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Question-Led Innovation: Public priorities for enhanced weathering research in Malaysia

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ABSTRACT

When upscaling novel techniques for Carbon Dioxide Removal (CDR), public attitudes are crucial, yet there is a serious lack of social science research outside of Western nations. CDR research can clearly benefit from maximising inclusion and opening up to diverse perspectives, including those of local communities, and ideally should involve public insight into the questions we should be prioritising. This paper reports results from a major deliberative study on public perceptions of CDR in Malaysia. We demonstrate a novel, transferrable methodology called "Question-Led Innovation", in which lay public and local stakeholders are empowered to ask actionable questions on a novel intervention or innovation. These questions are then used as the basis for identifying priorities for future scientific research. We apply the methodology to a case study of CDR via Enhanced Rock Weathering (ERW) on tropical palm oil agriculture in Sabah. We find that much of the current research on ERW is actually in-line with what our participants most wanted to know about, particularly regarding the rock resource and its sources. Nevertheless, significant knowledge gaps remain, particularly on life-cycle CO_2 emissions and sequestration, and impacts on aquatic life. Many questions also related to socio-economic factors, particularly around governance, regulation, and cost, therefore we argue that such topics should be a priority for future research. Embedding Question-Led Innovation into an ongoing programme of scientific research shapes the future of ERW research to prioritise questions which matter most to people on the ground.

1. Introduction

Research on novel innovations emphasises the importance of engaging with diverse groups of people – including publics, communities, and wider society – at an early stage (Pidgeon et al., 2013, 2017; Wilsdon and Willis, 2004). Different groups may have varying perspectives and interests (Pimid et al., 2022; Etchart, 2017) and this is particularly important in a diverse and multicultural society such as Malaysia (Diansyah et al., 2022). In particular, there is increasing appreciation of the value of diverse forms of knowledge, including non-experts who can themselves be the source of 'better arguments' (Rizal and Nordin, 2022; Kamarudin et al., 2022; Ioki et al., 2019), and as a guide for the development of effective governance strategies (Saba et al., 2021). However, research on public perceptions of novel climate interventions such as Carbon Dioxide Removal (CDR) is notably lacking outside of Western nations (Spence et al., 2021; Waller et al., 2024). In practice, this means that mitigation pathways often include scaling-up of CDR in precisely the regions where research on public perceptions is absent (Smith et al., 2023; Strefler et al., 2021). Cultural differences matter, and Western understandings of public perceptions of climate topics cannot be unproblematically applied elsewhere without undertaking empirical research (Leiserowitz et al., 2023; Thaker et al., 2020;

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Baum et al., 2024). Rayner et al (Rayner et al., 2013). also note a long history of the developed world exporting hazards to developing nations, therefore governance of research activity (field trials and experiments etc.) should seek to engage potentially affected publics and interested parties in an early and locally appropriate manner.

There are many reasons why we might wish to understand public attitudes toward climate interventions. However, a valid criticism of such work is that the outcomes often fail to have impact outside of a small group of social scientists, leading to a persistent failure to 'act on' otherwise valuable social science insights (Stilgoe et al., 2013a; Macnaghten, 2020). Simply moving public engagement 'upstream' in a technology's development timeline does not overcome problems of power and knowledge deficits, nor does public engagement alone always lead to reflexivity on the part of technology developers (Pidgeon, 2020; Ng et al., 2023; Riggs et al., 2021). Upstream engagement may aim to 'open up' to diverse perspectives (Stirling, 2008; Lehoux et al., 2020), and to maximise inclusion (Stilgoe et al., 2013b), but this only works if the mechanisms are in place to enable space for acting on the concerns identified (Datta, 2011). This is the challenge we seek to tackle in this paper, by setting out a novel, transferrable methodology called 'Question-Led Innovation', and demonstrating it using a case study of a novel innovation for Carbon Dioxide Removal.

Terrestrial enhanced rock weathering (ERW) is a strategy for removing carbon dioxide from the atmosphere, based on amending soils with crushed silicate rocks to accelerate removal of CO_2 (Beerling et al., 2020; Lewis et al., 2021). Crushing the rocks increases the grain surface area to accelerate weathering rates (Baek et al., 2023), whilst potentially providing co-benefits such as improved soil fertility and increased agricultural production (Kelland et al., 2020; Kantola et al., 2023; Nair et al., 2022). However, significant uncertainties remain about the technique and its ability to sequester CO_2 and deliver co-benefits. One major appeal of ERW is that it can operate synergistically with existing agricultural land uses, thus avoiding pressure on land resource compared to some other CDR proposals (Beerling et al., 2018, 2024): particularly relevant for techniques in tropical areas, where land-use conflicts are well-documented (Wook, 2019; Ratner et al., 2017; Andersen et al., 2016). However, operating ERW with existing land uses may raise additional questions regarding the interaction with existing economies, communities, publics, and the surrounding environment (Baum et al., 2024; Low et al., 2024). Interest in ERW from both academia and the private sector is growing extremely fast, with large numbers of new small-scale private-sector projects appearing, and one of the most significant carbon offtake agreements in the history of the global voluntary carbon market in 2023 (Frontier, 2023). However, in terms of both natural and social science, the ERW literature is tiny compared to many other CDR techniques (Smith et al., 2024).

With 30 million hectares (ha) of commercial and smallholder plantations in 2022 globally, oil palm is a clear sector of interest for ERW, and around 25 % of global palm oil is produced in Malaysia (Ritchie, 2024). Our study is located in the Malaysian state of Sabah on Borneo island in the South China Sea, where 1.51 million hectares of land is dedicated to palm oil production (MPOB, 2024) and near to ongoing field trials on a palm oil plantation in eastern Sabah (see Larkin et al (Larkin et al., 2022)., and Methods: Field Trials). Oil palm's popularity in the area stems from its high yields per unit land area compared to other oil-producing crops, particularly on low fertility acidic soils (Ong et al., 2011; Meijaard and Sheil, 2019), plus financial support received in the 1960s as part of efforts to diversify Malaysia's agricultural sector (Courtenay, 1984). The warm and high rainfall tropical climate regions of Malaysia are ideal for chemically accelerating rates of silicate rock weathering (Edwards et al., 2017). The potential for ERW to improve soil structure on depleted tropical soils may also make it particularly relevant for the palm oil sector in SE Asia.

