Deliberating enhanced weathering: public frames, iconic ecosystems, and the governance of carbon removal at scale

Abstract

Meeting goals for 'net zero' emissions may require removal of previously-emitted carbon dioxide from the atmosphere. One proposal, Enhanced Rock Weathering (ERW), aims to speed up weathering processes of rocks by crushing them finely and spreading them on agricultural land. Public perceptions of ERW and its wider social and environmental implications will be a critical factor determining its potential; we use six two-day deliberative workshops in England, Wales and Illinois to understand public views. Consideration of ERW deployment in tropical countries led participants to frame it from a social justice perspective, which had been much less prevalent when considering Western agricultural contexts, and generated assumptions of increased scale, which heightened concerns about detrimental social and environmental impacts. Risk perceptions relating to 'messing with nature' became amplified when participants considered ERW in relation to 'iconic' environments such as the oceans and rainforest.

Keywords: Carbon Dioxide Removal; Negative Emissions Technologies; enhanced rock weathering; upstream engagement; public perceptions; responsible innovation

1 Introduction

To avoid potentially catastrophic impacts from anthropogenic climate change, the global average temperature increase should stay well below 2°C. Yet the majority of scenarios used by the Intergovernmental Panel on Climate Change (IPCC) to represent a 'likely' chance of remaining below 2°C do not achieve this through emissions reductions alone; in the AR5 report, 104 of 116 2°C pathways rely on large-scale implementation of techniques to remove CO_2 from the atmosphere (Fuss et al., 2016). Such techniques are collectively known as Carbon Dioxide Removal (CDR), or in some cases Negative Emissions Technologies (NETs). CDR proposals are still relatively controversial, with well-justified concerns regarding risks of overreliance on under-developed technologies, the possibility of reduced incentives for stringent emissions reductions, and various ethical concerns (Cox et al., 2018). However, as each year passes without any reduction in the pace of increase of global CO_2 emissions, the window of opportunity for mitigating catastrophic climate change in the absence of large-scale CO_2 removal is closing.

1.1 Carbon Dioxide Removal via Enhanced Rock Weathering

CDR proposals are numerous and varied, differing substantially in their sequestration potential, estimated costs, technology readiness levels, the longevity of the CO_2 removal, and their political and legal implications. One suite of techniques known as Enhanced Rock Weathering (ERW) was relatively unknown a few years ago, but has since gathered considerable academic and policy attention, and may be capable of sequestering large amounts of CO_2 for millennia (Royal Society and RAEng, 2018). ERW techniques emulate the natural breakdown of rocks and minerals in the environment: as part of the carbon cycle, this process draws CO_2 from the atmosphere and sequesters it as stable bicarbonate in soils, plant root systems, and the ocean. The principle of enhanced weathering is to speed these processes up by crushing rocks finely to increase their surface area and spreading them thinly, making them break down faster. Unlike some CDR techniques such as forestry and land management, CO_2 storage using ERW is very long-term and does not risk subsequent re-release of carbon by disturbances such as forest fires or field tillage; nor does it rely on deep geological storage of the CO_2 (Royal Society and RAEng, 2018).

This research focuses on ERW using crushed basalt, which would be ground to a fine dust and then spread on land (Beerling et al., 2020). The land used would most likely be agricultural, due to accessibility and availability of spreading machinery, and potential for increased nutrient availability to plants (mainly K, Ca, Si and micronutrients) and improved pH to boost yields (Edwards et al., 2017; Kantzas et al., 2022). Inputs of the additional alkaline bicarbonate to the oceans may also reduce or reverse some aspects of CO_2-induced ocean acidification, although the impacts of this on ecosystems are highly uncertain (Gore et al., 2018). Field trials are currently underway on maize and soybean agriculture in the US and UK, palm oil plantations in Malaysia, and sugarcane in Queensland, Australia. Estimates for ERW sequestration vary widely, from $4.9GtCO_2y^{-1}$ to $95GtCO_2y^{-1}$ globally, at an estimated cost of between $\$24/tCO_2$ and $\$578/tCO_2$ (Fuss et al., 2018). For this, very large amounts of rock will be needed, with potentially high energy costs for mining, crushing and transporting the rock (Strefler et al. 2018). ERW is currently at a relatively low technology readiness level, and if the technique is to contribute in any way towards climate mitigation targets by 2050 it will require rapid resolution of the existing scientific uncertainties, followed by significant effort for scale-up and deployment.

1.2 Public perceptions of novel techniques

Ultimately, public perceptions may prove to be just as important for the future of ERW as the scientific considerations detailed above (Beerling, 2017). A small number of papers examine public perceptions of ERW. Wright et al. (2014) investigated six climate engineering strategies, and found that perceptions of ERW were more neutral and 'muted' than most other techniques; they suggest that ERW has a "less distinct concept image". Carlisle et al. (2020) replicated these findings cross-nationally, and additionally found some support for small-scale trials. Pidgeon and Spence (2017) found that people are generally undecided and neutral about the risks of ERW, although slightly more people support than oppose. A cross-national survey by Spence et al (2021) found that support is mainly dependent upon perceived risks and benefits, and concern about climate change. Jobin and Siegrist (2020) surveyed perceptions of 10 climate engineering techniques, finding fairly strong support for research into ERW, as well as greater perceived benefits than for many other techniques (with the exception of afforestation). Interestingly, in the case of ERW, trust in the responsibility of science, government and industry was a particularly strong predictor of support. Overall, the existing research on public perceptions of ERW is dominated by survey studies, with a lack of qualitative and deliberative research.

