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Author for correspondence:
Trisha R. Shrum
e-mail: tshrum@uvm.edu

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Behavioural frameworks to understand public perceptions of and risk response to carbon dioxide removal

Trisha R. Shrum[1], Ezra Markowitz[2], Holly Buck[3], Robin Gregory[4], Sander van der Linden[5], Shahzeen Z. Attari[6] and Leaf Van Boven[7]

[1]Department of Community Development and Applied Economics, University of Vermont, Burlington, VT, USA
[2]Department of Environmental Conservation, University of Massachusetts, Amherst, MA, USA
[3]Institute of the Environment and Sustainability and School of Law, University of California, Los Angeles, CA, USA
[4]Decision Research, University of British Columbia, Vancouver, BC, Canada
[5]Department of Psychology, University of Cambridge, Cambridge, UK
[6]O'Neill School of Public and Environmental Affairs, Indiana University, Bloomington, IN, USA
[7]Department of Psychology and Neuroscience, University of Colorado, Boulder, CO, USA

TRS, 0000-0001-8660-155X; HB, 0000-0001-8940-1238

The adoption of carbon dioxide removal (CDR) technologies at a scale sufficient to draw down carbon emissions will require both individual and collective decisions that happen over time in different locations to enable a massive scale-up. Members of the public and other decision-makers have not yet formed strong attitudes, beliefs and preferences about most of the individual CDR technologies or taken positions on policy mechanisms and tax-payer support for CDR. Much of the current discourse among scientists, policy analysts and policy-makers about CDR implicitly assumes that decision-makers will exhibit unbiased, rational behaviour that weighs the costs and benefits of CDR. In this paper, we review behavioural decision theory and discuss how public reactions to CDR will be different from and more complex than that implied by rational choice theory. Given that people do not form attitudes and opinions in a vacuum, we outline how fundamental social normative principles shape important intergroup, intragroup and social network processes that influence support for or opposition to CDR technologies. We also point to key insights that may help stakeholders craft public outreach strategies that anticipate the nuances of how people evaluate the risks and benefits of CDR approaches. Finally, we outline critical research questions to understand the behavioural components of CDR to plan for an emerging public response.

1. Introduction

Meaningfully addressing climate change will require a massive, multi-faceted societal response that spans many levels of decision-making and governance, from the individual to the international community. In addition to reductions in carbon dioxide and other greenhouse gas emissions, this response will almost certainly require developing and deploying multiple approaches to remove carbon dioxide from the atmosphere [1].

Carbon dioxide removal (CDR) approaches, sometimes referred to as negative emission technologies, include methods that increase natural sinks for carbon in the physical environment (such as afforestation and reforestation [2]) and approaches that use industrial processes to remove CO_2 and store it geologically (such as direct air carbon capture and storage [3]). Notably, CDR approaches only yield 'negative emissions' if they remove more carbon than they emit during their lifecycle; CO_2 that is captured but then used to make new products such as fuels is considered 'carbon capture and utilization'. Much discussion of CDR has emphasized technological research and development (e.g. [3]) with relatively little focus

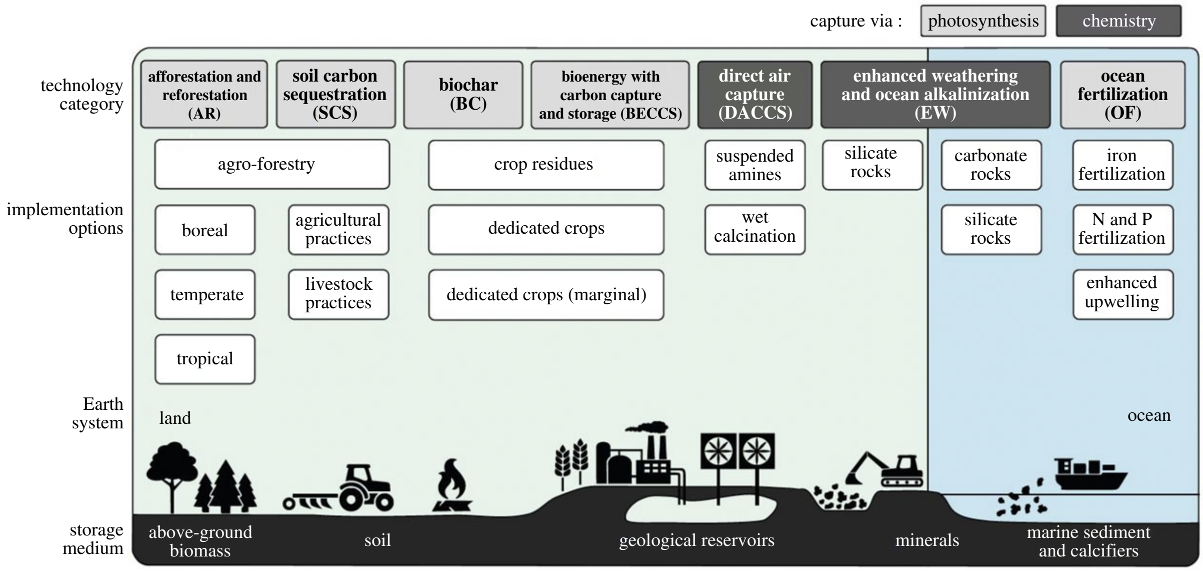

Figure 1. A summary of carbon dioxide removal technologies. Reprinted from [3].

on the social, political and ethical dimensions of CDR [4,5]. Yet deploying CDR will depend on both technological innovation and social choices [4,6] in addition to massive scaling of efforts world-wide.

As with the broader climate change response effort, the effective implementation of CDR will involve decision-makers and stakeholders in every sector of society and the economy [7]. Many CDR efforts will involve deploying new technologies at massive scale (e.g. carbon capture and underground storage) and thus require engineered solutions, policy tools and public acceptance to be successful. Others will rely on changes in practices and choices that are implemented at the individual scale by decision-makers (e.g. agricultural or forest management decisions that are only partially driven by climate change mitigation considerations); these individual decisions can scale up with widespread participation in these practices.

Deploying CDR technologies at the scale needed to achieve overall drawdown of carbon emissions [8,9] will require technological and behavioural uptake across multiple levels of decision-making. There is thus a critical need to understand the factors that influence how the broader public perceives and makes decisions about CDR technologies. Although CDR decisions share some relevant characteristics with other decisions about climate change (e.g. high uncertainty and complexity; long-time horizons and temporal discontinuity between actions and their effects; financial costs in the present for future gains; need for massive scaling-up) as well as with public acceptance and understanding of other novel, emergent technologies (e.g. hydraulic fracturing; see [10]), the diverse set of CDR technologies and approaches also present unique challenges to decision-makers. These might include new dimensions of risk perception, new associations with ideology and political identities, low public awareness and potential for moral licensing effects owing to the perceived climate change 'panacea'.