1.1. Question-led innovation methodology

The goal of this research is to understand public concerns and salient issues for ERW research in Sabah, Malaysian Borneo. In doing so, we ask: what are the *questions* we should be asking when researching, developing and upscaling ERW? What are the priorities for research, as defined by publics in critical tropical locations such as Sabah? In this way, we go beyond work on baseline understandings of perceptions of ERW (e.g (Baum et al., 2024; Low et al., 2024; Cox et al., 2020a).) to elicit detailed and nuanced information on what matters to local communities, and most crucially, to encourage scientists to *act* upon this information. We propose a new methodology called 'Question-Led Innovation', which uses the questions asked by lay publics and local stakeholders as the basis for identifying priorities for future research across multiple disciplines including the natural sciences. Our goal is to show that research with local communities can inform discussions concerning the priority research questions around ERW which matter to people on the ground. In doing so, we aim to challenge the notion that knowledge flows 'from the Global North to the Global South' (critiqued by Giwa, (Giwa, 2015)), toward valuing the knowledge and insights of Malaysian publics in determining the future of ERW research there.

The Question-Led Innovation method builds on the wide range of longstanding methods and techniques for public engagement that exist (see Rowe and Frewer (Rowe and Frewer, 2005)); particularly participatory engagement, of which other types include citizen's juries, action planning workshops, and consensus conferences. In addition, the process owes much to methods for 'upstream engagement', i.e. public participation which takes place early on in a technology's development and before the establishment of firm public attitudes or social representations about an issue (Wilsdon and Willis, 2004; Pidgeon and Rogers-Hayden, 2007). The intention is that Question-Led Innovation should sit within a wider deliberative workshop, ensuring that participants have the tools and information available – and the inter-group trust built between participants – to enable meaningful discussion of complex, nuanced and novel topics.

We use data from five day-long deliberative workshops on public perceptions of ERW. The workshops as a whole employed participatory engagement mechanisms of controlled selection, facilitated elicitation, an open response model, and flexible information input from the researchers (cf (Rowe and Frewer, 2005).), alongside upstream engagement techniques for engagement in situations of low prior awareness (cf (Pidgeon and Rogers-Hayden, 2007; Macnaghten, 2010).). Then, at the end of each workshop, participants were invited to 'ask the expert' any questions they had, and to elaborate the reasons for their questions alongside their general thoughts and feelings about the technique and about carbon removal in general. During this process, the expert was asked to leave the room, in recognition of the power dynamics that the expert's presence could create, and to encourage participants to speak freely. This mirrors the expert questioning method developed and used by Pidgeon et al. in the very first embedding of upstream public engagement in a formal 'responsible innovation' process for a climate modification technology (Pidgeon et al., 2013). In this paper, we present the questions and key themes which emerged, including participants' underlying desires, concerns and priorities, and we respond to these questions with insights from natural science expertise on ERW. In doing so, we identify key gaps in knowledge for ERW from a public perspective, highlighting public priorities for future research.

2. Methods

First, a brief note on our positionality. We are an interdisciplinary team comprising a Malaysian field researcher, three social scientists from the United Kingdom (UK), a Malaysian social scientist, and a UK-based biogeochemist. As such, our team is asymmetrical in terms of representation, and the Western lens will undoubtedly impact the way in which the research was designed, implemented, and analysed. In this

paper we prioritise references from Malaysian scholars, as a first step toward correcting this imbalance, although in some cases this was not possible due to research gaps. There is also debate over whether Global North researchers should ever lead research in the Global South (cf (Sovacool, 2023).), with some arguing for the need for more North-South partnerships (Delina, 2021), as we have sought to foster here. It is also worth noting that everyone involved in this study has some degree of 'outsider' status in the communities where we conducted our research (Giwa, 2015), due to our job status (e.g. none of us are landowners or agricultural workers), cultural backgrounds, or language. Even when conducting research in Malay, our conversations within the research team whilst in the field were all conducted in English, thus potentially reinforcing our outsider status with our participants. In addition, this may have created certain power dynamics in our workshops, with one of the biggest facilitation challenges being the tendency for participants to hold back views seen to contradict the power-holding facilitator (Gailing and Naumann, 2018). As with all deliberative work, questions of power and responsibility need continual reflection and questioning (Macnaghten, 2020). Ethics permission for the study was given by the Cardiff University ethics committee in the UK following full scrutiny. In addition, we received research approval from the Malaysian Ministry of Economy. To ensure confidentiality, all data was fully anonymised, and all participant names used in this paper are pseudonyms.

2.1. Workshops

We conducted five day-long deliberative workshops with local residents, in five locations in June 2023. The first three were in Kota Kinabalu (KK), the capital city of Sabah, with two groups of randomly-recruited members of the public, and one group of specialists. The public workshops were advertised 'topic-blind' through a flyer and QR code distributed through local networks on social media, using the Instagram page, website, WhatsApp and Facebook for the South East Asian Rainforest Research Partnership [SEARRP]). We aimed for a balance of age and gender, but the latter proved difficult to achieve, with more women than men in most of the groups (Table 1). Participants in group 3 represented relevant government agencies, industry and non-government agencies that have some current works or knowledge on climate change or CDR in Sabah, termed 'specialists' here for ease of distinguishing from the other groups. They were recruited by emailing selected contacts with a formal invitation letter detailing the purpose of the workshop (not topic-blind).

The remaining two groups were conducted on the other side of Sabah, in the town of Lahad Datu (LD) and the nearby village of Kampung Tampenau. These locations were chosen because Lahad Datu is one of the largest oil palm plantation landscapes in Sabah. Kampung Tampenau is a relatively accessible village which is involved in agriculture including oil palm, and familiar with SEARRP, which was important for practical recruitment reasons. Participants in these groups were recruited through the neighbourhood association network using WhatsApp, and via the village head of Kampung Tampenau.

