Greetings alumni and parents,

I’m very much looking forward to discussing with you my First Year Seminar formally called **GENS 176: Making Powerful Arguments**. My section (Q) is entitled **Climate Change: Earth Scale, Human Experience**. In preparing and facilitating this course, I draw upon my double decades of experience as an MIT-trained geochemist and as a science educator at Whitman since 2006. I also draw upon my personal experience as the daughter of a 3rd generation rancher from Wyoming who lived an agrarian life in the dry, high plains of the Powder River Basin.

Speaking of Wyoming, at this moment I honor my responsibility to acknowledge the original inhabitants of North America, whose ancestors were devastated by diseases brought by European Americans and by acts of genocide. I was born and raised on lands of the Hinono’eiteen (Arapahoe Nation), the Tséhéstáno (Cheyenne Nation), and the Lakȟóta (Lakota Sioux Nations). I live now in the Walla Walla Valley and foothills of the Blue Mountains, the traditional lands of the Cayuse, Umatilla, Walla Walla and Nez Perce. My research takes me to the lands of the Unangax people, an area now known as the Aleutian Islands. I recognize my responsibility to join in caring for these lands and I pay my respects to the elders of these Nations.

In designing the **Climate Change: Earth Scale, Human Experience** course, the syllabus also acknowledges what scientists have come to understand over three decades: we must speak with people from our experience grounded in science, mindful of the role of emotion, capitalizing on how communities build consensus, and in partnership with all the creative arts. It’s a tall task for a single course! In this course we do not examine policy or economics because these are not my strengths. It’s also neither my goal nor that of the First Year Seminar. My goal is to inform students and help them process the difficult and joyful emotions raised by a close examination of climate change, all while mentoring their writing. The arc of the course is toward realization that solutions, such as facilitated carbonation of rocks and solar and wind energy, can help us avoid the most destructive legacies of the Industrial and Technological Ages in this time that many geoscientists call the Anthropocene. But only if science communicators and artists work together.

I invite you to join this discussion having read and reflected on five of the texts that the course presents to students. I will also append optional texts for those of you who want another poem, an indigenous Karuk Nation perspective shared via video, and/or who delight in the chemical aspects of the Earth System. This sounds like a lot, but three of the recommended texts are poems.

1) Squarzoni, Philippe. *Climate Changed [Saison Brune]: A Personal Journey Through the Science*. New York: Abrams ComicArts, 2014. We will read 16 pages, however this is a graphic memoir (of 473 pages!) that features little text and many images.

2) Brulle, Robert J. and Norgaard, Kari M. Avoiding cultural trauma: climate change and social inertia, *Environmental Politics*, DOI:
We will read the first 3 pages, although the entire article is assigned to students.

3) Kathy Jetnil-Kijiner: Dear Matafele Peinem  The poet reads her poem at this link (https://www.kathyjetnilkijiner.com/united-nations-climate-summit-opening-ceremony-my-poem-to-my-daughter/). The text, if you wish to read it at the same time, is just below the video.

4) Natasha Threthewey, Liturgy  The poem Liturgy is in this pdf. If interested, it is also available online at https://iwp.uiowa.edu/sites/iwp/files/Trethewey_Home_Land.pdf which is a five-page essay by the poet herself.

5) Simon Armitage: In Praise of Air is available at this link: https://writingsheffield.com/locations/in-praise-of-air-simon-armitage.

Optional texts:

6) Solli Raphael Why is it… https://www.youtube.com/watch?v=gDA50VW-mdQ

7) Panaunu’thivthaaneen xúus nu’èethtiheesh We’re Caring for Our World (video) (created by the Karuk people and Dr. Kari Norgaard) If you wish, watch the 2nd video (~8 min) at https://pages.uoregon.edu/norgaard/salmon-acorns-feed-our-people.html


Please anticipate that we will start with ~ 10 minutes of introduction of my experience, the Keeling Curve, and robust projections. Then I invite you to participate in ~30 minutes of small-group discussion in breakout rooms with about 5-7 participants. The small group discussion time always flies by! Lastly, we’ll spend ~20 minutes of whole group discussion followed by an open Q&A. We will end with some examples of concrete actions that need support.

I have chosen this format so that you may experience the best of online teaching engagement similar to that experienced by students during the 2020-21 academic year. During this academic year, I would teach with the same sequence for an individual class, yet happily with small groups formed in person, in the classroom.
“Great scholarship on all facets of the climate problem. . . . A true feast.”
—Jean Jouzel, IPCC vice-chair, co-recipient of the Nobel Peace Prize.
I WAS JUST FLIPPING THROUGH YOUR AL GORE BOOK ABOUT GLOBAL WARMING...

IT'S FASCINATING...

THIS PHOTO OF THE EARTH FROM SPACE...

IT WAS TAKEN IN 1972 BY THE LAST APOLLO MISSION. THERE WAS THIS MOMENT WHEN THE SUN WAS ALIGNED RIGHT BEHIND THE SPACE CAPSULE.
Even though, really, part of the Earth is always in the dark, and from space, you usually only see a slice or a crescent, like the moon.

But what's interesting is that, not only is it the only photo there is of the Earth round like that...