There is now a small but growing body of research focused on identifying how members of the public perceive (for a review see [11]) specific components of CDR such as carbon capture and storage (CCS) (e.g. [12–15]) and the broader umbrella of geoengineering, which includes CDR and solar radiation management (e.g. [16–20]), as well as the factors that shape (dis)-engagement (e.g. [21,22]). Combined with broader insights from the behavioural science of climate change (e.g. [23–26]), this work holds the potential to help policy-makers, resource managers, engineers and other stakeholders better understand the factors that are likely to influence how, whether and to what extent the general public engages with CDR.

In this paper, we review broad social–behavioural frameworks that influence the attitudes, beliefs and preferences of the general public's engagement with CDR. These 'behavioural' factors may play important roles in determining the development trajectories for various CDR technologies and approaches. The design, implementation and scaling of CDR technologies will obviously involve decision-makers in many different roles at different levels and at different nodes within a complex system of actors—from engineers and ecologists to investors and entrepreneurs to policy analysts and policy-makers. Our aim is not to provide a comprehensive list of different decision-making roles, but to focus on well-established and actionable behavioural features exhibited by the general public. Enacting substantive policy without public support is difficult, if not impossible. A critical aspect of most CDR technologies is that they need to be implemented at a massive scale to meaningfully impact climate change. Forecasting and understanding the general public's response to CDR technologies will be important for such scaling, not only to understand public acceptance of CDR technologies but also to support the widespread behaviour change entailed by scaling CDR. The frameworks we present are designed to support more effective engagement between experts and the public in making decisions about CDR.

1.1. Overview of carbon dioxide removal technologies

CDR technologies vary widely, from those that predate human history, such as forestation, to those that are in the early stages of technological development, such as direct air carbon capture. The technologies vary in terms of how the public views their familiarity, potential negative effects, the certainty of successfully removing and storing CO_2, cost, and overall 'naturalness', to name just a few. Figure 1, from Minx *et al.*

[3], summarizes and categorizes seven major CDR technologies based on implementation and storage mechanisms. Afforestation and reforestation and soil carbon sequestration (SCS) are based on photosynthesis and ecosystem-based biomass storage. Biochar and bioenergy with carbon capture and storage (BECCS) use biomass from crops and crop residues and convert it into other usable and more stable forms of carbon. Direct air capture and carbon sequestration (DACCS) draw in ambient air, pull CO_2 out of the air through chemical processes and store the CO_2 to prevent it from re-entering the atmosphere. Enhanced weathering takes the natural process of rock weathering, which draws CO_2 out of the atmosphere through interactions with silicates and water, and accelerates the process by adding powdered silicate rocks to land; the same process applied to ocean surfaces is called ocean alkalinization. Ocean fertilization adds iron or other nutrients to the ocean surface to stimulate phytoplankton growth to remove CO_2 from the air through photosynthesis.

For illustrative clarity, we will focus on two examples of CDR technologies: SCS and DACCS. SCS includes technologies and practices that predate the industrial revolution as well as new technologies that are still being developed. For example, The Land Institute in Salina, KS, USA, has been working for decades to develop new strains of domesticated perennial wheat and other grains that would increase soil carbon through plant root mass and the elimination of the need for soil tilling [27]. SCS focuses largely on agricultural techniques that increase how much carbon is stored in the soil, which also increases soil fertility and health, water infiltration and agricultural productivity [28].

DACCS, in contrast, is still in the experimental stage. DACCS draws in ambient air, pulls CO_2 out of the air through various chemical processes and stores it to prevent it re-entering the atmosphere. CO_2 drawn from the atmosphere through direct air capture can be used or stored in various ways from enhanced oil recovery to long-term geological storage to creating new products or fuel. The direct air capture process currently requires a substantial amount of electricity. Depending on how CO_2 is used, it is also likely to require transport through pipelines and other infrastructure. The feasibility of DACCS was demonstrated in a pilot plant [29], but is still in development.

We focus on SCS and DACCS because they represent strong variation in public perceptions of familiarity and naturalness and they share key similarities and differences that enable the exploration of behaviourally relevant features of CDR. They help illustrate how these and other factors play a role in people's perception, judgements and responses to CDR technologies. These examples are not necessarily in competition with one another; indeed, the alternative to implementing a particular CDR technology is most often the status quo that includes the myriad risks associated with higher concentrations of carbon dioxide in the atmosphere.

2. Section 1: behavioural foundations for valuation and risk

How will the general public react to CDR technologies? Will people see CDR as risky or safe? Will they interpret CDR as a gain in the fight against carbon emissions? Or as a potential loss of longstanding business as usual? Will CDR elicit widespread feelings of hope and optimism or of fear and dread? Answering such questions requires an understanding of social and psychological factors underlying people's attitudes, beliefs and preferences. Such 'behavioural' principles of emotions, value, reactions to risk and considerations extended across time are often at odds with traditional economic theory frameworks that underlie much of the cost–benefit analysis of CDR technologies.

We provide a brief review of well-established findings from social–behavioural science that can be used to answer such questions, with a focus on dimensions of value, probability, time and how emotional factors amplify these behavioural tendencies.

2.1. Behavioural insights and traditional economic theory

Behavioural approaches are distinct from those based on traditional economic theory. Standard economic models, which underlie many cost–benefit and efficiency analyses, assume that people have stable, coherent preferences and make rational decisions to maximize utility. If people rationally optimize utility using the best information available, then their preferences and choices would reveal consistent valuation of CDR technologies and response to risks. And the primary goal of public engagement would be to accurately communicate information about CDR costs and benefits.

Behavioural frameworks, in contrast, suggest that people's decisions reflect a constellation of mental shortcuts, decision tendencies and emotional processes. These behavioural tendencies mean that, even when fully informed, people's decisions can vary substantially across contexts, how information is framed, whether the information is emotionally evocative and how costs and benefits are distributed over time. These tendencies can produce predictable deviations from rational economic models.

Behavioural science from the past half-century indicates that judgements and decisions can be broadly characterized as reflecting the interrelation of two metaphorical systems of reasoning [30]. System 1 is fast, automatic, associative, emotional and intuitive; system 2 is slower, more effortful, deliberative and analytical (figure 2 [31,32]). Both systems can reflect conscious or non-conscious processing. Intuitive system 1 responds rapidly based on associations, past experience and heuristic processing. Analytical system 2 responds more slowly, if at all, based on a rule-based effortful analysis. Both systems can produce departures from the consistent integration of available information that might be expected based on rational choice theory. For example, system 1 may lead people to be highly swayed by transient emotional factors such as fear and dread that might be associated with the less-developed, potentially unnatural and unfamiliar DACCS, while giving limited consideration to less-emotional numerical information regarding the extremely low probability of such events. Or system 2 may lead people to be highly swayed by analytical calculations of the expected value of low-probability risks with limited consideration of the emotional costs of fear and dread experienced by the broader public. These two systems operate in tandem—reasoning system 2 can be activated to monitor and correct the output of intuitive system 1. But the operation of the two systems is highly context-sensitive and results in less consistent responses than implied by standard economic models. For example, system 1 is strongly swayed by evocative imagery, so information about risks and benefits presented