The workshop was designed via three pilot studies, two in the UK with Malaysian students and one in Malaysia with participants from the general public, as well as being informed by workshops on similar topics conducted previously in the United States (US) and UK (Cox et al., 2022, 2020b). Each workshop was 5 hours in length, containing several components, several of which are not analysed in this paper; however, since the relevant activity for this paper occurred near the end of the day, it is worth reporting the whole process, to understand some of the workshop context and framings preceding the gathering of the data reported here. The full workshop time-plan is shown in Supplemental 3.

The first sessions revolved around local land use issues (proposed by participants), climate change, and climate policies in Malaysia. The second session (again, not analysed here) used three posters around the room to present three techniques for carbon removal: reforestation, bioenergy with carbon capture and storage (BECCS), and enhanced rock weathering (ERW). These techniques were chosen because they represent likely foci for carbon removal in Malaysia. This activity is where participants first encountered ERW, and will have contributed significantly to their opinion-forming; a copy of the poster is available in Supplemental 4. Participants wrote sticky notes anonymously on the posters which were then discussed as a group; this provided the initial discussion of ERW, and participants' initial chances to voice their opinions, on ERW as well as the two other carbon removal techniques. Finally, participants were presented with more detail on the three techniques, in the form of cards showing major 'advantages' and 'drawbacks' of each technique, from the literature (Supplemental 4). Data from these sections of the workshop is being analysed and written up separately.

The final workshop session is the focus of this paper, and focused entirely on ERW and its role in addressing climate and broader goals. First, participants watched another short presentation on ERW, which also introduced the field trials happening in Lahad Datu area (Supplemental 4). Participants were then asked whether they had any questions which they wished to 'ask the expert'. The expert – in this case, a field researcher working on the ERW trial in Sabah – was asked to leave the room, to avoid the temptation for participants to defer to the expert when formulating their questions or whilst considering and discussing their reasoning (Macnaghten and Szerszynski, 2013; Bellamy and Lezaun, 2017). The questions were written down on a flip chart by the facilitator; this also allowed the facilitator to identify topics which were underlying in the discussion, but which had not been worded as questions by the participants initially, and to work with the participants to translate them into questions which could be asked to the expert. All

Table 1
summary demographics.

Location		**Group 1** KK	**Group 2** KK	**Group 3** KK specialists	**Group 4** LD	**Group 5** Rural, near LD
Number	*Total N (35)*	7	6	7	7	8
Gender	*Male*	0	2	5	2	4
	Female	7	4	2	5	4
Age	*18 – 24*	4	2	-	-	2
	25–34	1	3	2	3	-
	35 – 44	-	-	1	1	2
	45 – 54	2	1	1	1	1
	55 – 65	-	-	3	2	2
	65–74	-	-	-	-	1
Highest level of Education	*Primary School*	-	-	-	-	1
	Secondary	5	2		7	6
	Pre-university	-	-	-	-	1
	Bachelor's Degree	1	3	3	-	-
	Master's Degree	1	1	2	-	-
	Doctorate Degree/PhD	-	-	2	-	-

participants were asked to suggest questions.

During this process, participants were asked to elaborate on their reasons for asking their questions, with other participants invited to comment also. This gave participants the chance to air their broader views on ERW, carbon removal, and other relevant topics, which had also been discussed at earlier points in the workshop. It also gave facilitators the chance to dig down into the underlying views and values which were guiding participants' questions – in other words, allowing us to interrogate the 'why' of their questions, as well as the 'what'. This is crucial for understanding perceptions in more depth, which in turn can give us a more rounded understanding of the gaps in knowledge and the priorities for ERW research. Once the group had no more questions or points they wished to make, the expert then re-entered the room to answer the questions, in order, with no grouping or choices over which questions to answer taking place within the groups themselves.

All workshops were facilitated by the author team – the groups in KK were conducted in English, but with Malay interjections where suitable English words were unavailable, whereas the groups in LD were conducted entirely in Malay. All materials were first written in English and then translated into Malay by SEARRP. Everything was initially direct translated, then rewritten for easier communication in local workshops. Public participants were given an honorarium of 100 Malaysian Ringgit.

For analysis, the flip charts were photographed, and the recordings transcribed and translated by a third-party company (Groups 4 and 5 were translated from Malay to English), with translations checked by the Malaysian research team. All transcripts were fully anonymised by the research team before starting analysis; the photographs of the flip charts were already anonymous. The flip chart questions were then grouped into themes, corresponding to the sub-sections of the results; the full table of coded questions, and the photos of the flip charts, are shown in Supplemental 1. The transcripts were then qualitatively coded line-by-line, to interrogate the underlying reasons for people asking the questions. Using the transcripts from the workshops – around 2.5 hours of recorded data in total – and focusing on cross-cutting themes across multiple topics and workshops, we can explore the underlying reasons for participants' questions, and what this might tell us about their desires, concerns, and priorities for future work on ERW.

2.2. Enhanced weathering field trials

The responses to the participants' questions were informed by an ongoing open-air field trial on ERW, currently being conducted at Sabahmas Plantation in Lahad Datu. The main objective of the field trial is to assess weathering rates of basalt and to investigate how basalt application influences oil palm growth and yields within the plantation area.

The basalt used is categorised as basaltic andesite, a type of mafic igneous rock that contains calcium- and magnesium-rich silicate minerals, as well as phosphorus and potassium. The basalt is crushed and screened at the quarry prior to delivery. Most of the particle has a size smaller than 5 mm and contains minerals that weather at a slower rate compared to other basalts elsewhere globally (Lewis et al., 2021). To maintain consistent characteristics of basalt used in the oil palm plantation, a sample was collected and tested during each delivery to investigate its composition. To optimize the preparation and application of basalt, a landing yard was constructed near the experimental plots at the project site. Crushed basalt, approximately 210 tonnes, were transported from the quarry to this yard on an annual basis. The basalt was stored in gunny sacks (20 kg) at the landing yard before being delivered and applied in the plots.

In the field trial, three pairs of plots were selected within the oil palm plantation, with plot sizes ranging from 0.6 to 1.8 ha. Each plot comprises two distinct catchments and oil palms planted within the area that are hydrologically isolated and discharge into a stream. One catchment from each pair was treated with an annual 50 t ha^{-1} of basalt, while the other catchment was untreated. In addition to catchment plots, 10 pairs of untreated and experimental plots (60 m * 60 m) were established to focus on palm growth, herbivory, and yield study. All the oil palms in the field trial were transplanted from younger oil palms in 2017 and all replicates were established at least 200 m apart from each other.

