds to known concerns about heavy metal accumulation on fields from olivine, and potential concerns related to the relatively little-studied steel and recycled concrete feedstocks. For highly variable feedstocks (e.g., recycled materials), compositional differences may not only impact CDR efficacy but also health risks and should be well quantified. In all cases, health concerns declined with stage progression. We did not evaluate the health risks of mining, processing, or transporting the material, which was considered out of scope. Wollastonite, in particular, has received attention for potential lung damage due to commonly being found in a small, needle-like form and contaminated with asbestos. However, studies are mixed and may depend on other factors; no significant relationship was found between wollastonite mining and lung damage when controlling for smoking[65]. Overall, there is a dearth of literature on any specific health hazards regarding EW material mining or application, which must be considered, especially if the practice is to scale feedstock usage to globally relevant magnitudes.

To build confidence in agricultural EW as a CDR strategy, strategic research to target the largest magnitude uncertainties is needed[66]. We identified a wide range of reported metrics that would improve confidence in global potential and efficiency estimates (Fig. 1, full dataset). In particular, the pH dynamics of deep soils, the potential for pedogenic carbonate formation and secondary material formation, unknown flowpaths, biological feedbacks and interactions, and the possibility of non-carbonic acid weathering were noted as sources of uncertainty. One of the core challenges expressed was the lack of empirically based studies that synthesized the entire system. One exception, though solely for aglime, is the Mississippi River basin. Studies have estimated an approximately 40% increase in alkalinity export from the Mississippi River, partially attributed to cropland application of limestone since the 1940's[67]. Air-sea CO_2 exchange as the river enters the Gulf of Mexico, studies have also been conducted, though not in the EW context, with net exchange depending on season, salinity, nitrogen export, and other factors, ranging from neutral/small source to substantial sink[68]. This could suggest that a large fraction of the CDR potential of limestone applied to the US has been realized over the past roughly 90 years[49,67]. Some large river systems are characterized by calcite supersaturation[69]. There is debate on the extent to which supersaturation may drive burial or export of calcium carbonate that would lead to a substantial inefficiency in the EW process[37]. A focus on catchment-scale studies of historically limed or silicate amended watersheds[70] provides one approach for investigating the efficiency of alkalinity and cation transit through a watershed. More work in a range of agricultural settings is an immediate opportunity that could help resolve some of the uncertainties in carbon leakage estimates. However, this work suggests that many researchers in the enhanced weathering community see a potential for high to moderate carbon leakage during the EW process in many typical agricultural soils.

Timing is another major research need, as it impacts both the timeline of climatic benefits and the strength of the signal in measurement at any given point in time. Cation sorption and the slow movement of cations from limestone applications through the soil are basic concepts in soil science and agronomy, but the timing of this process in a CDR context is poorly constrained. Many recent soil mesocosm studies suggest the majority of cations released by silicate weathering are retained in the soil column[71]. In the aquatic stages, experts had concerns about the lack of knowledge regarding calcite formation (and redissolution), biological feedbacks, and fine-grained information on water chemistry. The marine system was considered to have the highest estimated pass-through efficiency, meaning from inflow to ultimate long-term storage. Deep ocean characteristics, especially alkalinity and dissolved inorganic carbon (DIC) profiles, were cited as information that would improve those estimates. We do note that we had relatively fewer marine experts than terrestrial experts, which could lead to some of the reported uncertainties. This reflects a relatively lower amount of research in the literature relevant to ERW processes beyond the farm field. However, the same basic concepts controlling marine EW carbon leakage have been discussed extensively recently in the ocean alkalinity enhancement literature, and ongoing research will inform both pathways.