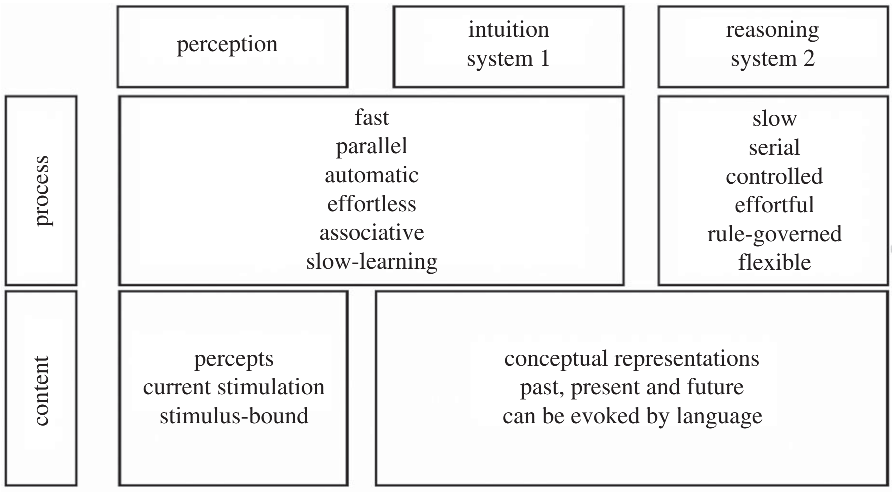

Figure 2. Schematic representation of information perception and processing through system 1 and system 2 cognition. Reproduced from [31].

through emotional pictures may be processed differently from the same information presented in numerical formats, which prompt more extensive system 2 processing. And because system 2 requires more time, effort and cognitive capacity, contexts that strain resources or call for rapid reactions may circumvent more careful reasoning processes.

2.2. Behavioural decision theory for carbon dioxide removal

Within behavioural decision theory, decisions and preferences are represented as choices among alternatives. Alternatives vary in potential outcomes (value/utility), uncertainties (probability) and time [33]. The three dimensions—value, probability and time—correspond to three distinct behavioural functions, each of which implies unique patterns. Recent evidence suggests that emotional processes moderate all three functions. Further, the reactions of individuals occur within broader social contexts that can influence attitudes, beliefs and preferences.

Consider the broader public's evaluation about whether and how much to support public subsidies for the development and deployment of DACCS. That evaluation reflects reactions to (i) value associated with various potential outcomes associated with DACCS, including the construction and appearance of infrastructure, effectiveness at carbon removal, the effectiveness of carbon storage, possible impacts on local weather and so on; (ii) the weight of various probabilities that those outcomes would occur such as the likelihood that the technology will successfully remove carbon, the likelihood of carbon storage failure and so on, with a probability associated with every possible outcome; and (iii) discounting the present value of events that occur over a broader timeline, such as the duration of construction, the amount of carbon removed over time and the longer term consequences of reducing overall emissions. These three functions of value, probability and time would be included in any comprehensive cost–benefit analysis of public response. Each of these dimensions can be analysed through behavioural principles, as discussed below.

2.2.1. Utility and value

The utility is a measure used by economists and behavioural scientists to capture people's subjective value of objective outcomes. Behavioural decision science reveals three broad principles about the nature of utility [34,35].

First, people have decreasing marginal utility for increasingly large outcomes, reflecting basic principles of perception and psychophysics [36]. The subjective difference between, say, \$0 and \$10 is much larger than the subjective difference between \$1000 and \$1010 even though both represent a change of \$10. In the context of DACCS, a difference between capturing 1 million and 10 million tonnes of carbon seems larger than 101 million and 110 tonnes of carbon even though both increases represent a change in 9 million tonnes. Diminishing marginal utility is important because it means that people are relatively less sensitive to changes at a massive scale than they are to changes at a small scale.

Second, people are highly sensitive to departures from reference points. They regard outcomes as gains or losses relative to what they are using as a basis of comparison, which is typically the status quo [37,38]. This gain/loss *reference dependence* can strongly influence preferences. Simply framing the same choice as gains rather than losses can invert risk preferences without changing the underlying mathematics. People tend to be risk averse when considering positive outcomes while they are risk seeking when considering negative outcomes. The question of framing and risk preference is critical because CDR technologies—and, indeed, the broader climate conversation—inevitably involve trade-offs between risk and different alternatives that can be described as relative to different reference points. With the reference of current atmospheric levels, focusing on removing CO_2 from the atmosphere may activate loss framing whereas focusing on adding CO_2 to ecosystems or geological formations would activate a gain framing. For example, even the popular terms of 'carbon dioxide removal' (which may be perceived as a loss frame) compared with 'carbon sequestration' (which may be perceived as a gain frame) may impact public support. Prospect theory tells us that, when a situation is framed as a loss rather than a gain, people tend to make more risk-tolerant decisions. Thus, focusing on a loss framing for CDR may increase the level of CDR technology risk that people are willing to tolerate.

Third, people are more sensitive to losses than they are to gains [35,37]. *Loss aversion* can produce a seemingly irrational 'endowment effect' in which people would demand more compensation to part with a good they 'own' than they would be willing to pay for the same good they did not own [37,39] and can lead people to be biased towards the status quo [38]. For SCS, these findings point to a possible strategy of emphasizing the age-old practices of regenerative agriculture that are often lost in modern agriculture rather than introducing them as revolutionary changes from the status quo. Loss aversion also helps explain the well-established disparity between the public's willingness to accept versus willingness to pay for public goods such as reduced carbon emissions [40].

These behavioural components of utility pose broad challenges to analysing and predicting public responses to CDR. They imply that public preferences and decisions can shift dramatically based on the framing of magnitudes and of gains versus losses. The sensitivity to framing highlights the need to carefully structure value elicitation to measure public preferences and incorporate them in decision-making. Without knowing how CDR technologies will be framed and how the public will interpret such framing, it is difficult to predict the public response to the adoption of CDR.

2.2.2. Risk perception and probability weighting

Behavioural frameworks provide two broad ways of understanding responses to risk: people's intuitive, non-technical sense of threats in their environment and people's weighting of explicitly stated risks [41–43]. For example, people might deem DACCS as relatively 'dangerous' or 'safe' and these judgements are distinct from how people respond to a stated probability of a 0.001% chance that a DACCS facility malfunctions and does not properly sequester captured carbon. The first reflects risk perceptions; the second reflects probability weighting.