The basalt was spread by hand, to address challenging topography and to ensure a uniform distribution across the undulating terrain. Basalt was applied in the second half of 2018 for four months, and six cycles had been completed by the time the public workshops were conducted. To analyse water quality at the stream, real-time measurements were taken, and samples were collected for further analysis at three different locations: 1) in-house laboratory at the oil palm plantations, 2) local accredited laboratory in Sabah and, 3) the University of Southampton. Soil, crude palm oil and oil palm leaves were sampled and processed locally before delivered to the University of Southampton, University of Sheffield and Yale University for analysis. All scientific activities conducted on the oil palm plantation were approved by the management of oil palm plantation and samples transported outside of Sabah and Malaysia were permitted by the Sabah Biodiversity Council.

3. Results

In total, 60 questions were asked across the five workshop groups, shown in Table 2. In the first stage of the analysis, we grouped these into

Table 2
themes and sub-topics, derived from thematic analysis of the 60 questions asked. The questions are grouped into topics and combined to remove duplicates and similarities. For a verbatim list of questions from the flip charts, see Supplemental 2.

Theme	Sub-topic	Question
Material & scale	Materials	What material is used?
		Why these rocks?
		How are they processed?
	Resources	How much material is available?
		Will the resource deplete?
		How much is needed?
	Mining	How many mines are required?
		Do we need to open new mines?
Crops & farms	Benefits	Will it help local farmers?
		Will it benefit Sabah?
	Crops	Can this be used on other crops, or just oil palm?
	Yield	What is the effect on palm productivity / crop health?
		Do the rocks act as fertiliser?
Health & environment	Aquatic ecosystem	Is there an impact on river life and river quality?
		What are the effects in the ocean?
	Terrestrial ecosystem	What happens to animals if they step on the waste?
		Are there side effects for the local ecosystem?
	Health	Is there anything toxic in the materials?
		What are the health impacts for workers?
		Does dust cause health problems?
Sites & regulation	Decision-making	Why go down this route at all – who decides?
		How do we know this is worth doing?
	Field Trial outcomes	Is the project successful so far?
		What have we learned?
	Regulation	Is regulatory approval needed to do this?
Carbon	Life-cycle emissions	Do they include truck and mining emissions in calculations?
		How much CO_2 is absorbed?
	MRV	How possible is it to track the carbon stored?
		In which case, how do we know this is worth doing at all?
		How long does it take to produce the desired effects?
Cost & profit	Cost & profit	What are the costs involved?
		Will it add to the palm oil owners' costs?

six major themes and 15 sub-topics (Table 2; see also Supplemental 2). This results section proceeds in two halves. Firstly, using the qualitative analysis of the workshop transcripts, we explore the themes and topics raised by participants, along with the underlying reasons for participants' questions, and what this might tell us about their desires, concerns, and priorities for future work on ERW. Secondly, we examine the questions asked by participants in light of the current scientific knowledge on ERW, drawing on our team's natural science expertise as well as literature from ERW studies around the world. This enables us to identify the priorities for ERW research, as defined by our participants.

3.1. Desires, concerns, and priorities

As shown in Fig. 1, the most numerous of the questions asked were about the materials used and the scale of the material required. Most of these questions focused on whether new mines would be needed for rock extraction, connected to concerns about land use, long-term sustainability of the technique, and over-prioritising carbon reduction at the expense of other locally important goals such as biodiversity conservation. For instance, Dira (group 2) said:

"But for the foreseeable future you may actually need a larger area, so you would be going into areas that have not already been mined and extracting rocks from there? Would it be sufficient to only take waste materials from existing mines, or are you looking to actually going into a forested area and taking rocks from areas that are not already being mined?".

Participants' concerns reflected on the problematic history of mining in Sabah, wherein mining operations in Sabah have been linked to significant environmental and social consequences, sometimes resulting in the loss of land and homes (Vanar.; Patrick, 2019; Miwil, 2024). For example, Siti (group 1) said: "Mineral mining is, to me, always never good. It scars a lot of different environments. I don't understand why it's being used in this technique that's supposed to be helping the environment and getting rid of carbon dioxide." Many of the questions about the rock resources – and many questions in the dataset as a whole – stemmed from concerns about the overall *sustainability* of a technique which requires a continual supply of a non-renewable resource. In other words, feeling that the mining aspect of ERW could render it a 'non-transition' for Sabah (Cox et al., 2020a; Lefebvre et al., 2019). For instance, this exchange between Mina, Adriana and Raheem in Group 5: "Can this weathering process last longer because of the mineral rock?" "We need a lot of rock, if we dig the rock will run out." "More trees will be cut down." Across all groups, opening new mines was seen as undesirable, as found similarly by Low et al. in focus groups across multiple countries in the Global South and Global North (Low et al., 2024). Amongst our participants, this undesirability was for several reasons, including 'messing with nature' concerns, e.g.:

> "These rocks are natural in any hill around the world. Should it be scattered like that or leave it native because for example, like a tree. If the tree is left alone, it will absorb carbon dioxide. So those rocks, do they really need to be broken and spread?" (Ayaz, Group 4).

A prevalent cross-cutting theme across all five workshops was a desire for assurances regarding the *feasibility* and *effectiveness* of ERW for Sabah, in terms of carbon sequestration, cost, and practical implications to farmers for applying this to their land. Many questions concerned crops and farms, particularly oil palm production, a critical economic sector for Sabah and one which is directly relevant to the lives of participants in our two Lahad Datu groups. For instance, Ayaz (Group 4) said, "Maybe the rock in my area could be the same material, fertilizer? Does it improve the growth rate of the crop? Can it replace chemical fertilizers now?" Even in the urban groups, the impacts of ERW for farmers were a primary concern, reflecting the importance of agriculture to the economy and some underlying concerns about ethics and distributional justice; for instance, Fatin in Group 2 in Kota Kinabalu, who asked: "Is it only applied on palm oil, or… This method maybe can be done for locals? Maybe if this method is, like, good method for all, even the local farmer can use this method." Participants in all groups expressed the importance of the effectiveness and feasibility of the technique as an underlying, cross-cutting concern, although explicit questions about carbon were only voiced in the city groups. Although not using the technical terminology, participants demonstrated a considered and nuanced understanding of the importance of life-cycle assessment of emissions (LCA), and of monitoring, reporting and verification (MRV), in determining the viability of ERW as a climate change technique, with questions such as "Do they include truck and mining emissions in their calculations?" and "If after these trials it's still difficult to track, monitor, and verify, how do we know that this is worth doing or not?" Such questions reflect underlying concerns about whether ERW would create more problems than it manages to solve.