...but it's also the one that's always used when someone wants to show a picture of the Earth from space.
NINETY-NINE TIMES OUT OF A HUNDRED, WHEN WE SEE A PHOTO OF EARTH, IT'S THIS ONE.
THAT'S FASCINATING... I DIDN'T KNOW THAT.

ME NEITHER.

ALL THE SAME, THOUGH—THE EARTH'S ROUND. SO WHEN PEOPLE HAVE TO PICK A PHOTO, THEY PICK THE ONE THAT MATCHES THE IMAGE WE HAVE IN OUR HEADS.

RIGHT, RIGHT, THAT MAKES SENSE...

WE CHOOSE AN IMAGE THAT FITS THE IDEA THAT WE STARTED WITH... SO WE HOLD ON TO THAT IDEA...

SO WE KEEP CHOOSING THAT SAME IMAGE...

BUT IT GIVES A FALSE IMPRESSION OF THE PLANET. BOTH CORRECT AND SKewed AT THE SAME TIME.

A PERFECTLY ROUND AND PRETTY PLANET. WITHOUT ANY SHADOW OVER IT.

SO THIS PHOTO ISN'T ONLY A REFLECTION OF THE SHAPE OF THE EARTH AS IT IS. IT'S ALSO AN ICON THAT SHAPES OUR IDEA OF IT...

AND, BANG!

WE'RE STUCK IN A LOOP OF ONE VISION OF THE WORLD.
...The principal source of energy for humans was wood, which, in burning, provided heat and light.

Mechanical energy was furnished by working animals and manual labor.

Energy consumption exploded during the Industrial Revolution with the discovery of fossil fuels.

For six generations the burning of coal, oil, and natural gas transformed human society...

...and fueled the development of modern civilization.

and also caused climate change.
IF OUR LIFESTYLE ISN'T SUFFICIENTLY VIRTUOUS, WHOSE FAULT IS IT?

HOW CAN WE MODIFY OUR BEHAVIOR SO THAT IT PRESERVES THE CLIMATE?

HOW CAN WE AS INDIVIDUALS HELP SOLVE THE PROBLEMS?

BECAUSE CLIMATE CHANGE IS NOT JUST A MATTER OF INDIVIDUAL BEHAVIOR.

THE PROBLEM LIES IN HOW OUR WHOLE SOCIETY IS STRUCTURED.
After energy production, the industrial sector is the world's next largest emitter of CO₂.

The production of basic materials—metals, glass, cement, paper...

...accounts for 80% of emissions due directly to manufacturing for all the gases combined.

The rest are emitted by the manufacture of finished goods.

In general, finished goods are thought to generate up to two times their weight in carbon emissions.
Manufacturing a 90-pound (41-kg) dishwasher or a 165-pound (75-kg) washing machine creates an emission of 40 to 180 pounds (41 to 82 kg) of carbon equivalent.

The manufacture of a 1-ton car generates 1 to 2 tons of carbon equivalent before it’s even on the road.

Everything that contributes to more consumption of material goods helps destabilize the climate.
WE STAND AT A CROSSROADS.

WE CANNOT STOP THE PLANET FROM HEATING UP OVER THE NEXT FEW DECADES. BUT THE SCALE OF THE IMPENDING DISRUPTIONS DEPENDS ON HOW WE REACT.

TO STABILISE THE AMOUNT OF CO₂ IN THE ATMOSPHERE, WE HAVE TO BRING OUR EMISSIONS BACK DOWN TO A LEVEL WHERE THEY CAN BE ABSORBED BY NATURE—OCEANS, PLANT LIFE, THE SOIL.

TO DO THAT, CO₂ EMISSIONS HAVE TO FALL BELOW THE LEVEL OF 3 GIGATONS OF CARBON EQUIVALENT A YEAR.

IN OTHER WORDS, WE HAVE TO REDUCE OUR EMISSIONS BY 75% BEFORE 2050.

WHERE DO WE START?
When there were only 6 billion people on the planet, 3 gigatons a year distributed across the entire population was roughly 1,100 pounds (500 kg) of carbon equivalent per person per year.

In Mali, the average person’s consumption produced emissions of 22 pounds (10 kg) of carbon equivalent a year...

...which leaves room to increase that carbon emission.

But people in China already produced on average 1,323 pounds (600 kg) per person per year.

The average person in Mexico was at almost two times that 1,110-pound limit.

The average French person produced 2.7 tons a year.

For Americans, who produced an average of 6.8 tons per person per year, it meant a 92% reduction.

Which meant a need to decrease emissions by 75%.
Regional trains, subways, and public buses emit on average 0.5 to 1.1 ounces (15 to 30 g) of carbon equivalent per passenger per 0.6 miles.

In France, the trains generate only 0.1 ounces (3 g) of carbon equivalent per passenger per 0.6 miles, thanks to the use of nuclear and hydraulic energy.

In any case, trains are the most economical mode of motorized transportation in terms of greenhouse gases.

In Great Britain, where electricity is mostly generated from coal, it is over 0.7 ounces (20 g) in any case. Trains are close to those of trains, but that accounts for a very small percentage of passengers.
Whether we like it or not, there are greenhouse gas emissions in every part of our lives.

Our way of life and CO₂ emissions are inextricably linked.

From our food, our homes, our cars, our pastimes.

All our activities are part of the climate crisis, all our wants...

Every product we purchase...