Research on the psychometrics of risk perception [44] highlight two primary dimensions of the broader public's representation of emerging technologies and their potential hazards: *dread* and *familiarity*. In psychometric models of risk perception, dread is how much individuals perceive technologies, hazards, policies or other targets as (un)controllable, catastrophic, reversible and (in)voluntary. Nuclear energy and nuclear weapons are prototypically dreaded risks. Familiarity (also referred to as the 'known/unknown' risk dimension) is how much people perceive targets as (un)observable, (un)known to exposed individuals or communities, having a delayed versus immediate effect and being (un)known to scientists working in relevant domains. Dread influences people's motivation to reduce risks and support for government regulation more than familiarity [41,44].

Recent research on public risk perception suggests that naturalness is an additional important dimension of CDR risk perception [45]. In a study of risk perceptions of nuclear energy, for example, 'tampering with nature' largely displaced the impact of other psychometric dimensions on overall perceived risk [46]. Generally, people view things that are considered natural as more desirable than things considered unnatural [46–49]; however, the perception of naturalness is not clear cut. For example, when DACCS is framed as working like 'artificial trees' instead of '[involving] a chemical process with large industrial machinery', support for 'geoengineering' increased [50]. Thus, while afforestation and reforestation, biochar and agricultural interventions like SCS are often delineated as natural whereas DACCS, BECCS, enhanced weathering and ocean alkalinization are not, these labels and their associated impact on risk perception can vary depending on how the technology is presented and which aspects are emphasized [49].

To illustrate the dimensions of risk perceptions, consider the results displayed in figure 3 of a survey ($N = 113$) of Amazon MTurk participants regarding how they perceive various CDRs along dimensions of dread risk (y-axis), known or unknown risk (x-axis) and naturalness (colour gradient). This survey is meant to provide some initial exploratory insight into how members of the general public in the USA might perceive CDR technologies, but it is not a nationally representative sample.

The results suggest that dread, familiarity and naturalness are interrelated such that more 'natural' CDRs such as afforestation and SCS are less dreaded and more familiar than 'non-natural' CDRs such as ocean fertilization and DACCS. Research on public perceptions of geoengineering suggests that public support increases when technologies are viewed as analogous to natural processes [50]. An important task for future work will be to more carefully examine the dimensions of risk perception that the general public associates with CDRs, how these dimensions might be shaped by science communication and how they might vary by environmental values, ideology, numeracy and other demographic factors. Related questions concern the degree to which dread, familiarity and naturalness independently predict perceived effectiveness, support for public investment in these technologies and support for the regulation of risks.

Distinct from the study of how people perceive risks along psychological dimensions of dread, familiarity and naturalness, probability weighting refers to how much explicitly stated probabilities influence decisions [34,35]. For example, expert analysts might calculate the probability of carbon sequestration equipment failure at less than 0.0001%, and one could examine how much that stated probability influences people's attitudes toward DACCS.

Behavioural decision theory reveals three principles of probability weighting [34,51]. One is that people tend to overweight small probabilities, such as treating a 0.0001% chance of failure as substantially larger than it is. Second, people are highly sensitive to shifts away from or towards certainty. People are consequently willing to pay substantially more to reduce the risk of a deadly accident from 1% to 0% than they would be willing to pay to reduce the risk from 11% to 10%, even though both entail equal changes in the likelihood of an adverse event. Finally, people are insensitive to most changes in probability, even though they are highly sensitive to changes away from certainty.

Behavioural risk responses are important for CDR because they mean that, even if expert analysts have an informed, consistent and dispassionate reaction to risks, public response to risk may be inconsistent—overweighting small probabilities and being highly sensitive to certainty yet insensitive to most changes in probability. For example, the public may put a premium on eliminating risks even as they are insensitive to reductions that do not (and cannot) move risks to 0%. At the same time, the public may be overly sensitive to very small risks, further increasing resistance to CDR technologies that inevitably entail some trade-off between risk and reward [52]. Additionally, people do not view different kinds of risk as equivalent [43]—for example, a 1% chance of dying from natural causes is weighted differently from a 1% chance of dying from a catastrophic accident. These psychological and social responses to risk more generally should be taken into account

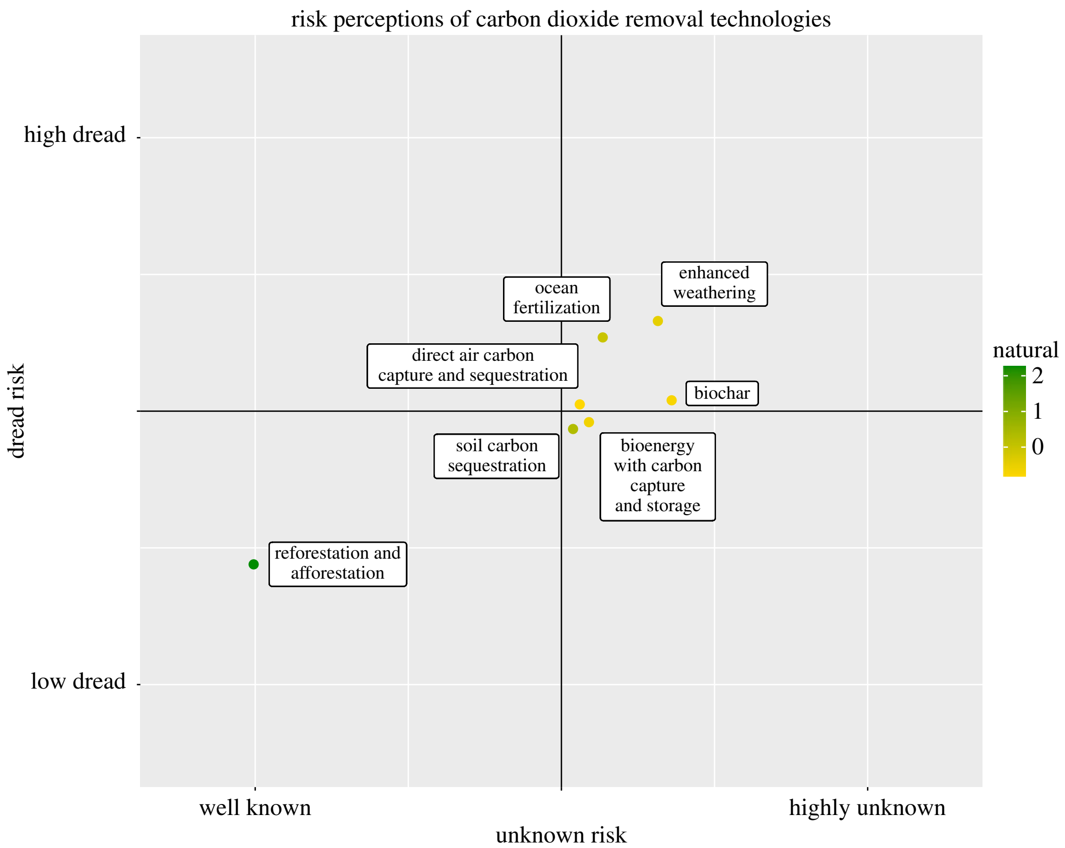

Figure 3. Estimated factors of risk perception: known/unknown risk and dread risk. Colour coding indicates naturalness. Values are the average of estimates from a survey of Amazon MTurk participants and should not be considered a representative sample ($n = 113$).

when evaluating CDR risk perceptions. As with utility and value, these potential inconsistencies heighten the importance of structured processes to measure public response to risk and the importance of careful risk communication strategies.