The 'health and environment' theme connected human and environmental health, seen by many as mutually inclusive due to human dependence on the resources provided by the environment in Malaysia. Questions about human and terrestrial ecosystem health were raised more often by the urban groups, with a focus on the rights of rural people and workers, with questions such as "When they workers throw away the dust, is it a possibility that he or she breathes in the dust? Is there any health consequences by breathing in the dust?". All groups

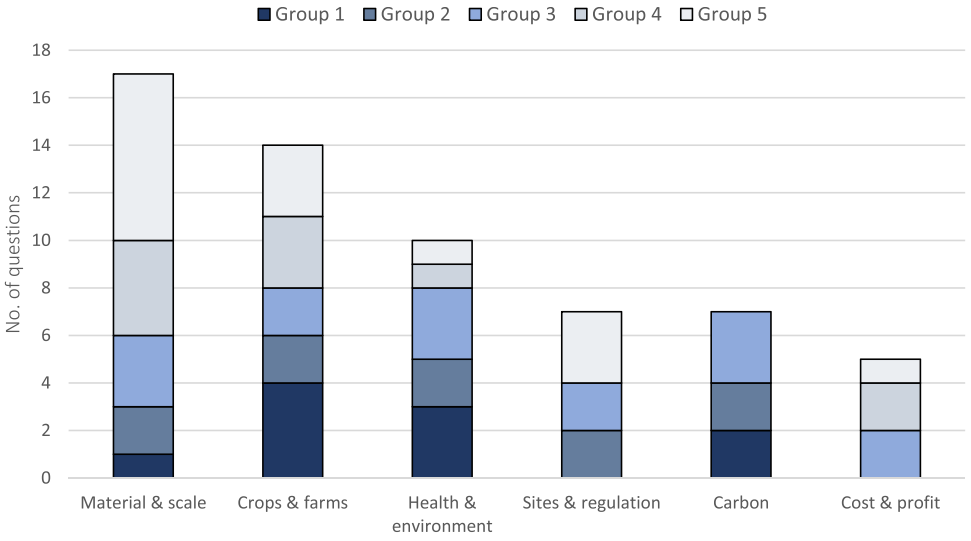

Fig. 1. number of questions asked by participants, according to 6 themes which emerged from thematically grouping the data, grouped by 5 workshop groups.

voiced concerns about impacts on the aquatic ecosystem; for instance, Sofia (Group 1) said "What would happen to the aquatic animals once the minerals are washed out to the rivers? Will it endanger the aquatic animals?". This was connected to concerns about messing with nature (Cox et al., 2021; Corner et al., 2013; Wolske et al., 2019): "Because there's river life as well, and there's wildlife who depend on that water. When things happen in small amounts that's fine, but when it's happening in the quantities like this, how does it affect the health of the water?" (Dira, Group 2). This underlines the importance of addressing knowledge gaps regarding the aquatic impacts of ERW.

In our choice of groups and our recruitment of participants, we had five quite different groups, which sometimes presented distinct discourses. The Kota Kinabalu city groups (Groups 1 and 2) were particularly concerned about land use competition: "I think because if they use that, but at the end you can't use that area again, they might need more bigger area for that." (Alya, Group 1). Land use concerns were also expressed in relation to other Malaysian policy goals such as habitat conservation, expressing an underlying concern about *over-prioritising carbon goals* at the expense of other goals. Interestingly, only the KK groups – spatially distant from the application sites – raised concerns about mineral toxicity and occupational health. Meanwhile the specialists' group (Group 3) had a rather distinct discourse with a strong focus on techno-economic issues (found similarly in (Cox et al., 2022)). Specialist participants expressed a desire for more concrete data on carbon sequestration potential, MRV, LCA, and cost, as well as equity concerns about the burden of costs and benefits to smallholders. Cost questions mainly appeared in Groups 4 and 5 in the palm growing region, reflecting a desire to explore the feasibility of new options for farmers, as well as in the specialists' group, mainly in relation to impacts on farming and agriculture, e.g. "[I want to know] whether doing all this will also add cost to the palm oil, oil palm owners, the plantation owners" (Hakim, Group 3).

Finally, our smallholders' group (Group 5) also voiced many concerns about the sustainability of the rock resource and the feasibility and effectiveness of the technique; but interestingly, they also saw themselves as potential *enablers* of this technique, both as early adopters on their land and as advocates in their community (Rizal and Nordin, 2022), contrasting an expert discourse which sometimes sees lay publics in a negative, oppositional role (Cox et al., 2020b). For instance, Raheem (group 5) asked, "After this workshop, my question is what do you suggest for the participants? I raise that question because who knows we can also help to introduce this method, technique to the public." Shahirah (also group 5), asked: "How does the minerals be processed? Are they using machines?" (Facilitator: "Why are you asking that?"). Shahirah: "Might have an interest upon the technique. Hence, want to ask if you can just do it manually! [Laughs]." The KK city groups also emphasised this enabling role for publics: their questions about the scale of the technique were often rooted in a vision of ERW as being practiced at small scale across multiple sites with broad public participation, for instance this exchange between Dira and Fatin (Group 2): "Even right down to everybody in their garden. Just like, can you spread this in your garden? Every home-owner can actually do this in their own home." "Yes, yes. Like my durian trees! Can I put this [on my trees]?"

3.2. Identifying gaps in knowledge

In this section, for each of the sub-themes asked by participants, we respond to participants' questions with information on the state-of-the-art of ERW research. Here, we introduce a multi-disciplinary way of acting on public questions and concerns, by interrogating the extent to which existing ERW science is adequately responding to the questions our participants asked, and the topics they prioritised. The data cited throughout this section are from the Sabahmas field trials, supported by additional knowledge from across a larger research programme, which includes field trials of basaltic ERW in four other countries (US, Australia and UK), as well as mesocosm experiments and modelling studies (Leverhulme Centre for Climate Change Mitigation, 2023).