...the way we eat, get around, keep warm.

Eradicating so much CO₂ from our way of life won’t be easy.
WHAT DO WE CUT OUT FIRST?
Avoiding cultural trauma: climate change and social inertia

Robert J. Brulle & Kari Marie Norgaard

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Avoiding cultural trauma: climate change and social inertia

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ABSTRACT
The failure of societies to respond in a concerted, meaningful way to climate change is a core concern of the social science climate literature. Existing explanations of social inertia display little coherence. Here, a theoretical approach is suggested that integrates disparate perspectives on social inertia regarding climate change. Climate change constitutes a potential cultural trauma. The threat of cultural trauma is met with resistance and attempts to restore and maintain the status quo. Thus, efforts to avoid large-scale social changes associated with climate change constitute an effort to avoid cultural trauma, and result in social inertia regarding climate change at individual, institutional, and societal levels. Existing approaches to social inertia are reviewed. An intellectual framework utilizing the work of Pierre Bourdieu is proposed to integrate these different levels of social interaction. Social processes that maintain social order and thus avoid cultural trauma create social inertia regarding climate change.

KEYWORDS Climate change; social inertia; neo-institutionalism; cultural trauma; post-politics; framing

Since May 2018, when atmospheric CO₂ levels topped 410 ppm, it has become apparent that the earth’s climate is entering a new phase. Climate change impacts are advancing across the board. Yet despite extreme weather events and urgent warnings from the scientific community, action to mitigate carbon emissions is stalled. Global efforts to bring carbon emissions under control have been unsuccessful. In 2018, only seven of the 195 signatories to the Paris Accord were within range of meeting their commitments under the treaty. Not a single major northern industrial country has met its pledges (Climate Action Tracker 2018). The recent United Nations Framework Convention on Climate Change Conference in Katowice Poland featured several events celebrating coal production and was unable to fully recognize the most recent work of the Intergovernmental Panel on Climate Change. The relentless march of carbon emissions continues. In 2017, carbon emissions increased 1.4% (IEA 2017), and are projected to increase 2.7% in 2018 (Dennis and Mooney 2018).
Moreover, climate change continues to be a low-salience issue. In the USA, polling by the Gallup Organization shows that since 1970, the state of the environment has remained a peripheral concern for Americans, with never more than 3% of the population identifying it as the Most Important Problem facing the US. Since 2014, when Gallup first included climate change as a standard issue in its surveys, the topic has ranked nearly dead last. The gap between the severity of the problem and its lack of public salience is visible across the world. In an international comparative regional poll (PEW 2015), the US was ranked as the fourth most concerned region, behind Latin America, Africa, and Europe, but ahead of the Middle East and China. However, the difference between attitudes in the US and Europe was not great. The percentage of the European population that identified climate change as a very serious problem was 54%; in the US, it was 45%.

There has been insufficient mobilization and engagement to affect the level of public urgency and even interest that the predictions of climate scientists would warrant. Rather, efforts to address climate change have encountered substantial social inertia, the interrelated cultural, institutional, and individual processes that inhibit actions to address this pressing issue. Why is this?

The failure to realistically address climate change is a dominant theme across the social science literature. However, explanations for social inertia vary widely across disciplines and remain piecemeal, and the interdisciplinary conversation remains dominated by natural science and economic perspectives. As shown by Brulle and Dunlap (2015, p. 5–14), these approaches suffer from substantial limitations. What has emerged is, by and large, a confused mixture of disciplinary perspectives that fails to cohere into a comprehensive approach capable of explaining the present paralysis or guiding future action. Extending earlier attempts to develop a comprehensive approach to understanding social inertia (see Leahy et al. 2010), we seek here to develop a conceptual framework and theoretical argument to explain the interrelated social processes that drive different levels of cultural inertia on climate change.

We focus our theoretical examination on the notion of avoidance of cultural trauma. Cultural trauma is a social process that involves the systematic disruption of the cultural basis of a social order. The individual routines, institutional behaviors, ideological beliefs, and overall regime of practice become subject to questioning and uncertainty, resulting in profound challenges to routine, taken-for-granted ways of interacting (Alexander 2004, 2012, Sztompka 2004). We argue that climate change constitutes a potential cultural trauma in two senses. First, the unusual natural events linked to climate change, such as fire and flood, can serve as a direct disruption of social practice and thus create potentially traumatic outcomes. Second, climate change constitutes a profound symbolic challenge
to the existing social order and is thus a potentially traumatic threat (Zizek 2010, p. 326–327, Hamilton 2012, p. 728). This is because the social construction of climate change as a collective concern challenges the underlying narratives of collective identity and invokes a symbolic process of meaning construction based on a new narrative of the social order. The risk of cultural trauma is met with resistance and attempts to restore and maintain the status quo. These actions to avoid cultural trauma result in social inertia on climate change at the individual, institutional, and societal levels.

We start our analysis with a summary of existing social science approaches to understanding different forms of inertia on climate change. This review illustrates the piecemeal nature of this literature and its limited focus on single dimensions of the social order. To move beyond this limitation, we utilize the tripartite framework of social order developed by Bourdieu to propose an integrated approach to social inertia that synthesizes existing approaches across individual, institutional, and societal levels. We apply the Bourdieu’s framework of habitus, field, and doxa to discuss how a potential disruption of social order in the form of a cultural trauma leads to actions at the individual, institutional, and societal levels to maintain the current orientations and to ensure social and cultural stability, thus avoiding the social disruption associated with climate change. We conclude that social inertia on climate change is not an irrational or unexpected response, but rather the normal and expected functioning of existing social control mechanisms.