Within a context of climate urgency, there is a danger that rapid upscale of CDR could end up creating some of the same environmental and social problems that climate action is trying to avoid in the first place, as shown by experience with technologies such as biofuels (Buck, 2016); it is therefore important to ensure that technology development is both effective and ethical. To support this aim, scholars have recommended the broad involvement of a spectrum of stakeholders, including publics as well as experts, at an early stage in technology development (Wilsdon and Willis, 2004). Instead of asking publics whether they 'accept' an innovation which has already been developed and is delivered to them in discrete artefact form – which might imply a degree of tolerance or even resignation on the part of publics (Firestone et al., 2017) – such 'upstream' public engagement proposes a dialogic form of two-way communication which also seeks to engage publics in the decision process itself (Macnaghten, 2017) prior to both commercialization or widespread technology deployment (Rogers-Hayden and Pidgeon, 2016).

Public perceptions studies on CDR have often employed broad, generic descriptions of the technology in question, to avoid biasing results according to the framings of the researchers and to avoid 'information overload' for participants (Bellamy et al., 2016; Cox et al., 2020a; Spence et al., 2021; Wibeck et al., 2017). Yet risk concepts are always made sense of in particular socio-economic and cultural contexts, and public perceptions of any new technology are to some extent dependent upon a value judgement as to the level of risk people wish to accept, as well as being conditional upon the precise conditions of its deployment (Pidgeon

and Demski, 2012). It is clear that publics may encounter CDR in a range of different ways, aligned with particular locations, actors, policies and economic frameworks, and therefore perceptions are likely to depend on the specific socio-technical context in which they are developed, incentivised and deployed. Indeed, support for Bioenergy with Carbon Capture and Storage (BECCS) has been found to be inextricably linked to people's attitudes towards the policies used to incentivise it (Bellamy et al., 2019). Gough and Mander (2019) argue that research on BECCS has moved beyond generic notions of 'public acceptability' to provide a more nuanced account of social impacts and contexts; support or opposition cannot easily be predicted, because it depends on when, where, at what scale, and how it is implemented.

Given that people are mainly unfamiliar with ERW (Spence et al., 2021), it is necessary to explore the context out of which public responses are likely to emerge (Macnaghten, 2020), including the way in which information is presented or 'framed'. Framing emphasises certain aspects of a subject or message, thus providing socially shared discourses within which people make sense of new and unfamiliar issues (Spence and Pidgeon, 2010). Quantitative experimental studies have demonstrated that attitudes toward CDR are highly susceptible to the way in which information is framed; for example, people are likely to feel more positively disposed toward techniques which are framed as more 'natural' (Corner and Pidgeon, 2015). Yet qualitative research exploring *how* and *why* people respond to message frames suggests that they will themselves construct competing narratives through which to understand the issue (Brügger and Pidgeon, 2018). The current study aims to examine in greater depth how members of the public respond to a range of different framings of ERW, using a deliberative approach to understand more about why people respond in particular ways.

2 Methods

This study used a deliberative methodology to understand perceptions of ERW in the general population, in the US and UK. For novel innovations such as ERW with low prior awareness, deliberative methods allow participants to learn about the topic over a longer period of time, improving their understanding of technologically complex proposals, and increasing the consideration they give to their responses (Burgess et al., 1988). This study consisted of six workshops: three in Illinois in the United States Midwest, two in East Anglia in England, and one in South Wales. The US and UK were selected for this study because they are currently hosting major research efforts, including field trials, on basalt ERW, as part of general efforts to significantly upscale the carbon removal potential and portfolio in each country. Illinois and East Anglia were chosen because they are major arable agriculture areas potentially suitable for this particular ERW technique, and are currently hosting field trials. This focus on agricultural land and communities does create a particular emphasis on one specific ERW technique in our study, and may therefore have foreclosed other potential framings of ERW (for instance as a forestry enhancing technique). The six locations were chosen to represent metropolitan cities (Cardiff and Chicago), medium-sized towns (Norwich and Champaign-Urbana), and two rural locations. Both the city and town workshops drew participants from the named location only; meanwhile the rural workshop participants lived across fairly large areas comprising villages, hamlets and isolated farms, and travelled to a workshop location in a local village.

All workshops were facilitated by the authors, with no technical expert present (cf. Macnaghten et al., 2015). Each workshop contained 7-8 participants, recruited randomly from the general population. Recruitment was topic blind, with participants invited to attend a focus group on 'solutions to global challenges'. Participants were not intended to be representative of the broader population, but we did aim for a mix of age, gender, socio-economic status and ethnicity. For the two rural groups, we deliberately targeted topic-specific 'interest groups' of farmers or those with connections to farming, in line with methods for studying topic-specific

groups for deliberative research (Macnaghten, 2017) and in line with our decision to focus on agricultural deployment. It is likely that farmers will be key actors for this type of ERW at all scales, and will to some extent determine early markets. However, for reasons relating to problems with recruitment, the "UK rural" group did not contain enough people with links to farming, therefore we had effectively just one farmer's group, in rural mid-Illinois ("US rural").