We differentiate between the state of knowledge for the field trial study location, versus potential upscaling to the rest of Malaysia and beyond. Participants were clearly interested in the particularities of the field trial itself, helping to connect the rather abstract concept of ERW to something taking place locally and in the real world; yet many questions were also rooted in governance- and justice-related queries about the actors and the decision-making processes involved, and the implications if the technique were to be upscaled.

Fig. 2 provides an illustration of the level of current scientific knowledge on each of the sub-themes proposed by the participants, according to the field trial location (x axis) and ERW if upscaled (y axis). Each bubble represents one of the 15 sub-themes shown in Table 2, with the size of the bubbles indicating the level of uncertainty.

Firstly, the 'material and scale' topics (Fig. 2a) cluster onto the right-hand side, showing a high level of existing scientific knowledge for the study location, although potentially lower for upscaling. There is a high level of knowledge of the types of materials used and how they are processed – indeed, we know the precise mineralogy of the rocks (Beerling et al., 2024; Shamshuddin et al., 2014; Anda et al., 2015; Panhwar et al., 2016), the processing techniques (Lewis et al., 2021), and the abundance of basalt in Malaysia and globally (Jorat et al., 2018). However, there is a distinction between a non-depleted resource (potentially requiring mining) versus a by-product of existing activities – a distinction which our participants were eager to point out. Accessing basalt for upscaling ERW may pose a challenge in rural areas or areas lacking access roads, (Boudinot et al., 2023) although our rural group were very interested in the potential for farmers to deploy this technique but did not raise any questions about local transport infrastructure.

As shown above, the number of mines required was a key issue for participants across all five groups. However, this encounters particular uncertainty if upscaling, because the number of mines required depends on balance between demand and supply from the quarry output (Kantola et al., 2023; Luchese et al., 2023), as well as on approval and regulation by the local government, considering the potential environmental, social, and economic consequences of establishing a new quarry, plus a comprehensive evaluation of the characteristics of the basalt (Lewis et al., 2021; Kemp et al., 2022). Crucially, it also requires consideration of the local context and history. Our participants pointed out that in Peninsular Malaysia and Sabah, mining activity in the past for mineral resources such as bauxite, copper and sand had resulted in negative impacts on the land and river ecosystems, physical illness and mental health of the affected local community (Yen and Rohasliney, 2013; Van Der Ent and Edraki, 2018; Abdullah et al., 2016).

In the top middle panel (Fig. 2b), the 'crops and farms' topics cluster into the top-right-hand corner, indicating reasonably high certainty for both the study location and for upscaling – with the exception of questions about whether the technique will help local farmers and benefit Sabah ('benefits'). One of the key rationales behind ERW is that amending soils with crushed basalt may increase crop yields and reduce fertiliser input by increasing pH levels and the availability of nutrients such as calcium and phosphorous (Beerling et al., 2024; Anda et al., 2015, 2013, 2009; Conceição et al., 2022). Indeed, research shows promise for ERW implementation and soil improvement across a range of crop types, including bean (Conceição et al., 2022), cocoa (Anda et al., 2013, 2009), maize (Kantola et al., 2023; Beerling et al., 2024; Luchese et al., 2023; Conceição et al., 2022), miscanthus (Kantola et al., 2023), oat (Skov et al., 2024), potato (Vienne et al., 2022), rice (Panhwar et al., 2016; Shamshuddin et al.), sorghum (Kelland et al., 2020) and soybean (Kantola et al., 2023; Luchese et al., 2023), thus fairly comprehensively responding to questions about whether it can work on other crops other than oil palm, e.g. for intercropping which is common in the area. However, assessing the economic viability for small farmers would need comprehensive farm-scale evaluation, which may be out of reach for many Malaysian smallholders. One social co-benefit to increasing production from existing basalt mines or opening new