Existing social science explanations of social inertia

Most social-scientific research into climate change can be divided into three distinct levels of analysis: individual values, beliefs, and behaviors; institutional transformations and disruptions of organizational practices; and macro-level cultural, political, and economic contests.

Individual-level approaches

By far the most prevalent approach to analyzing climate-change inertia centers on what Bulkeley (2000) called ‘the information deficit hypothesis’. Simply stated, society’s failure to respond proportionately to climate change is due to failure to widely promulgate appropriate scientific information to aid public understanding: ‘If people only knew, they would act’. There is also a second approach focused on the individual factors that limit action on climate change (Gifford 2011). In general, these factors include: provocation of anxiety, which leads to the systematic avoidance of engaging the issue (Mnguni 2010); failure to integrate knowledge of climate change into the formulation of daily behavior (Leahy et al. 2010); and understanding the
Rising levels of atmospheric carbon dioxide ($CO_2$) are driving increases in global temperatures. Enhanced weathering of silicate rocks is a $CO_2$ removal technology that could help mitigate anthropogenic climate change. Enhanced weathering adds powdered silicate rock to agricultural lands, accelerating natural chemical weathering, and is expected to rapidly draw down atmospheric $CO_2$. However, differences between enhanced and natural weathering result in significant uncertainties about its potential efficacy. This article summarizes the research into enhanced weathering and the uncertainties of enhanced weathering due to the key differences with natural weathering, as well as future research directions.

**ENHANCED WEATHERING AS A CARBON DIOXIDE REMOVAL TECHNOLOGY**

Anthropogenic emissions of carbon dioxide ($CO_2$) are increasing global temperatures via the greenhouse effect. The Intergovernmental Panel on Climate Change (IPCC) “business as usual” emission scenarios [the representative concentration pathway (RCP) model that considers radiative forcing values of 8.5 W/m$^2$ by the year 2100] project that global temperatures could rise by between 2.6°C and 4.8°C, compared to the reference period 1986–2005, by the end of the 21st century (IPCC 2013). The 2015 Paris Agreement, under the United Nations Framework Convention on Climate Change, established the target of limiting global warming to below 2°C. To meet this goal, carbon dioxide removal technologies are required to actively withdraw $CO_2$ from the atmosphere. Enhanced weathering (EW) of silicate rocks is a carbon dioxide removal technology that could help mitigate anthropogenic climate change by reducing atmospheric $CO_2$ levels.

The principle behind EW is similar to that of natural, geologic-timescale chemical weathering: when silicate minerals are dissolved in a reaction with atmospheric $CO_2$ and water, the products of this reaction, which include calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), and bicarbonate ($HCO_3^-$) ions, are transported to the ocean by rivers (Fig. 1) and are stored as carbonate minerals on geological timescales, thereby locking up atmospheric $CO_2$ in ocean sediments (Kasting 2019 this issue). Natural chemical weathering occurs slowly and consumes $\sim 0.26$ PgC y$^{-1}$ of atmospheric $CO_2$ as $HCO_3^-$ (Hartmann et al. 2009), as compared to the $\sim 10$ PgC of atmospheric $CO_2$ released per year by fossil fuel combustion. Enhanced weathering speeds up chemical weathering rates such that $CO_2$ is scrubbed from the atmosphere in meaningful quantities on human timescales (Fig. 2). Estimates suggest that if deployed on a sufficiently large scale, EW could draw down from $<1.0$ PgC y$^{-1}$ up to $\sim 30$ PgC y$^{-1}$ as $HCO_3^-$ (Köhler et al. 2010; Taylor et al. 2016; Strefler et al. 2018) and reduce the rise in atmospheric temperatures predicted for 2100 (assuming “business as usual” emission scenarios) by between 0.2°C (Köhler et al. 2010; Taylor et al. 2016) and 1.6°C (Taylor et al. 2016).

Enhanced weathering operates through the application of powdered silicate rock to soils (Fig. 1), although application directly into the ocean is also under investigation (Renforth and Henderson 2017). The theory behind EW has developed from the extensive literature on the controls on natural chemical weathering rates. Laboratory trials have shown that finely ground, unweathered rock has a high reactive surface area, leading to increased weathering rates (White and Brantley 2003). Powdered mafic rock (e.g., basalt) and ultramafic rock are those most commonly proposed for EW due to their relatively high proportion of olivine, a rapidly weathering, Mg-bearing silicate mineral (Hartmann et al. 2013). Agricultural lands are now the target for EW because interactions with plant roots and fungal hyphae, as well as organic acids, increase weathering rates, and because these sites are equipped with the infrastructure to apply rock powder on large spatial scales. Strefler et al. (2018) suggest that 5.1 Mkm$^2$ of tropical and 2.8 Mkm$^2$ of temperate croplands are suitable for treatment. Enhanced weathering is predicted to be most effective in tropical climates due to the relationship between higher temperatures and/or rainfall and higher chemical weathering rates (Edwards et al. 2017).

