Received: 25 October 2022 | Revised: 25 July 2023 | Accepted: 16 August 2023

DOI: 10.1002/wcc.857

ADVANCED REVIEW

WIREs CLIMATE CHANGE WILEY

Carbon removal demonstrations and problems of public perception

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Funding information
Natural Environment Research Council, Grant/Award Number: NE/V013106/1

Edited by: Simone Rödder, Domain Editor and Maria Carmen Lemos, Editor-in-Chief

Abstract

Expectations about the future removal of carbon dioxide from the atmosphere have mobilized projects which seek to demonstrate carbon removal methods, at various stages of development. Public perceptions play a critical role in demonstrations and funders widely require demonstration projects to identify and consult affected groups and communities. This review examines the extant research on perceptions of carbon removal, analyzing how studies have conceptualized the public and the role perceptions play in field trials and experiments of carbon removal methods. The paper develops a novel analytical framework distinguishing between "procedural" and "performative" approaches to demonstrations. Attending to performativity, we suggest, makes clear why demonstration projects often surface conflicting expectations about future technology development. We apply the analytical framework to the academic literature on perceptions of carbon removal using a systematic search and interpretive review. We find that much perceptions research on carbon removal adopts elements from linear models of innovation, foregrounding the problem of social acceptance and distancing the public from experimental presentations and displays. We situate these findings in a discussion of the roles that expectations about carbon removal play in demonstrations and the positioning of perceptions research as a tool for managing "opposition" from external audiences. Moving beyond instrumental approaches to public perception, the review makes the case for closer engagement in perceptions research with conflicting expectations that emerge around projects demonstrating the "promise" of carbon removal.

This article is categorized under:

The Social Status of Climate Change Knowledge > Knowledge and Practice

Perceptions, Behavior, and Communication of Climate Change > Perceptions of Climate Change

Climate, History, Society, Culture > Technological Aspects and Ideas

KEYWORDS

carbon removal, demonstrations, perceptions, performativity, publics

1 | INTRODUCTION

Demonstration projects today are powerful formats through which the technosciences evaluate the promise of an invention to address social and environmental issues (Barry, 2001; Jasanoff, 2005; Rosental, 2013). Understanding how the promise of early-stage technology is perceived by potentially affected groups and communities is critical to the process by which demonstration projects set expectations about future technology development, and it is not uncommon for demonstrators to elicit public concerns through consultations and focused discussion (see discussions in Laurent, 2011; Papazu, 2017; Chilvers & Kearnes, 2015; Wynne, 2015). There are now many examples where demonstration projects encounter resistance when such exercises fail to represent public concerns, which can lead concerned groups to mobilize and stage competing demonstrations of the issues at stake (e.g., Tironi, 2015). In this review, we approach the topic of public perception not only as a question of how projects manage communication with audiences, but also as a practical problem with which demonstrators must contend in staging "real-world" experiments.

As projects demonstrating methods for removing carbon dioxide from the atmosphere proliferate, this review examines the extant social science research on perceptions of carbon removal. The analysis presented here focuses on how perceptions researchers conceptualize the public and the role perceptions play in field trials and experiments.[1] Such questions are not only a matter for academic social scientists. Funders now widely require carbon removal projects to demonstrate "public engagement" and evidence measures taken to identify potentially affected communities and gather concerns.[2] The review of the academic literature is therefore situated within a broader exploration of the roles that perceptions research can play in interrogating the landscape of expectations in which demonstration projects intervene.

The relationship between demonstration projects and the public is a topic addressed in recent innovation literatures on carbon removal. Prominent in these literatures are models that position projects demonstrating carbon removal methods within a linear trajectory of technology development. Figure 1 appears in a review paper on the innovation of carbon removal conducted by an interdisciplinary research team (Nemet et al., 2018). In it, demonstrations are positioned as procedures for presenting proofs where future projections can be evaluated and learning can occur as technologies progress toward the phase of "scale up." Demonstrations in this model also serve to set expectations among policy and industry actors, and mobilize financiers to invest in early-stage development, addressing a problem formulated in innovation literatures as the "valley of death" that suggests technologies will not make it to commercial phases of development without sufficient financial incentivization (Nemet et al., 2018).