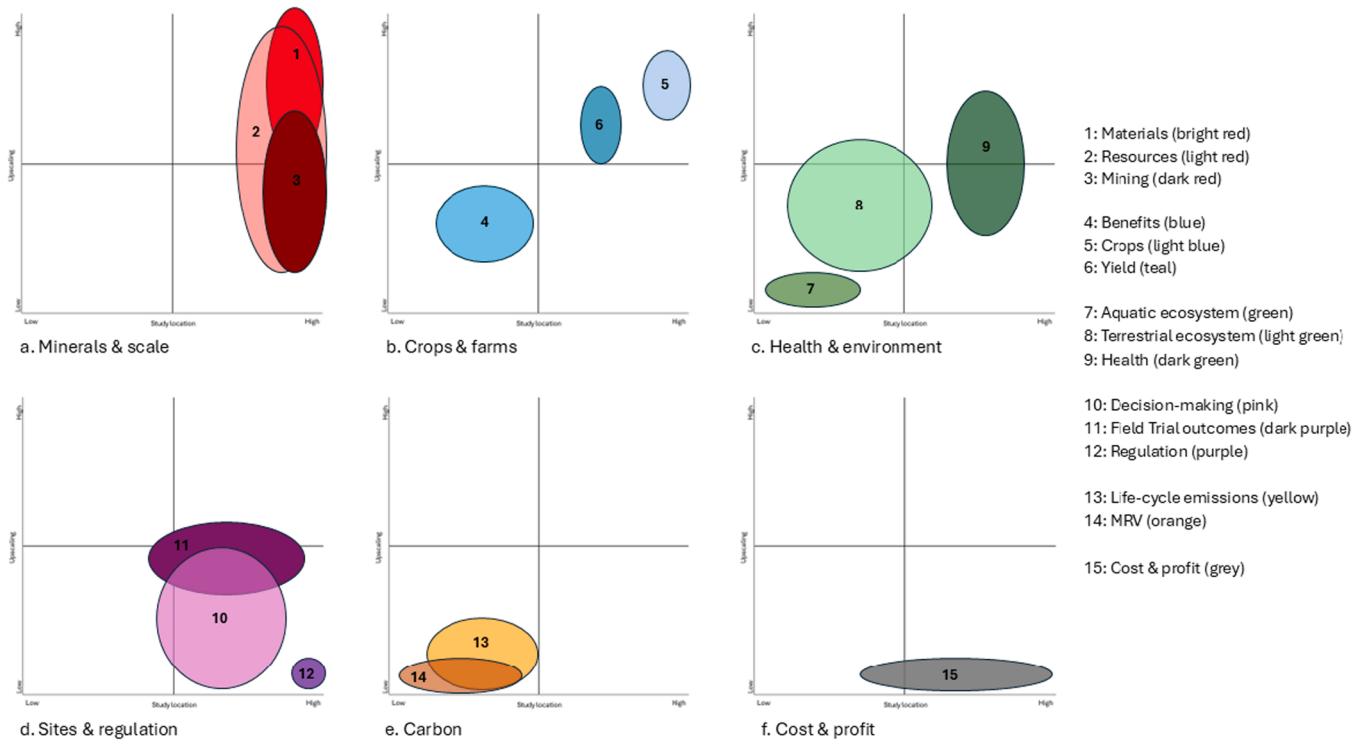

Fig. 2. Qualitative conceptual map showing authors' assessment of the level of current scientific knowledge (low to high), on two axes – the study location of the field trials in Sabah on the horizontal axis, and for ERW if upscaled on the vertical axis. The larger the bubble, the greater the uncertainty over our assessment of the state of knowledge, and/or the greater the heterogeneity in the possible data availability, for example in cases where a question contains multiple interpretations, which we explain in the text.

mines could be greater employment within that sector; yet this has not been empirically demonstrated thus far.

The 'health and environment' topics (Fig. 2c) show possibly the greatest uncertainty, stemming in particular from uncertainties over impacts on terrestrial and aquatic ecosystems, due to the vast diversity of different organisms; thus the level of knowledge depends on which specific aspects of the ecosystem or particular groups of species are of interest. The largest gaps in knowledge here concern aquatic ecosystems, with participants asking *"Is there an impact on river life and river quality?"* and *"What are the effects in the ocean?"*. In the Sabah field trials (Larkin et al., 2022), stream water chemistry through each catchment is monitored, but diversity and abundance of aquatic life within the streams is not. Considering that impacts on aquatic ecosystem health and functions emerged as a key concern for our participants, this represents a crucial gap in our understanding of ERW impacts, and requires further assessments (Harrington et al., 2023).

Meanwhile questions about human health (Fig. 2c) mainly concerned toxicity of the materials and health impacts for workers; exposure to basalt dust can potentially irritate the respiratory system, although the precise health risks depend on the mineralogy of the basalt used (Choi et al., 2021). Workers at the Sabah field trials adhered to safety protocols and were provided with protective clothing and equipment, with no reported health incidents, although the application of heavy rock could impose physical strain, especially if continued for years under a programme of upscaling. Interestingly, these concerns were raised particularly in the city groups, and less so by Groups 4 and 5 in the palm growing regions where most of the workers are currently based. That said, the workers at the site were employed by the plantation rather than the research project and could not be interviewed as part of this study, therefore we are unable to respond to participants' underlying concerns about equity and treatment of workers.

Finally, the 'carbon' and 'cost' themes clearly identify gaps in knowledge. The cost topics (Fig. 2f) appear at the very bottom of the y axis, showing that knowledge is very high for the field trial itself but much lower for any potential upscaling. If a farm owner decided to implement ERW, its economic viability would need to be evaluated (Strefler et al., 2018) in terms of buying and transporting the basalt, packaging and application at the farm, as well as detailed information on soil health, yield, and quality of crops, as these are known to impact the effectiveness of ERW and thus farm profits. The costs of the trial are well known, but such costs might differ significantly even for neighbouring farms not linked to the research programme.

In terms of carbon (Fig. 2e), participants wanted to know, *"Do they include truck and mining emissions in calculations?"* and *"How much CO_2 is absorbed?"*, both of which require life-cycle emissions accounting. LCA is being gradually applied in the palm oil sector in Malaysia, but remains fairly minimal (Hafizan et al., 2021). Although such explicit interrogation of LCA and technical carbon topics was only present in the specialists' group (Group 3), broader concerns about whether ERW was 'worth it' in terms of net carbon sequestration were present across all five groups. Calculation of life-cycle CO_2 removal by ERW requires accounting for CO_2 emissions associated with mining, grinding, transport, and distribution of rock dust, which in turn depends on decisions at farm-level application. Questions also concerned how we can track the carbon stored, e.g. *"In which case, how do we know this is worth doing at all?"* Again, this was crucial for participants in terms of the feasibility and effectiveness of the technique; but tracking carbon removal in agricultural settings is a complex and challenging task, requiring careful consideration of factors including the specific rock type, the applied quantity, local climate conditions, and fertiliser inputs by the farmer or landowner (Deng et al., 2023). Participants – including in the non-specialists' group - demonstrated an intuitive understanding of this complexity, and linked it to concerns about impacts on terrestrial and aquatic ecosystems, in-line with ongoing debates over the nature and purpose of MRV frameworks (cf (Schulte et al., 2024).).

4. Discussion

Public support can be a driving force behind policy changes, including CDR strategies (Cox et al., 2020a; Friedmann, 2019); therefore, involving the public from the beginning of the innovation process enables a more comprehensive understanding of their perspectives (Macnaghten, 2020; Lehoux et al., 2020), and can contribute toward anticipatory governance of research (cf (Borth and Nicholson, 2021; Aczel et al., 2022).). This paper presents data from a major deliberative study on public perceptions of ERW in Sabah, and demonstrates a novel, transferrable methodology called "Question-Led Innovation", in which lay public and local stakeholders are empowered to ask actionable questions on a novel intervention or innovation. In this case, our focus is ERW on tropical agriculture and palm oil, but the method is transferrable a wide range of topics. The questions asked by participants reveal priorities for research, which can be used to inform ongoing efforts to respond to public concerns as part of a process of responsible research and innovation.