Consideration of behavioural tendencies in risk reactions highlights that people's responses to CDR technologies such as SCS and DACCS are extremely difficult to predict without appreciating how those risks are perceived, communicated and construed. DACCS might be seen as unfamiliar and evoke feelings of dread, which would make it seem 'dangerous', if public discourse emphasizes novelty and emotionally evocative imagery of large industrial machinery. SCS might be seen as unreliable because the carbon storage processes are reversible and there is a risk that carbon will return to the atmosphere after it is sequestered. Such reactions could vary tremendously depending on the nature of communication, even if the factual content is the same.

2.2.3. Choice over time

Humans did not evolve to make decisions over long-time horizons, certainly not over multi-century time scales. Survival has only recently begun to depend on it. Behavioural decision theory explores the special characteristics and challenges of intertemporal choice—decisions in which the consequences are separated in time from the decision, such as exercising, education and saving for retirement. Climate change poses especially difficult challenges for intertemporal choice because addressing it requires substantial short-term investment to mitigate, if not reverse, the worst consequences. The critical questions of the stability, risks and benefits of CDR over the span of decades or centuries are intertemporal and intergenerational; the impact of each decision is spread over a long-time horizon.

Economic theory has traditionally examined intertemporal choice using the discounted utility model [53]. The discounted utility model says that utility today is worth more than utility tomorrow and the relationship between utility over time is explained by a discount rate. As the amount of time increases between a decision and its impacts, the value of the impacts declines according to a steady rate of exponential decay. According to the discounted utility model, if a CDR technology is market-ready, a monetary policy mechanism, such as a carbon tax or a cap-and-trade system, would be sufficient to lead to the socially optimal level of CO_2 removal since the monetary policy could equate the marginal costs and benefits [54].

But behavioural research indicates that people are often inconsistent in their time preferences and steeply discount non-immediate outcomes [55]. People behave as though they discount near-term impacts relative to the present at a steeper rate than they discount long-term impacts over moderately distant impacts [56]. People may be aware that climate change will exact catastrophic outcomes in the future; they may be willing to invest future resources to address climate change, and yet they might be reluctant to invest near-term sources to address climate change. Such present bias tendencies can inhibit decisions that require an upfront investment for longer term pay-offs [57] such as afforestation, reforestation and SCS.

The barriers to optimal choices over time are exacerbated by long-time horizons that stretch across generations. Psychological distance—the feeling of disconnection because of a separation in time, geography and social connection—is a significant barrier to considering the benefits of one's decisions to future generations [58,59]. The issue of consistent choices over time and across generations is especially important for CDR efforts that are reversible. Carbon stored in a forest can be released back to the atmosphere if the forest is cut down or burned. This could occur as a result of changes in circumstances (e.g. a landowner requires an influx of cash because of financial circumstances) or changes in ownership as land is sold or inherited. Emphasizing the value of legacy can increase intergenerational generosity [59,60], and this kind of messaging could be employed to increase maintenance of sequestered carbon. Perhaps formalizing the legacy aspect by encouraging naming of forests that are designated for CDR might leverage cross-generational legacy motives for continuity of CDR; people may be more hesitant to clearcut a forest named for their grandfather than a nameless tract of land. Additionally, making the good intentions of past generations prominent in decisions increases generosity towards future generations [61]. Creating narratives of legacy and intergenerational beneficence around reversible CDR efforts may help engender preservation across generations. However, explicit policy mechanisms to ensure continuity of carbon sequestration should also be explored. The legal structure of land trusts that limit changes in land use may be a useful starting point.

Inconsistent temporal discounting and present bias pose special challenges to CDR technologies that require large short-term investment and ongoing costs but will not yield observable dividends until the distant future. For DACCS, a critical challenge is implementing technology at scale, which will always require near-term costs—manufacturing and installing infrastructure, for example—while the benefits will always be in the distant future. For SCS, farmers may invest less than is socially beneficial because the immediate costs tend to be overweighted compared with the longer term benefits. Subsidy programmes (or carbon pricing scheme) that provide carbon-based payments ahead to offset the costs of investing in regenerative practices may improve adoption. Similar attention to the timing of financial support for DACCS and other CDR technologies, such as capital investment subsidies or accelerated depreciation instead of (or in addition to) per tonne of CO_2 sequestration subsidies, may help overcome temporal inconsistencies in choices with upfront costs and longer term benefits.

2.2.4. Emotional amplification

Emotional factors profoundly shape utility, value, risk response, probability weighting and choice over time. When people's emotions are heightened, often by evocative imagery or claims of existential threat, they are even more likely to display many of the tendencies discussed above. For example, people are even less sensitive to changes in outcomes and probabilities in highly emotional contexts than they are in less-emotional contexts [62,63]. When a choice and its potential outcomes are emotional, people are even more sensitive to departures from certainty (e.g. 0% to 0.1%) and less sensitive to changes in intermediate probabilities (e.g. 40% to 60%).

In responding to risks, people rely largely on the emotions they experience, even ignoring factual information about probabilities [52,64,65]. Instead of analytically assessing the risk and outcomes of a choice, people tend to assess how they feel about the decision, a phenomenon known as the affect heuristic. And when making choices about outcomes over time, people are even more present biased when they experience intense emotions; the emotionally laden 'hot' wrestles control from the 'cool' and people tend to act on immediate desires, disregarding future outcomes [66,67].

The emotional amplification of behavioural tendencies presents at least two challenges to CDR. One is that the vested interests' heated rhetoric, and anxieties surrounding climate change, imbue CDRs with emotionally evocative potential. The emotionality of public discourse surrounding CDR is unpredictable, yet can powerfully influence behavioural responses. For example, if SCS is framed as a climate change mitigation strategy, then how farmers feel about the issue of climate change could influence their decision about whether to adopt SCS practices through the affect heuristic. Introspection and deliberation also can help. In many cases, for example, stakeholders' emotional concerns are not supported by the likely impacts of management initiatives; as part of work with forest scientists in British Columbia, Canada, examining management alternatives under climate change, experts' initial emotionally charged views were tempered by a careful analysis of the predicted consequences of different strategies [68]. Communication about CDR, with science experts as well as the public, will benefit from careful attention to emotional considerations and the inclusion of primes that encourage introspection, providing a structured opportunity for reflection and deliberation to inform initial, and potentially misleading, intuitions.

Another challenge is that people tend to underestimate how much emotional factors will influence their own and other people's decisions [69]. The dispassionate analyst or policy-maker may underestimate people's risk aversion when contemplating new technologies, and these 'empathy gaps' could lead them to make decisions or design policies that fall on deaf ears. An analyst who evaluates the low risks and high upside of DACCS may fail to appreciate the negative emotional reactions to large, highly visible machinery and how those negative emotions inflate ordinary people's risk perception and insensitivity to the risk–reward trade-off.