Linear models of demonstration position the public at the end of a technological trajectory, and have been long critiqued by historians and sociologists for over-simplifying the role played by experimental research in technology development (e.g., Bijker et al., 1989). Because they are designed as recipes for successful innovation, linear models typically offer only external (and sometimes circular) explanations for why some technologies succeed while others do not, ignoring the specific problems that organize research and the ways problems may be modulated through technology development. For the purposes of social analysis, such models may obscure more than they reveal about the different roles demonstration projects can play in technology development and innovation practice (see Markusson et al., 2011 for an example in the context of carbon capture and storage (CCS)). Nonetheless, the prominence of linear models indicates the power of this way of representing the roles played by science, industry and the public in (future) carbon removal; as affirmed by its republishing in the *State of Carbon Dioxide Removal* report (Smith et al., 2023).

Drawing on insights from the social study of demonstrations, this review develops an analytical framework against which to assess the literature on perceptions of carbon removal. This framework foregrounds the "performativity" of demonstration projects: outlining how practices of demonstrating bring emergent publics into being. Rather than treating the public as a distant audience passively waiting to receive and accept a technical proof—as linear innovation

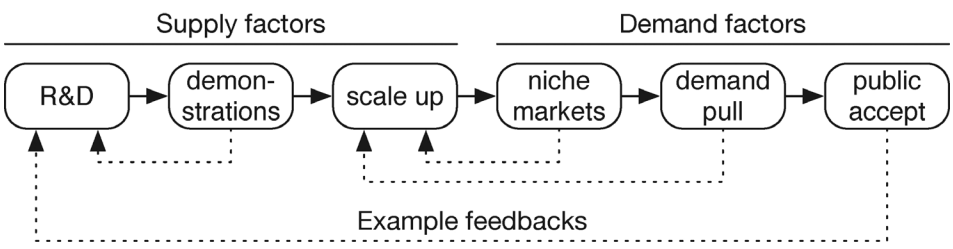

FIGURE 1 Stages of innovation. *Source*: Reproduced with permission from Nemet et al. (2018).

models tend to—, performative approaches attend to the collectives mobilized by demonstrators' public presentations and displays; what the late Bruno Latour (1993) called the demonstrator's "theater of proof." Following the conflicts that surface around the staging of real-world trials and experiments, we suggest, can bring into view issues that may be obscured when the public is distanced from the scene of demonstration.

In Section 2, we synthesize literatures on the social study of demonstrations to develop the review's analytical framework, mapping the distinction between *procedural* and *performative* approaches across four dimensions of demonstration practice. Each of these dimensions are summarized in a key question asked of the carbon removal perceptions literature in Section 3, where we undertake a systematic search and interpretative review of the academic literature on the topic. In Section 4, we discuss strategies for engaging research on perceptions with conflicting expectations that surface around demonstrations. We conclude by pointing toward the wider relevance of the findings and framework developed here for understanding and interrogating the "promise" of carbon removal demonstrations.

2 | THE PERFORMATIVITY OF DEMONSTRATIONS

This section outlines an analytical framework for attending to the performativity of demonstrations, based on insights from social studies of experimental presentations and displays. We construct the framework around four dimensions of demonstration practice: sites, identities, media and instruments. These four dimensions of practice are likely to represent considerations that many demonstration projects on carbon removal will address. For each dimension we distinguish between *procedural* accounts, that characterize demonstrations in terms of generalized procedures independent of the particular experimental practice, and *performative* accounts that foreground the practical dilemmas involved in staging a demonstration (summarized in Table 1). These four dimensions of demonstration practice are not discrete categories and overlap in various ways. We have selected them to illustrate the contrast between *procedural* and *performative* accounts of demonstration from a variety of practical vantage points.

TABLE 1 Distinctions between procedural and performative approaches to demonstration mapped across four practical dimensions: sites, identities, media, and instruments.