Each five-hour workshop included a variety of interactive activities to allow participants to learn about potential responses to climate change, the concept of removing CO_2 from the atmosphere, and ERW (Table 1). Workshops were split across two evenings a week apart; this paper reports the results from the second evening, which focused entirely on ERW. Reconvening in this way allowed participants time to reflect on the first day, as the workshops introduced them to a lot of new information (cf. Pidgeon et al., 2013). The first evening focused on climate change and CDR, with posters used to introduce participants to three CDR options of ERW, BECCS, and Direct Air Capture with Storage (DACCS). The results from the first evening, as well as full protocol and stimulus materials, are reported in Cox et al. (2020a).

Day	Activity	Time
1	Introduction, ice-breaker	20 mins
	PowerPoint presentation on climate change, followed by group discussion	30 mins
	Information on three CDR options including ERW introduced via posters. Results reported in Cox et al. (2020a). ERW poster is shown in Supplementary Materials 2.	70 mins
	Participants given a 'homework task' to discuss with friends and family what they learnt on day 1, and invited to look up the techniques on the internet	5 mins
	Questionnaire part 1 (Supplementary Materials 1).	5 mins
2	Discussion of homework task. All participants report back. Results reported in Cox et al. (2020a).	30 mins
	Facilitator explains that this evening will focus on ERW. Participants reminded of the ERW poster from the day before	5 mins
	Participants split into groups of 2-3, according to who they were sat next to. Each group handed a quote on a piece of card, in random order.	
	Discussion in small groups [5 mins]	5 mins
	Small groups read their quote out loud and fed back to the rest of the group. All participants discuss	20 mins
	Small groups changed; people asked to move. Small groups handed another quote on a piece of card, in random order.	
	Discussion in small groups	5 mins
	Small groups read their quote out loud and fed back to the rest of the group. All participants discuss	20 mins
	Reflections, Q&A and feedback	30 mins
	Questionnaire part 2 (Supplementary Materials 1).	5 mins

Table 1: Workshop protocol

The second evening's activity was designed to explore six topics that had emerged out of a series of expert interviews we conducted in 2018 (Cox et al., 2020b). Quotes from the interviews were used to express each topic, presented to represent broadly 'positive' or 'negative' framings of the topic, as shown in Table 2. Participants were told that these quotes were from "experts working on Carbon Dioxide Removal", thereby providing a range of initial prompts for participants to begin to explore ERW in multiple ways. Participants were only presented with the quotes and not told which 'topics' each had been chosen to reflect. Rather than attempting to present ERW in a 'neutral' way, we sought to offer participants an equal number of positive and negative aspects of the technique, positioning ERW in terms of both current and potential future uses, and in

terms of its potential social, political and economic implications (cf. Macnaghten, 2020). Participants discussed quotes in small groups of 2-3, followed by discussion amongst the wider group (Table 1), during which the facilitator sought to enable open discussion amongst the participants, only intervening to ask for elaboration and to encourage participation from all members of the group.

We ended the workshop with a 'reflections' session, followed by a Q&A (placed at the end to avoid biasing the preceding discussions). Participants were welcome to ask questions throughout, but we emphasised that neither of the facilitators had technical expertise, and we probed the underlying reasons for their questions before attempting to answer them (Pidgeon et al., 2013). At the end of both evenings, participants filled out a short questionnaire which provided data on individuals' attitudes separately from the group dynamic and allowed us to track changes in perceptions over time (Supplementary Materials 1). Workshops were video and audio recorded, professionally transcribed, and anonymised; all names given are aliases. The qualitative analysis was carried out using thematic coding analysis, following methods set out in Macnaghten (2017) and Macnaghten and Myers (2004). Firstly, the lead researcher listened to the recordings repeatedly, becoming familiar with the data and using inductive processes to identify key themes. This generated a coding framework, which was used to code the data using N-Vivo software. The inductive development of the themes was informed by ongoing readings of the existing literature, which provided the theoretical basis for interpretation and helped to reduce bias, with constant comparison being made between the coded data, the recordings, and the existing literature.