Furthermore, EW is an attractive potential carbon dioxide removal technology because, in addition to removing $CO_2$ from the atmosphere, there may be substantial co-benefits. An extensive literature exists on the application of powdered basalt to croplands. This work has largely investigated rock powder as a sustainable and cheap alternative to chemical fertilizers and demonstrated that it improves soil quality and increases crop yields (Van Straaten 2007; Beeling et al. 2018). Through increased uptake of silicon from soil following rock powder treatment, crops also have increased...
resistance to pests and disease (Beerling et al. 2018). Due to these interactions, EW may help alleviate the threat to global food security posed by climate change, as well as reduce the need for harmful fertilizers.

Ocean acidification is another negative side effect of climate change. It causes the dissolution of carbonate structures in marine organisms such as corals, as well as plankton and some shellfish (e.g., oysters, scallops) (IPCC 2013). Some fisheries are threatened by ocean acidification, as are economies based on organisms further up the food chain through disruption to the marine food web. Through the addition of HCO$_3^-$ to the ocean, EW could help reverse ocean acidification in coastal waters (Köhler et al. 2010; Taylor et al. 2016; Strefler et al. 2018).

Here, we summarize the different approaches scientists are taking to assess EW as an efficient and safe carbon dioxide sequestration. First, we examine the key differences between EW and natural chemical weathering and how these differences introduce challenges and uncertainties to quantifying atmospheric CO$_2$ sequestration via EW. Finally, we discuss essential areas for further research.

**DOES ENHANCED WEATHERING WORK?**

At present, very few laboratory or field studies have been conducted with an explicit focus on EW. Studies that examined rock powder as a fertilizer typically report crop growth and yield under variable rates of basalt powder application, but only occasionally provide ion concentrations of soil water or exchangeable soil fractions from which chemical weathering rates can be gleaned (e.g., Anda et al. 2013, 2015; ten Berge et al. 2012). Despite significant inter-study differences in rock powder composition, grain size, and application rates, as well as starting soil material, vegetation, and climate conditions, such studies converge on three overarching conclusions. First, the application of powdered basalt to soil increases total chemical weathering rates (Fig. 3). Second, higher basalt application rates yield higher total chemical weathering rates (Fig. 3). Third, weathering efficiency declines with increased basalt load (Fig. 4). It is worth noting, however, that the experimental design of these studies is distinct from that commonly proposed for EW in that rock powder was applied only at the onset of each experiment, whereas EW models often assume repeated, annual application of rock powder. The impact of repeated rock powder application on soil saturation and chemical weathering rates over longer timescales, therefore, remains unclear. The studies above also monitored ion concentrations at some depth in the soil column. Chemical weathering and CO$_2$ consumption rates from EW derive from ion concentrations in discharge (Fig. 1), as this captures the net carbon sequestration following all chemical processes which occur throughout the soil column and during hillslope transport (e.g., CO$_2$ degassing).

**FIGURE 1** Diagram of enhanced weathering. Equation A is a generalized version of the fundamental weathering reaction behind enhanced weathering, that of silicate rock powder weathered by carbonic acid. Equation B is an example of weathering between nitric acid (derived from fertilizer) and carbonate, such as that which comprises lime. For a more complete roster of possible weathering reactions associated with enhanced weathering, see Hartmann et al. (2013).

**FIGURE 2** Carbon-cycle timescales relevant to enhanced weathering (EW). Superscript notes (1–5) are as follows: [1] Under field conditions, rock powder is likely to dissolve on timescales ranging from nearly instantaneous (e.g., calcite) to multiple years for some silicate minerals. [2] Crops such as maize are harvested in their entirety annually, whereas tree crops typically have their commercial products (e.g., fruits) harvested (sub-) annually but the tree itself could live for over a hundred years (e.g., apple trees). [3] Although the mean residence time of topsoil organic carbon is on decadal to centennial timescales, the residence time of deep soil organic carbon can extend to $>10^5$ years (Schmidt et al. 2011). [4] Pedogenic carbonate forms on timescales ranging from days to $10^4$ years, and persists in the soil. The mean residence time of pedogenic carbonate is $~80,000$ years (Zamanian et al. 2016). [5] Some C removed from the atmosphere by EW will become part of the long-term C cycle and remain sequestered for $>10^5$ years.
At an oil palm plantation, basalt powder left

\[
(Ca^{2+} + Mg^{2+} + Na^+ + K^+ + Si) \times 10^{-3} (\mu g L^{-1})
\]

\[
\begin{align*}
\text{relative weathering rate (W/ W)} \\
0 & 10 & 20 & 30 & 40 & 50 & 60 & 70 & 80 & 90 & 100 \\
\text{application rates.}
\end{align*}
\]