Dimension of demonstration	Procedural account	Performative account	Perception problem
Sites	The site of demonstration is a public space that is in principle open to all. Site-specific practices involved in experimental presentations have no bearing on the content of the experiment.	In practice, distinguishing spaces of experimental presentation from settings of experimental practice requires demonstrators to carefully manage access to demonstration sites in ways that both engage and exclude audiences.	Differentiating open spaces of experimental presentation from enclosed settings of experimental practice.
Identities	The public authority of experts is defined by the possession of technical knowledge. This can be demonstrated regardless of the success or failure of an experimental intervention.	In practice, the authority of demonstrators as experts is relational to "non-experts" and contingent on maintaining control over the objects shown or evidence displayed.	Connection between expert identities and practices of displaying objects or evidence.
Media	Media are communication technologies used to publicize demonstrations and diffuse experimental results to external audiences.	In practice, media are also technologies used in the conduct of experiments and can be deployed to stage more-or-less interactive styles of experimental presentation.	Appropriateness of media technologies/formats to the style of experimental presentation.
Instruments	Instruments used in experimental practice operate transparently, and their technical capacities are knowable independent of claims made by the demonstrators who deploy them.	In practice, instruments are often a focus of scientific controversies and can be deployed by demonstrators to contest issues and challenge what counts as relevant evidence.	Alignment between problem/issue definitions and the instruments used to produce evidence.

The concept of performativity has been widely deployed in debates about the roles that expectations about the future play in science and innovation (Brown & Michael, 2003; Konrad et al., 2016). Critical scholarship has highlighted ways in which the concept may help bring the politics of speculative carbon removal solutions into focus, as they are evaluated in the "world-making" practices of global climate assessments (Beck & Mahony, 2018; Carton et al., 2023). Alongside the concept's value for critical analysis, the capacity to be reflexive about practices of world-making is also integral to demonstrating carbon removal. As analysis of carbon offsetting projects shows, a prerequisite for establishing the future value of an intervention is demonstrating the "realism" of counterfactual scenarios (i.e., worlds in which there is no intervention) (Ehrenstein & Muniesa, 2013). Building on this work, we apply the concept of performativity to highlight that perceptions of demonstration projects as "real-world" trials and experiments—that is, as interventions that interrogate expectations in public as opposed to secluded research environments—rest on the ways that demonstrators navigate practical problems of presentation and display. Rather than separating the public from the practice of science and innovation, as procedural accounts tend to, we outline how practices involved in the staging of demonstrations can surface conflicts and emergent publics.

In the following sub-sections, we briefly outline distinctions between *procedural* and *performative* accounts of demonstration across the four dimensions of practice, linking problems of perception to practical dilemmas. For each dimension we generate a question, which we then pose for the perceptions literature in Section 3.

2.1 | Sites

Demonstrations necessarily entail site-specific presentations; yet demonstrators typically aim to generate effects in public spheres not defined by place. Social studies of science have long highlighted the contradiction between, on one hand, public discourses about experiments—which requires experiments to be staged in spaces that are, in principle, open to all—and, on the other hand, the practices of experimenters who may often restrict access to spaces of experimental display (Haraway, 2004; Shapin & Schaffer, 1985). Contestations over access to demonstration sites can bring into view competing constructions of the setting of experimental practice. For example, in the case of experimental research on Genetically Modified Organisms (GMOs), activists entered fields to destroy crops and stage street-style demonstrations in full daylight, thus transforming the sites of field trials into spaces of political protest (Bonneuil et al., 2008).

Sociological studies have examined the ways in which specific locations can both enhance and constrain the capacity of demonstrations to engage and persuade. For example, Latour's (1993) account of Pasteur's animal vaccination demonstrations in the late 19th century spotlighted the instrumental role played by a provincial French farm in engaging different actors concerned with the controversy over the relationship between microbes and disease. The power of the microbiology lab, Latour argued, is poorly understood if the farm-based demonstrations are disconnected from struggles over experimental closure of the controversy. However, overly-instrumental approaches to the sites of demonstration may also limit the capacity of an experiment to engage audiences. Lezaun's (2011) cautionary history of a 1970s worker participation experiment in Norway illustrates how an "offshore" location of demonstration on a merchant ship—a location crucial to the practical realization of the model democratic workplace—limited the experiment's impact, as an exemplar for wider workplace reform. In different ways, then, site-specific practices play a critical role in demonstrators' attempts to construct spaces of experimental presentation and display. Perceptions of demonstration sites as public spaces therefore relate not only to their accessibility to audiences but also to the techniques demonstrators deploy to differentiate sites of experimental presentation from settings of experimental practice.