Topic	Reason for inclusion	Positive or Negative Framing with Quote Used
Agricultural liming	Familiarity is important for risk perceptions (Fischhoff et al., 1978). We wondered whether linking ERW to a familiar, established practice might impact perceptions.	POSITIVE: "We've been adding lime to soil for hundreds of years… ever since the dawn of agriculture pretty much. So this is something that farmers are doing anyway, right, and so now you're talking about simply replacing one material with another that could have potentially the same benefits."
Use of waste rock resource	One of the key drawbacks of ERW is the need for mining large amounts of rock material. However, field trials generally use waste rock resource, and there is a possibility that this might represent a more viable route for the technique (Renforth, 2019). We wanted to see what impact this had on perceptions.	POSITIVE: "The material that we are actually using is the waste from the mine. They haven't figured out a useful rock product to make from it, because it's so finely ground. The guy who's been selling it to us has been attempting to get farmers to use this stuff for many years, and he's very excited because it's now taking off a little bit."
Job creation in developing countries	We wanted to encourage discussion of social aspects such as job creation, which could present a positive argument for deployment of ERW in tropical areas.	POSITIVE: "If you were to do this in places like Malaysia, some of the land there is too hilly to spread the rock by tractor, so you could employ local women to spread the rock by hand. It would create social benefits in the community."
Palm oil deployment	ERW works best in hot, humid areas with nutrient-poor soils (Edwards et al., 2017). Target sites therefore include tropical agriculture of which palm oil is a major type, and there is an ERW trial running on palm oil fields in Malaysian Borneo.	NEGATIVE: "Scientists are in the process of establishing field trials in Malaysia, in palm oil plantations. If we think about the palm oil plantations … they, in themselves, are controversial because you're getting rid of the jungle. Potentially, if we go for Enhanced Weathering on a big scale, you could be doing that." (Negative)
Ocean impacts	ERW may introduce alkaline materials to oceans, which may have ecosystem impacts which are as-yet highly uncertain (Gore et al., 2018). We wanted to explore perceptions of downstream impacts of ERW on oceans.	NEGATIVE: "I'm still nervous about the potential scale of enhanced weathering and the side-effects of it in terms of the impacts on ocean chemistry, which is where all the material ends up really, whatever route you do it."
Big business involvement	Trust is an important factor underlying risk perceptions, and people may be less trusting of organisations with a profit motive (Grove-White et al., 1997). We wanted to explore whether business involvement in research would impact people's perceptions.	NEGATIVE: "Who's proposing it? Who's going to be the winners and who's going to be the losers? I'm sceptical about big business funding research into these things. They don't care about people, they don't care about the environment, they're only concerned about profit."

Table 2: Quotes provided to participants for discussion

3 Results

In our research design, we set out to explore the six topics shown in the left-hand column of Table 2, as they had emerged as key areas regarding ERW from our expert interviews. However, it became clear in our analysis that participants had moved beyond simply discussing the topics we presented – rather, participants were considering ERW in terms of the broad contexts in which they envisaged it being researched or deployed, according to their own personal experience. In this way, participants actively challenged the framings introduced by the research team via the quotes, to introduce their own interpretations of the ways in which they envisaged ERW existing in the real world, including disputing and rejecting the researchers' positive/negative evaluation of the quotes. In our thematic analysis of the qualitative data, we identified four sets of participant generated frames: a geographical frame, a social frame, an economic frame, and an environmental frame. These were identified because of the way in which they cut across the topics, in all cases appearing consistently throughout the discourses in the workshops. In this way, our deliberative approach enabled us to go beyond experimental studies which seek to test the impact of pre-defined frames on attitudes (e.g. Corner and Pidgeon, 2015; Wolske et al., 2019), instead allowing our participants to both challenge and extend the pre-defined frames by exploring a range of ambivalences, limits and contradictions, while also re-interpreting them in terms which made more sense to themselves (cf. Brügger and Pidgeon, 2018).

3.1 Geographical frames

During week 1 of the workshops, participants generally assumed that the deployment would be local to them, or at least in a geographical context with which they were familiar. The ERW poster we used to introduce the technique in week 1 (Supplementary Materials 2) gave no information about deployment locations. In week 2, participants responded to the quotes by discussing the geography of deployment, which had seldom been mentioned previously. Participants also asked questions about existing field trials, which at that time included Illinois (US), Sabah (Malaysia), Queensland (Australia), and Norfolk (UK).

Most noticeably, thinking about ERW in a more global context seemed to spark assumptions of increased scale. Echoing our expert interviewees, participants often assumed that ERW would be spatially extensive and would raise ethical dilemmas over the use of land: *"At the end of the day, you're gonna have to scale this up massively. I know the last resort would be to use the rainforest, but (…) there's gonna be a point where they might have to say, "Oh God, you know what, we have to use that land." (Peter, UK city).* The geographical frame was linked tightly to the social frames discussed in the next section: participants framed issues relating to 'location' much more broadly than just physical geography.

Importantly, participants' geographical frames were not limited to the application sites. In our expert interviews, energy requirements from mining and crushing the rocks were mentioned frequently, but few experts mentioned transport. Yet several participants raised this as their main concern, possibly because lay publics are more familiar with transport emissions: *"Does it absorb more CO_2 than it uses to transport the minerals, which is one of the largest emissions that we have?" (Lucas, US town).* Our quote about using waste mine materials was intended as a positive framing on energy requirements, yet for our participants, this additional information did not ameliorate their life-cycle concerns. *"Where is the mine?..." "So then they've got to transport it 100 miles before it ever gets onto the field?" "Like my daughter said, one solution nine problems…" (Ashleigh, Elizabeth and Shaun, UK rural).*

The geographical discussions revealed that familiarity was an important factor, with many participants preferring the idea of deployment in western agricultural contexts, particularly because of familiarity with the existing farming infrastructure which would be required. Familiarity can be an important determinant of risk perceptions, particularly if people have become accustomed to a situation without adverse consequences (Fischhoff et al., 1978). Trust also played a role, with US participants viewing the University of Illinois (running basaltic ERW field trials at Champaign-Urbana) as a familiar, trusted actor. That said, participants did not always perceive familiarity in the way we had expected, challenging and reinterpreting the framings introduced by the research team. The quote about agricultural liming (an established technique) was intended to spark perceptions of familiarity, yet it produced the opposite response in many instances, with participants asking, *"if it ain't broke why fix it?" (Dave, UK city, and Claudette, US city)*. We expected agricultural familiarity to lead to heightened benefit perceptions in the two "rural" groups, but the opposite occurred in the "UK rural" group, who were very concerned about activity in their local area, and saw our workshop as an attempt to legitimise a deployment decision which had already been made: *"Are they thinking of testing that here then? [Facilitator agrees] That's where I thought we were going [sardonic laughter]" (Shaun, UK rural)*. By contrast, the farmers in the "US rural" group expressed favourable views about using existing farming practices: *"Culturally, that's familiar to us – the methods that we farm. That's initially what I thought when I read this was that it sounds like a liming process. And there's your branding, instead of mine waste, you could call it Platinum Lime [laughter]" (Randy, US rural).*