Carbon markets are actively supporting enhanced weathering in agriculture. The results here should not be interpreted as numerical guidance for any particular application protocol or a formal monitoring, reporting, and verification method, as they were not designed for that purpose. Rather, the results should inform the markets in two ways. First, by suggesting caution—they show the wide range of estimates from non-financially conflicted experts. There is substantial uncertainty in overall efficiency and at several key stages (see above). Any downstream losses are critical to understand if EW project developers are claiming CDR, as losses beyond the field are still losses to the atmosphere. Second, by encouraging data collection—the EW market is in a good place to strategically address uncertainties. Targeted data collection alongside commercial deployments could help close existing knowledge gaps; in particular, field and deep soil are within most current project boundaries, though the entire range (field to ocean) is part of the CDR system as a whole. Carbon crediting efforts, if they proceed, should focus on areas that are low risk for substantial carbon leakage while knowledge develops (e.g., regions where formation of secondary mineral products is expected to be low, for example, based on thermodynamic arguments). For now, however, most industry data remains private, and measurements are generally limited to the top ~30 cm of soil, leaving processes occurring in areas such as the deep soil understudied. Leveraging commercial data will be most effective if both sufficient data collection occurs at all stages of carbon dynamics in these systems, and if the data are available for evaluation and analysis.

The net value of EW as a CDR strategy must include all emissions within the system, including from SOC. SOC was incorporated into the broad global estimate of CDR potential reported here. However, SOC losses or gains were not part of the stage-based assessment of efficiency. Weathering influences SOC at broad scales[72], and experimental work suggests that rock applications can reduce SOC accrual rates via pH increases[42,45,73,74]; this also impacts adjacent freshwater systems[75]. However, the effect on net carbon uptake is variable[41,42]. For example, wollastonite additions increased soil pH and dissolved organic carbon concentrations, thereby increasing soil CO_2 efflux by approximately 330% across various land-use types[76], and basalt amendments raised soil pH and microbial activity, enhancing soil enzyme activities and priming[77]. However, SOC stabilization may also be promoted over longer timescales[45]. In contrast to the paucity of data on the role of silicates in mediating SOC storage, there is a much more robust set of observations on the effects of limestone application to agricultural fields. A recent meta-analysis on the effects of agricultural liming[43] suggests that the process has a positive impact on SOC stocks. To the extent that lime acts similarly to less-broadly tested silicates with respect to SOC (e.g., by raising pH and introducing more cations into the upper portion of the soil), it is reasonable to expect similar directionality over broad spatial and temporal scales. Nonetheless, there is a need for at-scale sample-resample studies[64] on SOC dynamics during EW deployments.

Conclusions

The expert elicitation here suggests that EW may be a viable CDR strategy, with best estimates generally positive at both the global scale and the regional efficiency scale. It also highlighted key unknowns, most prominently unconstrained loss processes in deep soils, freshwater systems, and a general lack of data in nearshore and marine endpoints for weathered products. As a result, confidence in the quantification of realized CDR benefits remains a challenge for actual projects. There are systemic uncertainties that still need to be properly characterized, including field-specific impacts on SOC, the role of secondary mineral formation in the deep soil (which would reduce CDR value), and the role of the biological community in freshwater systems, which could reduce CDR value or increase lag time between deployment and realized impact (among others). This issue is compounded by the fact that there is no widely agreed-upon set of rules for quantifying EW-impacts, which would provide consistency across projects for research[78]. We note that decisions made to guide the estimates are not normative decisions about how carbon accounting should be done in CDR. For example, we chose to ignore the production emissions for steel slag and concrete waste from our global estimates as we assumed steel and concrete would be produced regardless of EW activity; for the other feedstocks (e.g. wollastonite) we included estimated emissions, assuming they would primarily be mined for EW. In general, any estimate of the EW scale potential hinges on assumptions such as these about the rules underlying carbon removal quantification.

Ultimately, the value of EW as a CDR strategy rests on its ability to drive lower atmospheric greenhouse gas concentrations and climate warming, inclusive of upstream emissions and all system-level effects. However, the effects of agricultural production also need to be taken into account, given the large greenhouse gas footprint of food production. The results here, while lower than many models or commercial estimates, suggest real potential for EW to CDR. However, given the complexities of attributing change in atmospheric chemistry to any given process, quantification questions and data uncertainties are significant and should be resolved. A system-level perspective and strategic and focused research are necessary to place EW into the broader toolkit of CDR technologies.