> **Question 1.** *To what extent is research on perceptions of carbon removal situated in, or in relation to, specific sites where trials or experiments are staged?*

2.2 | Identities

The ways in which experts come to be perceived as sources of authority on public issues has provided a significant focus of critique in social and cultural studies of experimental practice. The capacity to conduct experiments has long been associated with forms of social stratification and the privilege of certain collectives to act in public (Ezrahi, 1990). Historically, for example, the experimental demonstration can be seen as a novel gendered form of civil interaction that not only excluded women from public spaces of science but also rendered invisible all forms of knowledge

production deemed feminine (Haraway, 2004). Procedural accounts of demonstrations thus offer a highly reductive account of experimental culture (Traweek, 1988), implying that the authority of experts stems solely from the possession of technical expertise which can be demonstrated regardless of the success or failure of an experimental intervention.

Empirical studies interrogating the authority of demonstrators have widely examined the relationship between expert identities and practices of displaying objects or evidence. Demonstrators themselves are often highly skilled performers who may act out well-rehearsed scripts in the public presentation of an experiment (Collins, 1988). Yet, even when presentations are highly scripted, such as software product launches by technology entrepreneurs, divisions between demonstrator and audience identities are often unstable and bound up with wider "regimes" that structure practices of demonstration in public life (Rosental, 2013). Particularly in early market-making activities, the performance of authority does not always derive from pre-given expert identities, and practices of demonstrating technologies often involve playing multiple roles and switching between technical skills (Pinch & Trocco, 2004). In the context of environmental disputes, strong distinctions between the expert and non-expert identities of demonstrators can obscure the material practices that lead to knowledge claims gaining public authority. For example, Barry's (2001) analysis of environmental road protests shows how direct-action techniques—where protestors used their own bodies to evidence potential environmental harms—proved powerful precisely because they could not be identified with established positions in the road building debate. Such analyses challenge procedural notions that the authority of demonstrators stems from the prior possession of expertise. We see here that perceptions of demonstrators as figures of public authority is contingent not simply on performing established expert identities but the ways such identities are connected with practices of putting objects and evidence on display.

> **Question 2.** *How are the identities of experts and other participants constructed in studies on perceptions of carbon removal*?

2.3 | Media

The roles played by different media in the presentation of experiments and audience interaction has provided a long-standing focus of social studies of demonstration. In procedural accounts of demonstration, questions about the roles played by media are typically confined to concerns about communication with external audiences and the diffusion of knowledge or expertise following an experimental presentation. By contrast, studies of media in demonstrations show how media-technologies often play a central role in the conduct of experiments and can enable the staging of more-or-less interactive styles of demonstration. Print formats of publicity have, for instance, occupied a central position in the history of experimental science as the primary medium through which audiences not physically present can "virtually witness" demonstrations (Shapin & Schaffer, 1985).

The interactivity of contemporary digital media often requires demonstrators to confront questions of public participation. As Girard and Stark's (2007) analysis of demonstrations by experts and activists around the post-9/11 inquiry into the rebuilding of Lower Manhattan showed, digital media technologies can not only expand participation in the process of gathering and presenting evidence but also reframe the issue and relevant spaces of public assembly (see also Moats, 2019). The interactivity of digital media technologies can also be harnessed by demonstrators to close-down issues. Tutton (2021), for example, highlights how styles of experimental presentation by technology entrepreneurs are designed specifically for digital platforms and the attention-seeking logics of engagement characteristic of Silicon Valley-style capitalism, evading issues relating to risks and dangers of technology development.

Concerns about the ways media can be deployed by demonstrators to restrict participation are not specific to interactive digital media. Whatmore and Landström (2011), for example, describe how a participatory flooding inquiry, involving an experimental research collaboration between scientists and local residents, was effectively erased in the reporting of the issue by news outlets and public authorities. Nonetheless, the proliferation of digital media has raised many questions about how the capacity to stage experimental presentations and displays is distributed in society. For instance, platforms and blogs have given rise to distinctive styles of experimental presentation ranging from "destructive testing" to "green living experiments" (Marres, 2012; Michael, 2018), shedding light on the heterogeneous social actors that participate in experimental culture today. Such instances make clear the roles that media technologies play not just in facilitating interaction between demonstrators and audiences but also in challenging perceptions of what

constitutes experimental practice and the social actors that participate in staging experimental presentations and displays (Lezaun et al., 2016).