If runoff is identical in all manipulations, this assumption is validated in the laboratory including higher atmospheric future climate change scenarios can also be simulated in the future laboratory and field trials will provide valuable opportunities to characterize the controls on EW and its capacity to sequester atmospheric CO₂. Laboratory studies allow for comparative tests that examine the impact of isolated variables on EW before scaling up to more involved and costly field trials. Variables that are likely best investigated in the laboratory include the impact of rock powder grain size and mineral composition, depth of rock powder transport under various tillage practices, as well as the effect of different crop species on weathering. To understand the potential efficacy of EW in the coming decades, future climate change scenarios can also be simulated in the laboratory, including higher atmospheric pcO₂ levels. On the other hand, it is commonly observed that weathering rates derived in the laboratory substantially exceed those documented in the field (White and Brantley 2003) and riverine chemistry can change during downstream transport towards the ocean. Field trials are, therefore, essential for determining the true effectiveness of EW as a carbon dioxide removal technology. Quantification of chemical weathering rates and CO₂ consumption rates from EW field

\[
\begin{align*}
\text{Diagram 3: Total dissolved cation load through time for a series of abiotic soils with variable rates (figure key) of basalt powder (<50 μm) application (Anda et al. 2015). Total dissolved cation load is proportional to total chemical weathering rate (Wtotal), when Wtotal (g km⁻² y⁻¹) = \sum(Ca^{2+} + Mg^{2+} + Na^+ + K^+ + Si) (\mu g L⁻¹) \times \text{runoff (mm y⁻¹)}, when runoff is assumed to be equal across all manipulations because of the identical pot size and uniform addition of water to treatments. The data indicate that total dissolved cation load, and therefore total chemical weathering rates, increase with time and with greater basalt powder application rates.}
\end{align*}
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\begin{align*}
\text{Diagram 4: Decline in weathering efficiency (i.e., weathering per ton of basalt powder) with increasing basalt powder application rates in both an abiotic laboratory trial ("laboratory"), having particle sizes <50 μm (Anda et al. 2015), and a small-scale field trial with cocoa plants ("field") having particle sizes ≤250 μm (Anda et al. 2013). Weathering rates (see Fig. 3 caption) of experimental manipulations (W.experimental) have been normalized to their respective control data (W.control) to generate a relative weathering rate and to facilitate inter-study comparison. In calculating a relative weathering rate, runoff is canceled out based on the assumption that runoff is identical in all manipulations. This assumption is based on either the identical pot size and uniform addition of water to treatments under laboratory conditions (Anda et al. 2015) or the equal area, similar slopes, and close geographic proximity of field plots (Anda et al. 2013).
\end{align*}
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\begin{align*}
\text{Diagram 5: Contrasting methods of basalt powder application in two field trials of enhanced weathering for the Leverhulme Centre for Climate Change Mitigation at the University of Sheffield (UK). (Left) Basalt powder is dispersed in a corn field by a machine traditionally used for lime spreading. Location: Energy Farm at the University of Illinois at Urbana-Champaign (USA). PHOTO CREDIT: ILSA KANTOLA. (Right) At an oil palm plantation, basalt powder is broadcast by hand in line with standard fertilizer application practice. Location: Sabahmas Oil Palm Plantation (Wilmar International Ltd.), Sabah (Malaysia). PHOTO CREDIT: CHRISTOPHER PEARCE.}
\end{align*}
\]
trials will require targeted approaches that monitor, at a minimum, discharge amounts and chemical properties such as major cation and anion concentrations, dissolved organic- and inorganic carbon concentrations, and likely cation source tracers such as radiogenic Sr isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$). Given that silicate and carbonate weathering reactions balance HCO$_3^-$ production with different cation stoichiometry, then mass balance equations that disentangle the proportion of dissolved species from each of these weathering reactions (in particular those pertaining to nitric acid weathering) must be developed to generate an accurate estimate of CO$_2$ sequestration from EW field data. Field trials also provide an opportunity to trouble-shoot the logistics of implementing EW. These trials also allow for the monitoring of environmental and public health concerns, such as biodiversity and water quality (e.g., heavy metal release, water turbidity). We note that ultramafic rocks may contain substantial quantities of heavy metals (Taylor et al. 2016; Beerling et al. 2018).

**DIVERGING FROM NATURE**

**Timescales of Weathering Reactions**

Although EW is conceptually developed from our understanding of geologic-timescale chemical weathering, the two processes differ in ways that introduce challenges to quantifying the ability of EW to sequester atmospheric CO$_2$. A key difference is the timescale of weathering. Whereas natural chemical weathering works on hundred thousand- to million-year timescales (i.e., geologic), EW is largely concerned with CO$_2$ sequestration on decadal to centennial timescales (Fig. 2). Short-term processes that can be dismissed in the study of natural chemical weathering rates are, therefore, significant to EW. For example, on geologic timescales, atmospheric CO$_2$ is not considered truly sequestered until it is locked into marine carbonate, limiting the relevant silicate mineral weathering reactions to minerals containing Ca and Mg. Although more research is needed on the longevity of C storage in the ocean (Renforth and Henderson 2017), both the millennial timescales of CaCO$_3$ compensation (Archer 2003) and the HCO$_3^-$ residence time of ~10$^5$ years (Renforth and Henderson 2017), suggest sufficient longevity to be relevant for climate change mitigation, equal to or greater than the terrestrial sinks of biomass and soil (Fig. 2). On these timescales, any weathering reaction that transfers atmospheric CO$_2$ to riverine HCO$_3^-$, such that it is ultimately stored in the ocean (Fig. 1), is a pertinent atmospheric CO$_2$ sequestration pathway for EW. Thus, HCO$_3^-$ generation via weathering of Ca- and Mg-bearing silicate minerals, as well as weathering of carbonates, will sequester atmospheric CO$_2$. One important consequence of this is that carbonate weathering, which results in no net change to atmospheric CO$_2$ levels over geological timescales (Kasting 2019 this issue), can lead to drawdowns of CO$_2$ that are significant over the timescales of anthropogenic climate change. The above accounting of weathering pathways assumes that carbonic acid (H$_2$CO$_3$) is the weathering agent, as is typically the case with natural chemical weathering (Fig. 1) but that may not be exclusively true with EW (see below). Additionally, pedogenic (soil) carbonate is a secondary mineral which forms slowly through chemical weathering. It has a mean residence time in soil of ~80,000 years (Zamanian et al. 2016), which makes its formation inconsequential to geologic-timescale weathering but a relevant additional CO$_2$ sink to EW, as long as the carbon comprising the pedogenic carbonate originated from silicate mineral weathering (Fig. 2). If, on the other hand, pedogenic carbonate carbon was derived from carbonate mineral weathering, then its formation has no impact on atmospheric CO$_2$ reserves.