Methods

Expert elicitation method

Expert elicitation is a research strategy designed to obtain informed, quantitative, and qualitative judgments and uncertainty ranges from experts, in situations in which there is insufficient data to determine those values directly[49,79,80]. The methodology relies on judgments from experts who are qualified to address the fundamental mechanisms under consideration. It is particularly useful in cases where insufficient data exists for well-constrained modeling estimation, and beyond that, in cases where the variability between expert opinions is also useful as a means to identify critical unknowns or differences across communities (for example, when the relative importance of various physical processes in driving Atlantic circulation responses to climate change[81]). In the case of enhanced weathering, relatively little data exists on CDR efficiency, especially when considering downstream (beyond field) processes to date. It is also useful for eliciting where gaps in knowledge need to be addressed to increase confidence. We followed established protocols, focusing on quantifying best estimates and uncertainty[82]. There is wide evidence in the literature that overconfidence in such judgments is ubiquitous[49]. Accordingly, readers are cautioned that the upper and lower range limits as expressed by the confidence intervals should best be viewed as a minimum range.

Description of process

Experts currently working on soil-based enhanced weathering for carbon dioxide removal were identified. We initially identified 51 potential participants active in ERW science (as identified from active publishing in the literature) across multiple focal areas: Agronomics, soil/field science, freshwater, and marine science. We attempted to ensure a broad list of potential participants equitably spread across expertise, geography, and gender. Of those participants, we screened out any expert with a conflict of interest in ERW, which we defined as any financial tie to a commercial ERW company and invited the remainder. Ultimately, 20 experts gave consent to participate in writing and joined the effort (research suggests that 6–12 experts are sufficient to get stable estimates[82]). All responses were weighted equally. The experts spanned the terrestrial and aquatic domains. Reported expertise is found in the complete dataset (see “Data availability” for link).

The expert elicitation process followed formal protocols[82]. Briefly, participants were given a survey (described below; Supporting Information 1). The survey was piloted with volunteers who were interested but could not participate due to our strict conflict of interest policy. Initial results were summarized, and the group was convened to ensure each question was perceived similarly by each participant (e.g., clarifying confusing language) and to resolve discrepancies. We did not attempt to reach consensus or agreement on the estimated values or other responses. After the meeting, the survey was modified for clarity and reissued. The second round of survey responses, which could have matched or differed from initial survey responses, comprised the dataset analyzed here. Initial results were discarded.

Four respondents were not present for the mid-project meeting. Those participants were contacted to discuss the proceedings of the meeting, and they also re-did the survey. To ensure bias was not introduced by this process, their responses were noted as “remote”. We checked for systematic differences in the overall average global estimates and the overall efficiency estimates (see below for details) with and without the inclusion of the remote participants. As there was no significant difference ($p > 0.05$, ANOVA), results are presented with the entire pool of participants included.

Estimating the net CDR potential of EW. First, to assess the global scale potential of EW, participants were asked to provide their best estimate of the global CDR potential of each of six feedstocks independently: lime, basalt, concrete waste, olivine-rich rock (hereafter, olivine), steel slag, and wollastonite-rich rock (hereafter, wollastonite). This estimate included the entire system, including other GHGs (e.g., alterations to N_2O production), organic carbon, and transport of the material. We also considered the entire production process for all feedstocks except steel slag and concrete waste. For those two feedstocks, which are waste products from ongoing manufacturing, emissions associated with that manufacturing were excluded. Constraints like material supply were considered but not quantitatively pre-determined (in other words, experts individually determined the likely magnitude of the future supply). Experts were then asked for their high-range estimate (95th percentile) and their low-range estimate (5th percentile) of CDR potential (in terms of CO_2e). Lastly, they were asked how confident they were that their estimated range contained the true value, from 50% (e.g., the real value had an equal probability of falling in or out of their range) to 100% (complete certainty that the 95% range contained the true estimate). For the precise wording and conditions, see the questions (Supplementary Information)