Question 3. *What roles are attributed to media in studies on perceptions of carbon removal*?

2.4 | Instruments

Instruments—the tools required for experiment—traditionally occupy a central place in experimental demonstrations as technical devices supporting the claims made by demonstrators. In procedural accounts of demonstration, the technical capacities of instruments are assumed to be knowable, independent of claims made about them by demonstrators. Such assumptions have been widely critiqued in studies of scientific controversies showing that instruments themselves frequently become objects of contention, around which claims made by demonstrators are contested (Shapin & Schaffer, 1985). Collins (1981), for example, described how the controversy over the existence of gravitational waves centered on the design and calibration of the devices used to detect them. Beyond re-opening age-old questions about whether inscriptions produced by instruments are more like words or "things" (see discussion in Hankins & Silverman, 2014), such studies highlight how demonstrators may variously reveal or obscure the inner workings of instruments in their attempts to settle a controversy (Latour, 1991).

Insights relating to the discursive construction of instruments have been taken up in experimental practice, informing the practice of demonstration across a range of fields. Some interdisciplinary research fields, such as "art-science" or "speculative design" research programs, have sought to design devices to put sociotechnical entanglements on display and unsettle scientific framings of public issues (Born & Barry, 2010; Wilkie et al., 2015). Such approaches do not necessarily involve creating novel instruments. The sandbox—long used in war planning and child psychology, among other things—was, for example, repurposed by Guggenheim et al. (2017) as a device for "breaching experiments" in disaster planning, aiming to provoke notions of disaster excluded by standardized knowledge-making procedures in this field. Other examples can be found in experimental collaborations between activists and researchers using low-cost sensing devices to evidence environmental harm in communities affected by noise or air pollution (Nold, 2017; Pritchard & Gabrys, 2016). Here, the data produced by such devices is put on display and circulated as a means to publicize lived experiences not represented by technocratic approaches to pollution monitoring (Gabrys, 2017). In such examples, instruments shift from playing a background role, as the static apparatus, to the foreground as devices that can be deployed by demonstrators to challenge perceptions of an issue and the kinds of evidence that are relevant to it.

Question 4. *What kind of instruments are referred to, used or relied on in studies on perceptions of carbon removal*?

3 | HOW PERCEPTIONS RESEARCHERS ENGAGE WITH DEMONSTRATIONS OF CARBON REMOVAL

In this section, we review the academic literature on perceptions of carbon removal, starting with a high-level overview, and then using the four questions set out in the previous section to examine how demonstrations are addressed and accounted for in this corpus. We conducted a systematic search and interpretive review of the literature on carbon removal perceptions in February and March 2022, using keyword queries in Web of Science (see Appendix for full queries).

First, we searched for studies on carbon removal, using keywords relating to carbon removal in general as well as to climate engineering, geoengineering, and a set of specific carbon removal techniques, drawing on the Royal Society's (2018) report on greenhouse gas removal. Second, we filtered the results for studies containing any of the following terms (and related stemmed words) in the title, abstract or keywords: "perception," "attitude," "opinion," "deliberation." We then read the abstracts of the results returned, screening out studies that were either (1) not original empirical research or (2) where filtering terms did not refer to the substantive focus of the research, for example, abstracts containing passing references to public attitudes. Table 2 shows the final corpus of articles we included. A handful of boundary cases—that is, studies that were underdetermined with respect to our screening criteria—were discussed and we decided whether to include or exclude according to the scope of our study. For example, we decided to screen out a

TABLE 2 Corpus of 49 perceptions studies on carbon removal.