**Agricultural Lands**

Whereas natural chemical weathering research has almost exclusively focused on pristine environments, EW is being largely considered for agricultural lands (Hartmann et al. 2013). These areas are often subject to heavy applications of nitrogen (N) fertilizers. The nitrogen cycle is of little importance to natural chemical weathering, but it has a strong influence on the chemistry of agricultural soils. Nitrogen fertilizers can generate nitric acid (HNO$_3$) and participate in chemical weathering (Fortner et al. 2012; Hartmann et al. 2013) (Fig. 1). Nitric acid weathering of silicate minerals will have no impact on atmospheric CO$_2$ levels, but under high concentrations of nitric acid, weathering of carbonate minerals will add CO$_2$ to the atmosphere (Hartmann et al. 2013) (Fig. 1). Carbonate minerals are widespread in agricultural lands due to the use of lime, and calcite is a common trace mineral in silicate rocks.

Nitrogen fertilizers also indirectly affect weathering in the soil column because root uptake of ammonium (NH$_4^+$) acidifies the surrounding soil, but nitrate (NO$_3^-$) uptake acts to raise the local pH (Taylor et al. 2017). Furthermore, although inorganic N is released from decaying plant matter as NH$_4^+$, which may be retained on soil exchange sites, nitrification processes convert NH$_4^+$ to non-exchangeable, highly mobile NO$_3^-$, potentially leading to nitric acid weathering. Easily leached NO$_3^-$ may also compromise the greenhouse-gas balance for a watershed by reducing dissolved inorganic carbon export and by possible in situ or downstream denitrification and release of nitrous oxide (N$_2$O), a potent greenhouse gas, to the atmosphere. The impact of N fertilizers on weathering will vary with crop type. Legumes, for example, host N-fixing bacteria on their roots such that N is adsorbed directly by the plant, eliminating the need for N fertilizers. Conversely, crops such as maize inefficiently recycle N and, thus, require substantial applications of N fertilizer. Waters draining maize fields exhibit high NO$_3^-$ concentrations as a result of both the extensive application of N fertilizers and annual tillage (Smith et al. 2013).

The natural weathering literature has established that plants can dramatically increase chemical weathering rates (Porder 2019 this issue), but agricultural ecosystems contain different plant species, and significantly reduced biodiversity, than natural settings. Under monoculture conditions, it will be particularly important to identify which crops best induce chemical weathering. Biological weathering of grain-scale weathering rates will be highest at depths where high microbial activity and root respiration of atmospheric CO$_2$ lead to high soil CO$_2$ concentrations, yet nutrient and water cycling beneath crops may cause significant delays between weathering in soils and increased fluxes of weathering products to the ocean. Additionally, biomass can sequester some weathering products which are then removed from the landscape at harvest, thereby disrupting natural recycling of carbon and nutrients. Productivity of crops may increase in response to EW before a significant carbon dioxide removal effect can be demonstrated from stream water chemistry.

**Rock Powder Surface Area and Mixing Depth**

The dependence of chemical weathering rates on temperature, runoff, and biology has been extensively documented in laboratory experiments, as well as through empirical relationships based on field data at the regional or global scale (Li et al. 2016; Porder 2019 this issue). Crucially, weathering rates are also constrained by the reactive surface area of mineral grains, which increases as particles are ground to smaller sizes. Although freshly milled, unweathered rock powders should initially have reactive
surface areas comparable to those used in laboratory experiments, the mineralogy, particle size and shape distributions will evolve with time and will change with soil depth. Processes such as secondary mineral precipitation may block reactive surfaces over time. The depth distribution of particles is also an important constraint on weathering because carbonic acid weathering depends on biologically respired CO₂ as well as CO₂ dissolved in rainwater (Fig. 1).

Modelling results (Taylor et al. 2016) suggest that mixing depths shallower than the depth of greatest biological CO₂ production could lead to lower carbon sequestration rates. The depth distribution of powder in agricultural soils is likely to be tillage- and site specific because the retention of particles depends on their size relative to the soil porosity. It is possible that repeated large applications of rock powder may change the soil permeability due to accumulation of slower-weathering phases where tillage pans restrict particle transport. Particle loss to stream water is also possible in soils that experience significant surface runoff, macro-porosity and shallow flow paths.