In the questionnaire at the end of week 2, we noticed that the majority of participants had increased their ERW score from the previous week, indicating that their feelings toward ERW had become more positive over

that period of time (Table 3). In the open-ended questionnaire responses, the most common reason for this was 'feeling more informed', with participants saying that ERW seemed more 'viable' or 'feasible' by the end of the workshop. Feeling more informed is a common response at the end of such deliberative workshops, but this should not be taken to mean that simple information provision 'improves' attitudes. Decades of research demonstrates that complex processes of interpretation and elaboration, alongside judgements of who and when to trust, are typically at play in such contexts (Sturgis and Allum, 2004). Our own interpretation of the questionnaire results is that providing the most basic explanation of ERW (as in Week 1) without then allowing space for the extended discussion and reflection around the multiple ethical issues and processes involved (as in Week 2) may have left people initially feeling uncertain or uneasy about the idea. In week 2 some degree of that wider uncertainty then became resolved for participants through the interaction with others present.

Unfamiliar techniques relied on assurances of safety from scientists and experts, which were often received with some scepticism: *"It seems to me that the [air quotes] 'scientists' are saying, you've been using lime all these years, so what's wrong with using these materials that we're going to spread. But for centuries, we know what's in the lime. Ain't nobody never fell out and died from me using the lime. So, I don't know what's going to happen to these new materials." (Camille, US city).* In the questionnaire, some workshop groups reported feeling generally more positive toward ERW than others at the end of the extended discussion in Week 2. In the "UK city" group (Cardiff), where the increase in scores was most noticeable, participants tended to express more positive sentiments about the workshop process and science in general, and thus may have responded more positively to the additional information provided by facilitators. We found the opposite in the "US city" (Chicago) and "UK rural" groups, where many participants expressed scepticism about the purpose and benefit of the workshop, and correspondingly had higher numbers of participants who decreased or did not change their scores.[1]

Group	N	W1 mean (SD)	W2 mean (SD)	Difference	Increase	Decrease	No change
US metropolitan city (Chicago)	8	2.88 (3.04)	5.00 (3.46)	2.12	5	0	3
UK metropolitan city (Cardiff)	8	2.13 (1.55)	7.38 (2.33)	5.25	8	0	0
US town (Champaign-Urbana)	8	4.63 (1.69)	6.13 (1.96)	1.50	7	1	0
UK town (Norwich)	8	5.63 (1.51)	8.13 (0.84)	2.50	8	0	0
US rural	7	5.00 (2.58)	7.00 (1.53)	2.00	6	1	0
UK rural	8	4.13 (1.96)	5.00 (2.39)	0.87	6	2	0
All groups	47	4.04 (2.35)	6.43 (2.44)	2.39	40	4	3

Table 3: Mean ERW questionnaire results, week 1 vs week 2, and no. of participants who increased/decreased their score. Participants (n=47) were asked 'How do you feel about ERW?' on a 1-10 scale of 'very negatively' to 'very positively'.

3.2 Social frames

During these discussions about the geographical context in which ERW might be used, the discourse went far beyond just the physical location of the proposed deployment, raising social concerns generated by consideration of the technique in a less familiar cultural context. Participants drew on attitudes and beliefs relating to social justice and equity, which had been less prevalent previously. Kieron (UK town) suggested that, *"The powers that be won't want to draw too much attention to that social aspect, [because it] would have a negative connotation if they're trying to sell it as a positive idea."*

The 'job creation' quote, intended to be positive, often sparked dismay and disbelief. Participants drew analogies with slavery, Native American exploitation, medicine testing in developing countries, and overseas call centres, framing the idea as a problematic social justice issue. One participant likened research in tropical

[1] The mean increase in Chicago was influenced by one individual who increased their score considerably, but did not state their reasons for doing so in the open-ended comments.

areas to the Tuskegee experiment in the 1930s, a shocking example of scientific misconduct in which 400 black men with syphilis were inadequately treated without informed consent. The analogy was used to express strong justice concerns: *"Are they [the ERW researchers] more concerned with this or with the health of their community, knowing that the community probably doesn't have the voice?" (Raven, US city).* There were also questions regarding the process of spreading the rock dust by hand, with participants asking, "*Why would you continue using those very outdated techniques? You have to move with the times!" (Elizabeth, UK rural).* Jack (US town) said, *"I don't see much 'enhanced' in this enhanced weathering!"* Yet participants disagreed over whether it is permissible to assert western ideals of social justice onto other geographical contexts, debating this issue with nuance and reflexivity regarding their own cultural bias. Discussion of tropical deployment also made some participants more favourable to the idea of deploying ERW in their local area: *"I would feel a little better about it if they did have protective gear and if they were making a good wage…" "I think New York just raised to $13 an hour for the minimum wage. So, if they were to do this in New York…" (Tiara and Grace, US town).*