2.2.5. Summary

Much of the current discourse among scientists and policy analysts about CDR and negative emissions implicitly assumes that decision-makers and members of the public will exhibit coherent, rational behaviour that weighs the costs and benefits of CDR without bias. This brief overview of behavioural decision theory should make clear that reactions of elected officials, industry leaders and public citizens to CDR will be different and more complex than implied by the rational choice theory. A behavioural analysis will be critically important to anticipate and understand public reactions to CDR technologies and policies. It will be critical to develop a fuller understanding of the surrounding communication and social and political landscapes as public discourse takes shape. A challenge is that public discourse is intertwined with social identity, group and social network processes.

3. Section 3: social constructive processes

The adoption of CDR at a scale sufficient to draw down carbon emissions will require both individual and collective decisions. The previous section considered individual behavioural decision tendencies that may influence the public response to CDR. We consider some social processes that shape individual and collective behaviour that could either facilitate or inhibit CDR adoption.

CDR at climate-significant levels will depend on social processes—the fundamental ways in which people interact and form social relationships. We will look at a few examples of these various social processes by looking through the lens of our two examples of SCS and DACCS. Drawing down enough carbon through SCS to make a difference in greenhouse gases depends on large, extended shifts of farmer behaviours, which would also entail strong policy support and incentives, necessitating broad public support. From the landholder perspective, SCS requires different agricultural equipment, planning, knowledge; perhaps different software or bookkeeping and forming relationships with buyers of carbon credits. Additionally, the costs and benefits of engaging in SCS differ depending on whether one is a landowner or renter. In this section, we consider three types of social processes: intergroup processes, intragroup processes and social network processes.

3.1. Intergroup processes

Intergroup processes describe the basic relations between members of different social groups, including the important role of social influence and social norms in governing (inter)-group behaviour. Broadly, the study of social influence explores how people are impacted by other people's thoughts, feelings and behaviours.

3.1.1. Social norms

Social norms are generally defined as 'rules and standards that are understood by members of a group, and that guide or constrain *social* behaviours without the force of law' [70, p. 152]. Social–behavioural scientists have distinguished between two separate sources of influence: normative (prescriptive) and informational (descriptive) influence [71–73]. Normative influence occurs when individuals act according to the beliefs and expectations of others about how one *ought* to behave whereas informational influence simply refers to statistical information about what others are doing. Social norms have been leveraged to influence and change a wide range of pro-environmental behaviours and are often regarded as one of the most effective ways to change behaviour [74–76]. In general, social influence processes could work both for and against adopting practices that sequester carbon and amplify opinion and behaviour across groups. For example, among some communities, there is a certain bragging about yield per acre, or an admiration of a well-tilled field of corn, reflecting the prevailing prescriptive norm about how to act in the community, and regenerative farmers—farmers that have chosen conservation practices, including those that store more carbon—have remarked that counteracting these norms can be difficult.

3.1.2. Norm perception

Similarly, perceived descriptive norms (what others are doing) can act as both a lever and a barrier to social change. Descriptive norms function as 'social proof' evidence that many others are thinking along the same lines or have adopted the same behaviour [77]. People will often converge towards group consensus in a heuristic fashion: 'If everyone is doing or thinking or believing it, it must be a sensible thing to do or think or believe' [71, p. 203]. Yet, people also frequently misperceive or do not know what the actual norm is around a particular belief or behaviour. For example, the majority of the population misperceives the degree of consensus among scientists (97%) about the fact that humans are causing climate change. This misperception provides a leverage point to correct people's perception of the norm, which in turn is associated with personal support for climate action [24,78]. Similarly, partisans can perceive false 'norms of opposition' to climate policy, which can undermine their own support for policies [79]. In fact, regardless of what the actual norm is around a given belief or behaviour, much psychological research has found that people's *perception* of the norm can be an important vehicle for social change because it is easier to influence people's perception than to change the actual norm [80]. For example, a farmer seeking to adopt regenerative agriculture may find it challenging if they do not know or accurately perceive people in their peer group who are engaging in similar behaviours. To this extent, the rise of the Internet has changed the picture—for example, many regenerative farmers can now access information via YouTube. Like many others who are embarking on this journey, and sharing information about it, the behaviour seems more possible and more popular. In other words, the more farmers perceive a new norm from influential peers in their network, the more likely they are to conform to it.

3.1.3. Group polarization

Another intergroup process, group polarization, occurs when a group makes decisions or moves in a direction that is more extreme than the positions that members would take individually [81]. For example, processes of group attitude polarization may be at work among entrepreneurs in carbon-tech, who may be moving in a more ambitious direction than they would on their own; regenerative agriculture advocates, who may draw support and inspiration from each other to make more strident claims about its carbon sequestration potential than they would on their own; and fossil fuel industry groups, who may be empowered to move in the direction of carbon management if an entire coalition is going that way. More research is needed to understand group polarization when it comes to CDR.

3.2. Intragroup processes

Intragroup processes often refer to relations and conflict between members of the same social group. Intragroup issues around social identity, political polarization and competition are some of the most relevant for carbon removal policy and adoption. Not least because climate change is a highly polarizing and competitive issue, especially in the USA, where the partisan gap has been increasing [82]. For example, over the last 10 years, the proportion of liberal Democrats who believe in climate change rose from 91% to 97% whereas the proportion of conservative Republicans who believe in climate change fell from 50% to 40% [83].

At the moment, carbon removal is a bipartisan area of compromise in the US policy arena, evidenced by the passage of legislation of a key tax credit for CCS in 2018 (45Q), and bipartisan introduction of bills to fund direct air capture and blue carbon research.

However, individual attitudes about carbon removal are likely to be influenced by partisan identities around climate change, as people who perceive climate change as a serious threat are generally more accepting of carbon removal measures [84,85]. Yet, other research has found that the effect of learning about large-scale carbon dioxide reduction technologies shares a more complex relationship with political ideology [86]. One study found that decreased threat perceptions led to reduced support for mitigation policies across the political spectrum, but that this effect was more pronounced for conservatives, and suggested that learning about certain types of CDR may lead to reduced support for mitigation by diminishing climate risk perceptions [86]. Another study found that the focus on human ingenuity inherent in geoengineering solutions fits well with the group identity of conservatives [87].