Given the complex set of processes that impact rock grains within the soil column, initial total surface area measurements using gas adsorption or estimating geometric surface area from the particle size distribution would need to be repeated with samples from several depths to elucidate grain-scale weathering processes. Changes in total mass, secondary phases or overall chemistry might be quantified by burying small bags of powder or by collecting soil cores for examination by X-ray fluorescence or X-ray diffraction. For detailed examination of individual surfaces, a variety of techniques such as atomic force microscopy, vertical scanning interferometry, or scanning electron microscopy could be employed, but it may be necessary to prepare pre-scanned mineral surfaces with fiducial marks. The depth distributions of particles, reactive surface area, pore-water chemistry and soil CO₂ would provide the detailed picture of weathering that is needed for process modelling and to estimate optimal carbon dioxide removal.

**GOING GLOBAL**

For EW to be implemented globally, field and laboratory trials must demonstrate that EW effectively and safely sequesters atmospheric CO₂. Enhanced weathering-specific models must also indicate that EW can remove sizeable quantities of CO₂ from the atmosphere across large spatial and temporal scales. However, the literature on natural chemical weathering has revealed the complexity associated with extrapolating brief, single catchment studies to larger scales (Li et al. 2016). For EW, the climate, soils, hydrology, crops, agricultural practices, and rock powder mineralogical composition will vary considerably not only from watershed to watershed but, in some cases, from farm to farm. The use of short-term time-series data from individual field sites may provide unexpected results in regional or global models because of spatial and temporal discrepancies between grain-scale weathering and dissolved ion fluxes. As crop harvesting repeatedly removes cations from agricultural soils, considerable discrepancies are expected between grain-scale weathering rates and stream water ion fluxes following EW treatments, even if biomass stubble is left on the fields. Global and regional models may not account for such discrepancies if they ignore productivity and nutrient cycling by the crops.

It is worth noting that annually, croplands emit an estimated 0.5–3.1 Mg CO₂-C m⁻² to the atmosphere through soil respiration (Muñoz et al. 2010), far exceeding C fluxes associated with weathering. Thus, changes in soil respiration resulting from EW treatments could potentially form a major part of the greenhouse gas balance but such savings have not been previously considered in carbon budgets of EW (Fig. 6). In any case, cropland greenhouse gas emissions depend on factors such as management practices of fertilization and tillage, which are outside the scope of this review.

The nitrogen cycle is also a key component of EW soil chemistry that is largely missing from current weathering models (Taylor et al. 2017). In addition to the impact of nitric acid on cropland weathering, EW treatments may also enhance stream water NO₃⁻ fluxes (Rosi-Marshall et al. 2016). Nitrate-reducing bacteria are largely responsible for the production of N₂O, a greenhouse gas. Thus, increased stream water NO₃⁻ fluxes may drive increased N₂O emissions in near-shore environments, offsetting some of the climate change mitigation impacts of CO₂ drawdown by EW. Conversely, pH buffering resulting from addition of HCO₃⁻ to soils may decrease cropland N₂O emissions (Kantola et al. 2017). Both CO₂ and N₂O fluxes to and from the atmosphere should be considered in models of EW: N₂O emissions are now being built into the land surface components of general circulation models. The net effect of EW on climate will depend on the fluxes of all greenhouse gases.

**FIGURE 6** Model estimates of the enhanced weathering CO₂ budget for different rocks and minerals (see axis captions). Note that Streffer et al. (2018) reference Moosdorf et al. (2014) for mining, transport, and spreading emission estimates. Köhler et al. (2010) combine mining and grinding emissions and so is here represented as grinding.

Finally, CO₂ emissions associated with implementing EW globally must also be considered when assessing its net impact on atmospheric CO₂ levels. The major processes that emit CO₂ are grinding of rock into powder, and transport of powder from source point to application point (Fig. 6). Preliminary calculations suggest that transport could emit up to 4% of the CO₂ sequestered by EW, while rock grinding may emit as much as 25% of the CO₂ sequestered by EW (Moosdorf et al. 2014). On balance, however, model calculations suggest that EW still removes significant quantities...
of CO₂ from the atmosphere (Fig. 6). Nevertheless, meaningful reductions in CO₂ emissions could be achieved through the use of basalt powder currently stockpiled as quarrying waste product or through mining operations that use green energies.

SUMMARY

Enhanced weathering of silicate rocks is a carbon dioxide removal technology that may be capable of removing sizeable quantities of CO₂ from the atmosphere relatively rapidly and, therefore, help mitigate anthropogenic climate change. However, current understanding of EW is largely based on previous studies of long-timescale natural chemical weathering. The true ability of enhanced weathering to sequester atmospheric CO₂ will depend on a multitude of weathering pathways and biogeochemical interactions that are unique to enhanced weathering due to the short timescale on which it operates, its agricultural landscape setting, and the central role of rock-powder weathering. Laboratory and field trials will play a critical role in better understanding these unique controls, determining the real-world efficiency of enhanced weathering, and driving global models. But these trials have only just begun.

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REFERENCES


Porder S (2019) How plants enhance weathering and weathering is important to plants. Elements 15: 241-246


Smith CM and 6 coauthors (2013) Reduced nitrogen losses after conversion of row crop agriculture to perennial biofuel crops. Journal of Environmental Quality 42: 219-228