The questions asked in the workshops show that our participants developed a sophisticated and nuanced understanding of ERW, engaging fully with complex and novel ideas. The largest number of questions were on the materials used, including detailed questions about the rocks and the processing techniques. This was the theme with the highest level of scientific knowledge, demonstrating that much of the research being carried out is, in fact, in-line with what our participants most wanted to know about. However, many questions about rock resources were rooted in broader concerns about the overall sustainability of the technique, in the context of a particularly problematic history of resource mining in Sabah, and linked to a worry about over-prioritising carbon goals at the expense of conservation and biodiversity goals. Interestingly though, most groups also emphasised a positive, enabling role for publics in the future of ERW, with farmers envisioning themselves as early adopters on their land and as advocates in their community (Rizal and Nordin, 2022), and city groups presenting a vision of ERW practiced at small scale across multiple sites with broad public participation.

Workshop participants clearly demonstrated an interest beyond the lifetime and scale of the field trials, and in many cases we have a fairly good understanding of the field trial itself, but much lower understanding of the implications if ERW was scaled up. This is particularly evident for 'materials and resources', 'sites and regulation' and 'cost and profit' (Fig. 2 panels a, d and f). For example, although the availability of the basalt resource are well understood, questions around its cost and LCA of different resource paths still represent fundamental data gaps. Furthermore, questions such as 'will it help farmers' are extremely broad, encompassing multiple issues including yield, cost, soil health, climate benefits, governance regimes, local farming practices, and credit/subsidy programmes, some of which may additionally trade off against one another (Boudinot et al., 2023; Honegger et al., 2021). In some cases, we may simply not know enough to be able to make definitive claims about ERW one way or another. Most importantly, many crucial questions for our participants related to socio-economic aspects of the technique – in particular on governance, regulation, decision-making, and cost. On this basis, we argue that such topics should be a priority for future research.

In this paper, we use Question-Led Innovation method to identify scientific gaps in knowledge concerning CDR and ERW in tropical palm oil areas. The application of basalt as a soil amendment for ERW has demonstrated some encouraging outcomes in promoting crop development and enhancing carbon removal (Beerling et al., 2024; Larkin et al., 2022), but there is still much to be understood regarding the potential advantages of implementing ERW technology, particularly in Malaysia, and we identify key areas in which scientific understanding needs to improve. Firstly, it is imperative to tackle logistical and practical challenges unique to the local environment prior to upscaling (Boudinot et al., 2023). In Sabah, these challenges encompass securing a sufficient supply of suitable silicate rock, identifying appropriate application techniques, and establishing MRV systems to ensure the efficacy of carbon storage (Kelland et al., 2020; Kantola et al., 2023; Larkin et al., 2022; Knapp et al., 2023). Mineral variability has also been shown to present a key challenge of ERW for farmers in the Global South, and access to soil testing can present a major barrier (Boudinot et al., 2023). LCA and MRV represent noticeable data gaps across both scales, and additionally encounter disagreement in the literature (Lefebvre et al., 2019). Participants expressed this concern in their questions around whether the carbon removed would be 'worth it' overall, as part of a desire for assurances regarding the feasibility and effectiveness of ERW for Sabah, thus more precise and granular LCA measurements could be a requirement for public support.

This paper is not without its limitations. First, it is important to note that this segment of the workshop came towards the end of a much longer workshop, in which ERW, carbon removal, land-use change, and climate policy had already been discussed. Therefore, many of these questions raised by participants here had been circulating earlier in the day. Hence, the way in which we present them here may appear divorced of that context, potentially obscuring other important questions which were asked during the rest of the workshop. Crucially though, the focus here on the questions that participants asked at the end enables us to focus on the things that participants ultimately felt that they wanted actioning, or reassurance on, and thus arguably represent the most important questions for ERW scientists to learn from and respond to. Second, as with any deliberative study, the responses will inevitably have been influenced by the stimulus materials (shown in Supplemental 4) and the framings that they provoked. In particular, we showed the rock dust at the field trial being spread by hand, in-line with common practices for fertiliser applications in Sabah: this may have impacted perceptions by provoking naturalness-type framings, or framings of small-scale participatory ERW. Third, the questions were of course addressed to the particular expert who took part in the session. While being out of the room when the questions were generated guards in part against this, we cannot rule out that choosing a different expert might have resulted in different questions being proposed (although we would argue here that the underlying values and sentiment being expressed are likely to be consistent across experts). Finally, there is a risk that aligning with expertise at all – in attempting to produce work of value to support the natural scientists working on ERW – may have acted to 'technocratize' the issue. In other words, did our question-led innovation methodology cause participants to focus more on technical topics specific to the technique and the field trials, rather than broader questions such as the societal or governance consequences of CDR, or why to consider carbon removal at all?

Upscaling ERW implementation is already underway (Frontier, 2023; Watson, 2023), yet our participants wanted answers to questions where there are still science or wider knowledge gaps, all of which would require significant research. It is worth emphasising that we are not arguing for an interminable science programme until all knowledge gaps are filled – at some point, deployment of a novel intervention has to proceed to upscaling. This may be especially salient in the case of CDR, since there exists a huge gap between the amount of CDR relied upon in climate pathways versus the amount currently being proposed or built, (Smith et al., 2023) and members of the public have expressed concern about the speed of CDR deployment in a context of climate urgency (Cox et al., 2020a; Nawaz et al., 2023). Rather, our purpose here is to highlight some areas for research in the coming years, with a focus on reducing knowledge gaps on the most socially-salient topics. Above all, we make the case that developing a socially responsible upscaling of ERW – and CDR more generally – should involve participatory processes such as this to embed the preferences of publics, and in particular of those who might be directly impacted by deployment. The Question-Led Innovation method is a particularly useful tool to help in this effort.

CRediT authorship contribution statement

Emily Cox: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Robin Lim:** Writing – review & editing, Methodology, Writing – original draft, Formal analysis, Data curation. **Elspeth Spence:** Writing – review & editing, Conceptualization, Methodology, Formal analysis, Data curation. **Melissa Payne:** Methodology, Project administration. **David Beerling:** Writing – review & editing, Supervision, Funding acquisition. **Nick Pidgeon:** Writing – review & editing, Conceptualisation, Supervision, Methodology, Funding acquisition.

Declaration of Competing Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2024.103977.

Data availability

Data will be made available on request.

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