For SCS, these processes of identity and competition may actually be less pronounced in many communities because farmers live near one another and share a community and the incentive to preserve social ties. But with other carbon dioxide removal techniques, such as DACCS, intragroup processes such as identity and competition may be highly relevant. People who identify as environmentalists, for example, take issue with using carbon captured with DACCS for enhanced oil recovery. It is not simply a matter of disagreement, but of social identity. The context matters: Dowd *et al*. [88] suggested that bioenergy plus CCS could receive greater support than bioenergy or CCS individually; Dütschke *et al.* [89] found that CCS is rated more positively if the CO_2 is produced by biomass rather than by coal; and Whitmarsh *et al.* [21] similarly indicated that bioenergy with CCS is more supported. Contextual factors could include the end-use of the carbon, the source of the carbon and the proximity of the site. Braun *et al*. [84], in a study in Germany, found that living close to a CCS site reduces acceptance of the technology, suggesting that this is because local populations bear the perceived risks from the site; this has also been observed in the Netherlands [90] and Switzerland [91]. Similarly, in a study in Indiana, 80% of the local residents supported the use of CCS in general, but a fifth of those would oppose CCS in their communities [92], positions that were influenced by respondents' worldviews, their beliefs about economic benefits and safety concerns. Thus although carbon removal has some bipartisan support at the moment, because individual attitudes on the issue can be influenced by partisan cues and identities, scholars have suggested that, if any lessons can be learned from the climate debate, trusted non-partisan messengers should be used to prevent 'ideological bundling' of negative emissions technologies [93].

3.3. Social network processes

Social network processes describe and formalize social connections between individuals, including emergent behaviour, the social amplification of risk and the diffusion of social and cultural influences. In this sense, social network theory subsumes a whole variety of intra- and intergroup processes, as groups are just an example of one kind of network structure. Social network processes reveal not only who belongs to a group (or multiple groups) but also the structure and nature of the relations among people both within and between groups and larger communities [94].

Social network studies reveal insights about the diffusion of information among strong and weak ties in a network and how the structure of the network can influence the flow and acceptance of information. For example, recent studies show that belief exchange about climate trends in a structured bipartisan network can reduce biased interpretation of climate data and belief polarization [95]. Returning to the example of farmers considering whether to change practices to ones that store more carbon, Evans [96] points out that adoption is strongly influenced by social networks, and decades of research shows that information from trusted peers is more valued than advice from extension agents or outsiders.

Cultural influences include values, such as naturalness. Wolske *et al.* [45] found that techniques like afforestation were preferred as they were believed to tamper with nature less. However, Thomas *et al.* [97], in a study of CCS, found that these perceptions could shift when CCS was re-contextualized to include information about the intermittency of renewables and that it can be used with bioenergy or industrial applications. The social amplification of risk [98], however, describes how intermediary processes (e.g. information channels, the media) may attenuate or amplify the communication of risk and may work counter to carbon dioxide removal, as concerns (e.g. about the risks of geological storage) could be amplified through social diffusion.

It is through these intergroup, intragroup and network processes that individual-level decisions are aggregated and come to influence culture and policy. Simply suggesting policy changes without considering these processes is unlikely to be successful. For example, a headline in the 17 July 2019 issue of the *Rural Messenger* reads 'These Programs Will Pay Kansas Farmers for Crops They Won't Harvest', and profiles the effort of Indigo Ag to start an SCS platform. As a farmer quoted in the article states, 'I don't understand why they would pay us, but if they do, I guess we'll take the money' [99]. But how many more farmers might adopt this behaviour if it involved more than just payments, but spoke to values, via their social networks? Similarly, public engagement around CDR technologies that addresses individuals in isolation without understanding these social processes is unlikely to be successful at a larger societal scale.

Importantly, social processes are not just at work within groups in the general public, but also within innovators, researchers, investors and those advocating for policy. As such, social processes are not simply an obstacle to be dealt with, but an opportunity for policy and social change. The potential for this kind of opportunity is exemplified by the example of the passage of the 45Q tax credit in the USA. This tax credit for carbon capture, revised in 2018, was done so by virtue of a coalition involving think tanks and NGOs like C2ES and the Great Plains Institute; energy companies like Arch Coal, Shell and Peabody; and labour unions and green groups like The Nature Conservancy—and building that coalition was a deeply social process, in which professionals aggregated information about what their neighbours were doing, questioned and clarified their identities, and built a social network that continues to inform carbon removal policy today.

These social processes combine with individual behavioural decision frameworks to produce powerful forces that may be harnessed to drive support for CDR technology development and deployment or to drive divisions along political lines that slow or block CDR efforts. For example, reference points that are critical to setting the baseline for loss aversion and risk aversion tend to be set by perceptions of social norms. If conventional agriculture that misses opportunities for carbon sequestration is perceived as the norm or status quo, then adopting practices that increase carbon sequestration will be viewed as a gain from the reference point and treated with a stronger level of risk aversion and be less willing to depart from their normal agricultural practices. Additionally, risk perception is heavily influenced by how people feel about the activity. The emotional component is in turn largely driven by the messages people hear from those around them and their trusted messengers and leaders in their social groups. Conversely, if, for example, environmentalists see DACCS as a technology promoted by those traditionally supporting oil and gas development, then they may create negative associates that lead to distrust and rejection of DACCS and other CDR approaches as a valid mitigation approach to climate change.

3.4. Summary

People do not form attitudes and opinions in a vacuum. For better or worse, our judgements and choices are influenced by the decisions of other people we care about. In this section, we have outlined how fundamental social normative principles shape important intergroup, intragroup and social network processes that guide support for or opposition to CDR technologies. A key take-away is that large-scale public support for CDR can only be achieved by carefully considering the social and cultural context that guides behaviour, public opinion and social interactions among farmers, policy-makers and other key stakeholders.

4. Section 4: research agenda for behavioural components of carbon dioxide removal

Trees were drawing carbon dioxide from the air long before human civilization existed. Yet the concept of carbon dioxide removal as a critical part of the climate change response portfolio is unfamiliar to the general public. People have not yet formed strong attitudes and beliefs about most of the individual CDR technologies or stances on policy mechanisms and tax-payer support for CDR. We have sought to highlight key behavioural science principles that are relevant for how the public views CDR technologies. We have also pointed to key insights that may help stakeholders craft public outreach strategies that integrate the nuances of how people evaluate the risks and benefits of CDR approaches.

Here, we incorporate these insights to outline a research agenda to understand the behavioural components of CDR and to anticipate and plan for an emerging public response. In planning this agenda, we must acknowledge a tension between two different views about the fundamental nature of attitudes, preferences and values. One is that people have stable, deep-seated, consistent preferences that are *revealed* through behaviours, decisions and responses to survey questions [100]. When asked for their opinion about SCS or DACCS, for example, people would retrieve from memory their past experiences and beliefs about each strategy's effectiveness, the urgency of addressing climate change and their personal values, and then integrating those concepts to generate a response. The formation of preferences is considered to be outside the domain of the analysis—what economists call 'exogenous preferences'. The view that preferences are represented by actions and decisions underlies the practice of public opinion polling. This view also underlies the common practice of contingent valuation where people are asked to express how much they would be willing to pay for a good directly or through tax policy support, such as polling to gauge support for subsidies to increase SCS or DACCS [101,102]. These methods assume that people consistently and reliably introspect about their underlying preferences to report them on surveys or translate them to monetary values.