We found considerable differences between the "US rural" farmer's group and the other five groups, with farmers displaying a high degree of faith in expertise and the scientific process. Rather than a dismayed response to the 'social benefits' quote, the farmers simply assumed that the quote must be from a more informed source: "*Evidently, that's how it works in Malaysia, I guess…" "…We're not really from Malaysia, I would have to assume it's somebody who knows more than I do about the society." (Skyler and Bill, US rural).* This illustrates an important point for future public engagement: professional actors with experience of working with climate or crop science might respond positively to aspects that lay publics receive very negatively. It is worth noting that self-selecting bias may have played a role here, despite the topic-blind recruitment technique. In the words of Randy: *"I think you may have an atypical group here, people who are probably attracted to this are those who understand the research you're trying to conduct and might have more appreciation for science in general*". Eli reported back on a conversation he attempted to have with his father (also a grain farmer): *"I mentioned the CO_2 and his immediate response was, 'Higher CO_2 means better crop yields', then he turned on power tools and was like 'get the hell out'" [laughter].* For the purposes of early uptake of ERW, however, the perspectives of interested and engaged farmers are much more relevant.

3.3 Economic frames

In all six groups, the quotes sparked considerable debate about the role of funding by for-profit entities. Perceptions of the role of the private sector were complex and ambivalent: in some cases, trust was lower where profit motives were involved, with concerns about transparency and that businesses might be *"beholden to their shareholders" (Emma, UK city)* rather than the public interest: *"It's not automatically a bad thing but it's reasonable to think that business has their own priorities of why they're funding the research." (Jack, US town).* In the US, the for-profit healthcare sector was used frequently as an example of this. Yet in all groups, participants countered that profits are important for spurring investment in research and deployment: *"It's just a bit of naivety in the sense that business is bad..." (Randy, US rural)*;*"I don't think anybody would go into this if they didn't care about the environment at all" (Jim, UK town).* Interestingly, the US participants saw little separation between the public sector, private sector, and scientific research: *"Who of our legislators are they connected to? Who is influencing them? There's never a clean slate; you're always going to be connected with someone who is investing money in this company or whatever" [sounds of agreement] (Nicky, US city).*

The participants' framing of ERW in economic terms was often aligned with discussions around equity, mirroring the "rich get richer" narrative found by Macnaghten et al. (2015), particularly in the "UK rural" and "US city" (Chicago) groups: *"We think obviously it's going to be the big corporations… they're going to take only the people with money and get into the boat and all the rest stays behind" (Mateo, US city).* ERW was seen as more likely to perpetuate or increase existing inequalities, rather than ameliorate them. A study by Carr and Yung (2018) on perceptions of climate engineering in communities vulnerable to the effects of climate change, found very

similar discourses to these groups, including that climate interventions should be responsive to local needs rather than for the benefit of distant elites. Rural Norfolk and Chicago are not commonly viewed as 'vulnerable', yet participants in these groups clearly saw themselves as vulnerable to the potential downsides of novel climate interventions.

The farmers in the "US rural" group generally took a far more techno-economic approach to appraising ERW across the six quotes, framing it in terms of cost and feasibility, whereas the other groups tended to prioritise ethics and sustainability. For example, when asked whether they would prefer new mines or greater transport distance, the non-farmer groups discussed social and environmental implications, whereas the farmers' response focused on cost: *"Got to be economic…" "Too many unknowns there. What's it cost to build a new mine versus cost of transport?" "I've got a feeling transport is probably going to be cheaper than a new mine..." (Bill, Henry and Randy, US rural).* Alison, the one participant in the "US rural" group with less of a direct connection to farming, was fairly quiet throughout, yet when she did speak, her discourse was similar to the non-farmer groups, suggesting that the farmers were responding as 'economic' or 'professional' actors rather than 'civic' ones. The need to ensure a viable livelihood lies at the core of a farmer's professional activities, therefore in responding as professional actors it is to be expected that techno-economic considerations would be at the forefront. Meanwhile in the "UK rural" group, originally intended to be a farmer's group, participants did not display many strong connections or interest in farming; their discourse was more similar to the four town/city groups, with participants appearing to respond as 'civic' actors rather than professional ones.

3.4 Environmental frames

ERW at scale would interact with several major ecosystems: agricultural land, watercourses, oceans, and potentially tropical forests. Participants' perceptions of ERW were, to some extent, dependent on the environmental context within which they saw ERW as operating. In particular, oceans were mentioned frequently across all groups, with ERW eliciting negative affective associations (i.e. instinctive negative feelings): *"I just don't like it. I just think it would affect, like, the sea…" (Ruby, UK city); "I just think it's quite concerning myself, personally. I don't like the idea of it. Really don't." (Charlotte, UK rural).* The environmental discussions suggested that mineral formation in the soil is likely to be perceived more positively than CO_2 sequestration in oceans and watercourses. Yet importantly for ERW communication, participants diverged when considering the impact of adding alkalinity to oceans and watercourses. Some were concerned about unintended consequences such as making watercourses "too alkali" and messing with nature: *"I know that will probably reduce the acidity. Are we changing the wildlife? Are we changing our structure of trees, reeds that all the wildlife need to live in? They're living in that water now perfect." (George and Shaun, UK rural).* Yet, despite the 'negative' framing of the quote, others became much more favourable toward ERW as a result of this information; these tended to be participants who expressed more positive sentiments about the workshop process and science in general. Thus in terms of wider science communication, attempts to communicate environmental benefits of ERW may sometimes help to address negative perceptions arising from considering the technique in an environmental frame, but only amongst those who are receptive to assurances from experts in the first place.