Second, to estimate where C may be lost to the atmosphere throughout the process, we focused on transfer efficiency through the overall EW system. While there is potential for EW deployment in a wide range of agroecosystems, we constrained the scenario to a hypothetical Midwestern US context to obtain realistic and comparable estimates. Specifically, efficiency estimates were for non-irrigated, non-tile drained loamy soils in the American Midwest with an average pH value of 5.5–6, a base saturation of 65%, and a cation exchange capacity (CEC) of 10 meq/100 mg. Participants assumed a feedstock grind size of <100 μm. The export pathway was through a major waterway (e.g., the Mississippi River) into the ocean. This hypothetical setting was constructed with the goal of selecting a representative setting that lacks characteristics of both ideal settings for EW (e.g., tile drains and very low CEC) and suboptimal settings (e.g., arid regions). The stages of this pathway were (1) the agricultural field, (2) deeper soils and groundwater, (3) freshwater streams, (4) nearshore marine systems, and (5) deep water marine systems. Participants were asked not to consider potential interactions with the organic C cycle (e.g., EW-induced changes in soil organic C cycling) in these transfer efficiency estimates (see "Discussion").

Each stage was framed individually. The field-stage involved application of raw feedstock to the bottom of the layer actively ploughed/tilled. The relevant questions were framed as "if enough material were applied to potentially fix 10 tons CO_2", such that the expert's estimates include judgment on the fraction of feedstock dissolved over the considered timeframe (20 years). The deep soil stage encompassed the movement of C captured in the field stage from the bottom of the tilling zone to free-flowing freshwater. For this and all other stages, transport efficiency (pass-through fraction, or the proportion of C that enters that stage and then moves through to the next stage) was assessed with a starting condition of 10 tons of fixed C entering that stage. The freshwater stage extended from free-flowing drainage from a field to brackish estuarine systems. The coastal ocean stage encompassed brackish water and the nearshore mixing zone. The marine stage included deeper waters. We allowed that C might be resident within each stage for up to 20 years. Ultimately, storage was considered to be >100 years in the ocean. The same range and confidence estimates used in the global estimate were collected at each stage (5th, 50th, 95th percentile, and certainty in range estimate). Because stages were evaluated independently, they could not be combined to calculate an overall field-to-marine pass-through fraction. So, a final question evaluated the anticipated fraction of the material that would successfully move through all stages from field application to marine deposition.

In addition, for each stage, experts were asked to estimate the current measurement error they would expect if we quantified efficacy by feedstock and stage. For example, a measurement error of 100% suggested the error in measuring EW efficacy at that stage was roughly the same as the magnitude of the CDR process itself, whereas an error of 200% meant the uncertainty was double that of the process itself.

Experts were also asked about the potential for each feedstock to cause significant human or environmental harm if deployed at broad scales (for each stage). Lastly, they were asked qualitative questions at each stage and feedstock regarding the three most important variables that influenced their estimate and the three most important unknowns, which, if better constrained, would improve the certainty of their estimate.

Here, data are primarily presented as the full range of individual responses to transparently display the range of estimates obtained. Where necessary, summary statistics such as means and ranges are included. All responses (anonymized) are available at the full dataset (see Data Availability).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Full dataset of individual elicitation responses (anonymized) is available on Zenodo[83].

Code availability

R code to replicate the analysis/graphing is available on Zenodo[83].

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Author contributions

B.B., D.R.G., M.G.M., and N.J.P. conceptualized the study. C.D., K.M., R.B.N., T.R., T.J.S., S.V., B.G.W., M.A., S.C., L.A.D., J.H., B.Z.H., Y.K., A.K., T.K., I.M.P., N.J.P., C.R.P., S.W.L., and S.Z. participated in the elicitation. B.B., D.R.G., and E.E. led the data analysis and initial drafting. R.B.N. and C.D. developed figures. All authors contributed to the final document writing and contextualization.

Competing interests

The authors declare no conflict of interest. N.J.P. was a co-founder of Lithos Carbon but has no financial ties to the company. C.D. acts as a scientific advisor to the Rock Flour Company but does not receive financial compensation for the role.

Additional information

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