A very different view is that people's preferences are *constructed* during the act of making decisions or responding to survey questions [41,103,104]. This view holds that people do not have stable preferences that are consistently expressed through behaviour. Rather, expressions of preferences such as stances toward CDR technologies are sensitive to context effects, question framing, emotional states, social contexts and other transient experiences. Preferences are formed within the domain of analysis—what economists call 'endogenous preferences' [105]. In generating responses, people integrate information that is readily available at that particular moment, often by relying on simplifying heuristics such as how easily responses come to mind [106,107], which objectives are most prominent [108] or how much an option generates positive affect [42,52,109].

The research reviewed above is more consistent with endogenous preference construction than with exogenous preference revelation. With malleable preferences, especially when preferences are not well defined as is currently the case with CDR, framing as gains or losses, the immediacy of intertemporal trade-offs and emotionally amplifying effects of vividness, intergroup pressures, intragroup processes and social network effects would have a strong influence on the construction of preferences. CDR strategies are relatively new and preferences about the overall strategy and about individual technologies are relatively unformed [19]. A critical question for future work is therefore to examine the degree to which CDR preferences are dependent on question phrasing and social contexts (see [100] for an illustration of measuring preferences while recognizing preference construction).

Examination of whether and how CDR preferences are constructed is particularly important because, once they are constructed, the expression of preferences can become stabilized and entrenched [110]. For example, oil companies have expressed interest in DACCS for its potential to enhance oil recovery. If people form opinions about DACCS by learning that it is being developed to enhance oil extraction, their views toward DACCS will be influenced by their opinions on oil extraction [93]. If oil extraction evokes feelings of dread or is aligned with opposing political groups, people may dread and dislike DACCS through affective association—more than they would have if they first learned of DACCS in association with researchers working to reduce atmospheric carbon dioxide concentrations. The narratives surrounding CDR are not yet set, but the context for public discussion is rapidly being shaped.

The association between CDR and fossil fuels can also be established indirectly through a concern about moral hazard. Moral hazards occur when insurance or other circumstances protect the decision-maker from the full impact of a reckless decision, thus creating an incentive to mismanage risks [111]. In the context of CDR, moral hazard has been talked about with regards to mitigation deterrence [112], leading some to argue that targets for carbon removals should be set separately from mitigation targets [113]. A randomized control experiment that tested how learning about different CDR technologies could decrease support for greenhouse gas mitigation found that learning about certain CDR technologies reduced support for greenhouse gas mitigation by decreasing the perceived threat of climate change [86]. In qualitative studies, respondents have expressed concerns that using CO_2 for enhanced oil recovery means that CCS will not be a bridge to renewables, but a means of continuing with a fossil fuel economy [114,115]. Studies examining the moral hazard of geoengineering found that presenting the technology as a partial solution to climate change did not trigger a moral hazard response [22,116]. If the narratives around CDR are presented as a cure-all for climate change, then decision-makers may place less priority on reducing carbon emissions.

The evolution of partisan public opinion on climate change in the USA is a stark example of how an issue can begin as non-partisan, but become polarized over time as preferences are linked to competing group identities. When climate change emerged as a significant issue in the national conversation in the late 1980s and early 1990s, Democrats and Republicans expressed nearly identical levels of concern in Gallup polls, after which partisan opinions became increasingly polarized [117]. One analysis of this polarization is that climate change became associated with prominent liberal leaders such as Al Gore and liberal media outlets [118], making it a wedge issue that differentiated the parties and made it threatening to Republicans [119]. Such ideological bundling, the phenomenon of associating issues with ideological stances and parties [93], could entrench partisan opposition to CDR as part of an overall climate strategy. Indeed, recent evidence suggests that, in the USA, attitudes towards the Green New Deal only recently became polarized as it became nationally prominent [120]. Examining how to avoid and counteract ideological bundling is a critical question for future work.

Another important question for CDR research is to examine whether the expression of preferences can be managed constructively through structured social processes of deliberation. Deliberative approaches have the potential to help people to comprehend the questions asked of them and understand more fully the reasons for others' differing perspectives [85,121]. The hope is that by embracing a more behavioural model people can learn enough about both themselves and the topic to express considered and relatively stable responses [122]. Structured decision processes, for example, help stakeholders and decision-makers follow a logical sequence of steps that encourages the comprehensive identification of their objectives (i.e. what matters to them in this specific CDR context) prior to evaluating policy alternatives, thereby encouraging the consideration of preferences that align with broader beliefs and are less susceptible to manipulative or haphazard influences. Examples in the domain of climate change adaptation have included key-informant interviews, small group meetings and large-scale regional and national surveys [85,121]. How best to implement structured deliberation for CDR narratives, integrating both expert and public input while minimizing framing effects and ideological bundling, presents important challenges for both policy analysts and decision-makers.

Another key area of enquiry involves how people learn about norms within their communities, which can be informed by their social networks. There is currently little research on the topology and structure of CDR social networks, but understanding the structure of social networks will also inform related questions about public perception of social norms regarding others' stances towards CDR and other climate policies [123]. There is ample existing evidence that perceptions of social norms strongly influence public concern about climate change [24], support for climate policy [79,124] and the prioritization of climate over other pressing issues [125]. This work indicates that it is difficult to overcome perceptions of social norms—even if those perceptions are incorrect—to shape personal stances towards climate policies such as CDR. Communication about CDR, both as a general strategy and about specific technologies, should therefore be particularly attentive to emerging social norms regarding CDR, and more research about social networks would also be useful in understanding how norms spread.

Consideration of social norms is especially relevant when deliberating the possible political polarization of CDR. People are influenced by political elites' stances on climate policy—largely, elites' stances convey information about broader social norms among ordinary citizens [79,124]. Preliminary evidence suggests that political elites only influence public opinion towards climate policy to the extent that elites' stances align with broader social norms [125]. It is therefore possible that structuring (as described earlier), measuring and communicating public attitudes could forestall political polarization of CDR—another pressing question for behavioural research.

5. Conclusion

Natural sciences and engineering have a clear role to play in developing CDR technologies to reduce global atmospheric concentrations of carbon dioxide. Yet, the history of climate change efforts has shown that science and technology cannot stand alone. Individual and social judgement and decision processes are powerful forces that shape the support for and deployment of potential technological solutions to climate change. In this paper, we have attempted to review relevant aspects of behavioural and social science in the context of CDR technologies. We cannot provide perfect advice for natural scientists, engineers and climate communicators because there are many questions that remain unanswered. However, we can proceed by attending carefully to what we already know about the ways in which people value outcomes, assess risk and make decisions over time as well as how social processes shape the information that is deemed relevant and salient for each decision-maker. We also call for a major push in the development of social science research on CDR technologies and efforts. These technologies offer great promise, but the social context and individual decision processes are absolutely critical to successful deployment of these technologies on a scale that is needed to rapidly address the problem of global climate change.

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