We found similar discourses when discussing the rainforest. Again, affect-laden discourses were strong: *"Everything natural in nature, it seems like everything is just gonna be, I don't know, robotic. It's just sad, isn't it?" (Denise, UK city).* Wildlife was mentioned emotively and was conceptualised as vulnerable and in need of protection, e.g. *"Destroying homes for little monkeys" (Jane, UK town).* Concerns about palm oil were especially strong for those participants who voiced pro-environmental values elsewhere in the workshops. When informed of the fact that the palm oil plantations might already exist, some participants expressed more positive positions *("Well, the plantations that already exist are done, you know what I mean? I guess you might as well do it" [Bill, US rural])*, whereas others reacted against perceived greenwash *("I wouldn't want them to be able to say, "Well, it's okay cos we're doing enhanced weathering" [Amy, UK town]).* Cultural specificity is also important: US participants were less

aware of and less negative toward palm oil, and stated that they are mostly familiar with domestic corn oil, whereas palm oil in the UK has been the subject of high-profile eco-consumerism campaigns. In both countries though, participants perceived certain environments or ecosystems – notably the oceans and rainforests – as being particularly special, vulnerable, and worthy of protection; notions of interference in these environments aroused feelings of loss and grief similar to those identified in research on coral reefs, conceptualised as 'iconic' environments (Marshall et al., 2019).

Despite the dominant techno-economic framings in the "US rural" farmer's group, the environment was extremely important to the farmers, with concerns that ERW would be incompatible with conservation agriculture techniques such as no-till. Scepticism about watercourse impacts was present in all groups but was viewed from a more technical angle by the farmers: *"We've got a lot of concern now about how much phosphorous and phosphate we're sending down the Mississippi, now we're going to be adding more? What's this going to do to our environment?" (Emmett, US rural).* The farmers were keen to see quantification of costs, risks and benefits, and the lack of accurate numbers at this stage may be problematic for early uptake by farmers, at least without considerable public subsidy.

4 Discussion

Our study aimed to explore public perceptions of Enhanced Rock Weathering using basalt on agricultural land, in response to six topics of interest we had identified from expert interviews. During the discussions, participants moved beyond simply discussing the issues presented, using their own personal experience to consider ERW in terms of the broad contexts in which they envisaged it being researched or deployed. In particular, considering ERW in a non-western context such as tropical agriculture had a major impact on the frames which participants used to discuss and understand the technique. Thinking about ERW in a global context generated assumptions of increased scale, which in turn appeared to heighten concerns about detrimental social and environmental impacts.

Participants expressed concern at the prospect of deploying ERW in distant tropical environments, with some saying they would prefer deployment in their own country. This seems contrary to what might be expected based on construal level theory which poses that abstract risks are perceived as more distant, with some research showing preference for new technologies to be situated elsewhere (Clarke et al., 2016; Trope and Liberman, 2010). In this case however, considering ERW in a more distant geographical context raised *additional* justice and ethical concerns regarding workers employed overseas, impacts on sensitive ecosystems, and the use of palm oil plantations. The discussions raised in the groups are not unexpected when reflecting on the justice literature and the idea of 'environmental dumping', where vulnerable communities and groups are seen as unfairly treated and may get little choice regarding application of this technique (McLaren et al., 2016). The fact that the globalisation of ERW was particularly problematic for participants has implications for the upscaling of novel CO_2 removal techniques. Our participants identified a tension between the way in which ERW is currently implemented (at very small scale, mainly in research institutions) and the globalised way it needs to be envisaged in order to constitute a genuinely impactful climate mitigation technique.

We found that concerns about 'messing with nature' became more prevalent when participants started considering ERW in relation to particular ecosystems, especially oceans and the rainforest. Previous research shows that perceptions of 'messing with nature' are a particularly strong predictor of attitudes toward CDR (Corner et al., 2013; Wolske et al., 2019). Yet conceptions of what constitutes 'natural' are fuzzy, dynamic and

culturally embedded (Bellamy and Osaka, 2020); our participants differed from those in Corner et al. (2013) in that they were generally unconcerned that agricultural applications would constitute 'messing with nature'. In this case, it appears that participants' ecological concerns may be more related to perceptions of loss and grief regarding 'iconic' environments such as the rainforest and the oceans (Marshall et al., 2019). This is supported by survey work showing that negative affective associations, particularly regarding environmental impacts, are one of the key factors influencing risk perceptions of ERW (Spence et al., 2021). This notion of 'iconic' environments, which has parallels with the concept of protected or 'taboo' trade-offs discussed in the cultural ecosystems services literature (Chan et al., 2012), may be a useful concept for understanding public responses to CDR more generally, as a potential source of amplified risk perceptions.

Participants' sentiments about the research process and science in general were an important factor in how they responded to additional information. Responses to information are influenced by people's perceptions of the person or institution communicating that information, and the social commitments or value positions implied by that information, which may be more important than the actual technical content of the information (Pidgeon et al., 2009; Siegrist, 2021; Wynne, 1992). Participants who expressed scepticism about scientific research and expertise appeared to view the workshops as a legitimisation exercise for decisions which had already been made (see also Zakhour, 2020), thereby undermining any expert assurances of safety and environmental benefit. It is sometimes assumed that communicating the benefits of a novel technique will improve public 'acceptance'; yet this assumption does not pay enough attention to the dynamics of trust and the diversity of publics (e.g. Cass et al., 2010).

One oft-stated response to this is to call for more public engagement, particularly in the early stages of technology development. Indeed, discussing ERW in the context of field trials already underway made many of our participants feel more comfortable with the idea, which could be because it made it seem more 'real'. The majority of participants reported feeling more positive about ERW by the end of the day 2 workshop, and it appears that the key drivers of this were heightened familiarity, lower uncertainty and 'feeling more informed'. Thus the use of techniques to make CDR more 'real', such as communication of real-time project data and cutting-edge Virtual Reality technology, could be an important way of engaging participants more deeply about such unfamiliar ideas. Importantly, we did not just provide information about ERW benefits – we provided a space in which people could learn about ERW from the research team and from each other, in a two-way process of discourse and deliberation, during which we endeavoured to ensure that people felt that they were being listened to. However, this should not be taken to imply that views about any technology will inevitably become more positive over time simply if such process conditions are met. Change over time also depends upon the particular topic under consideration and the available frames, some externally derived from relevant social and geographical contexts, within which the issue is interpreted by dialogue participants. The precise processes through which views can change over time in deliberative fora remains an important and relatively understudied research topic in science and risk communication (Pidgeon, 2020).

Whilst project-level engagement is valuable, it may not be sufficient for CDR techniques with global ambitions. Effective governance of CDR upscaling may therefore require a more systematic approach to public engagement. One proposal would be to implement a series of Citizens' Assemblies on CDR, at multiple scales including local, national, and cross-national. Dialogue-based instruments such as Citizens' Assemblies can help to integrate citizen viewpoints into governance processes (Devaney et al., 2020), which may be particularly useful for potentially controversial techniques such as CDR in a context of climate urgency. To live up to that promise, however, it is important that public dialogue forms part of a meaningful route to influencing governance processes, in ways which genuinely commit to act on the resulting recommendations. The literature on public engagement with science has highlighted a longstanding and recurrent gap in genuine

outcomes flowing from dialogue, where those in positions of responsibility fail to act fully upon recommendations (Bickerstaff et al., 2010). Otherwise, such processes risk retrenching existing power dynamics, and reinforcing the view – aired by several of our workshop participants – that deliberative efforts are merely a legitimisation exercise for decisions which have already been made. In addition, there is a clear gap in both understanding and engagement when it comes to the views of non-Western citizens, with little research on this topic, partly stemming from logistical and language barriers and capacity issues (cf. Delina, 2021). In addition to filling this gap by pursuing research overseas, existing public engagement and dialogue processes could consider involving non-Western citizens to give them more of a voice in discussions which assume international-scale deployment.

Clearly, our choice of quotes to present will have had an influence on the frames that participants ultimately used to debate the issues involved. However, we also provided initial generic information on ERW via a poster in week 1; therefore the responses to the quotes may have also in part reflected a reassertion of these earlier discussions. That said, our qualitative data demonstrated that new discourses did arise in response to the quotes alongside genuine reflexivity from participants, including continual questioning and challenging of their own and others' responses. By the second evening, the groups may be expected to have formed more trust amongst themselves, enabling them to understand and express their feelings more fully and to shift their views (Burgess et al., 1988). Indeed, participants who had been reticent in the earlier sessions participated much more as time went on, including challenging others' positions, demonstrating the value of extended deliberation sessions. Another potential limitation of our use of quotes is the fact that participants considered the six quotes in sequence, necessitated by the small group size, therefore responses will have been influenced by previous discussion. We attempted to control for this by introducing the quotes in random order, but it still makes it challenging to compare frames with one another. For this reason, our analysis focuses on cross-cutting themes which were not necessarily limited to one quote.

This study used deliberative workshops to study public perceptions of ERW in Illinois, England and Wales. We set out to explore six topics of interest to ERW, which emerged from a prior series of expert interviews. Our findings illustrate how members of the public are perfectly capable of debating a complex social-technological-environmental issue, both elaborating upon and going beyond the framings initially suggested by the researchers, when given the appropriate time and resources to do so (Pidgeon, 2020). In particular, thinking about ERW in a global context heightened concerns about detrimental social and environmental impacts, demonstrating that it is not just local populations who might be uncomfortable with imposed solutions. We also found that concerns about 'messing with nature' became more prevalent when participants considered ERW in particular environmental contexts such as oceans and the rainforest, and we propose the notion of 'iconic' environments as a potential source of amplified risk perceptions amongst publics. Participants' sentiments about research and expertise were an important factor in how they responded to additional information, and farmers responded differently, strongly emphasising techno-economic frames. We conclude that the upscaling of ERW and other CDR approaches may require more attention to the equity implications of globalised CDR, alongside a more systematic approach to citizen engagement. Such engagement could take place through the implementation of Citizens' Assemblies at multiple scales, aligned in a meaningful way to political and governance processes which commit to act on the resulting recommendations.

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