	Authors	Publication year	Location of authors	Addresses field experiments? (y/n)
1	Amelung & Funke	2015	DE	y
2	Bellamy, Chilvers, Vaughan, & Lenton	2013	UK	y
3	Bellamy, Chilvers & Vaughan	2016	UK	y
4	Bellamy & Lezaun	2017	UK	y
5	Bellamy, Lezaun & Palmer	2017	UK	y
6	Bellamy, Lezaun & Palmer	2019	UK	n
7	Bellamy, Fridahl, Lezaun, Palmer, Rodriguez, Lefvert, Hansson, Gronkvist & Haikola	2021	UK, SE	y
8	Bolsen, Palm & Kingsland	2021	US	n
9	Braun, Merk, Poenitzsch, Rehdanz & Schmidt	2018	UK, DE, ZA	y
10	Campbell-Arvai, Hart, Raimi & Wolske	2017	US	n
11	Carlisle, Feetham, Wright & Teagle	2020	NZ, AUS, UK	y
12	Carlisle, Feetham, Wright & Teagle	2022	NZ, AUS, UK	n
13	Carr & Yung	2018	US	y
14	Corner, Parkhill, Pidgeon & Vaughan	2013	UK	y
15	Corner & Pidgeon	2014	UK	n
16	Corner & Pidgeon	2015	UK	y
17	Cox, Spence & Pidgeon	2020a	UK	n
18	Cox, Spence & Pidgeon	2020b	UK	y
19	Cox, Pidgeon & Spence	2021	UK	y
20	Delina	2021	HK	y
21	Dumbrell, Kragt & Gibson	2016	AUS	y
22	Feldpausch-Parker, Burnham, Melnik, Callaghan & Selfa	2015	US	y
23	Forster, Vaughan, Gough, Lorenzoni & Chilvers	2020	UK	n
24	Fridahl & Lehtveer	2018	SE	y
25	Gannon & Hulme	2018	UK	y
26	Gregory, Satterfield & Hasell	2016	CA	n
27	Haikola, Anshelm & Hansson	2021	SE	n
28	Himmelsbach	2018	SE	y
29	Jobin & Siegrist	2020	SZ	n
30	Klaus, Ernst & Oswald	2020	DE	y
31	Mathur & Roy	2019	IN	y
32	McLaren, Parkhill, Corner, Vaughan & Pidgeon	2016	UK	y
33	McLaren, Willis, Szerszynski, Tyfield & Markusson	2021	UK	y
34	Merk, Klaus, Pohlers, Ernst, Ott & Rehdanz	2019	DE	y
35	Merk, Poenitzsch & Rehdanz	2019	DE	y
36	Pidgeon, Corner, Parkhill, Spence, Butler & Poortinga	2012	UK	y
37	Pidgeon & Spence	2017	UK	y
38	Romanak, Fridahl & Dixon	2021	US, SE, UK	n
39	Scheer & Renn	2014	DE	y
40	Schirmer & Bull	2014	AUS	n

(Continues)

TABLE 2 (Continued)

	Authors	Publication year	Location of authors	Addresses field experiments? (y/n)
41	Shackley, Carter, Sims & Sohi	2011	UK	n
42	Spence, Cox & Pidgeon	2021	UK	y
43	St-Laurent, Hagerman & Hoberg	2017	CA	y
44	Thomas, Pidgeon & Roberts	2018	UK	y
45	Wallquist, L'Orange Seigo, Visschers & Siegrist	2012	SZ	y
46	Wenger, Stauffacher & Dallo	2021	SZ	n
47	Wibeck, Hansson, Anshelm, Asayama, Dilling, Feetham, Hauser, Ishii & Sugiyama	2017	SE, JP, NZ, US	y
48	Wolske, Raimi, Campbell-Arvai & Hart	2019	US	n
49	Wright, Teagle & Feetham	2014	AUS, NZ, UK	y

Note: For full list of references see Appendix.

study on perceptions of ecosystem restoration on the basis that carbon sequestration was not the focus of the research, and including it would have required revising our initial query and conceptual bounding of carbon removal.

The latter example highlights the conceptually fuzzy and contested character of carbon removal. Long-standing controversies over carbon removal via land-based sinks have arguably been obscured by the association of carbon removal with "geoengineering" or "climate engineering," and the way in which carbon removal is treated in many integrated assessment modeling scenarios (Carton et al., 2020). Moreover, many studies on perceptions of methods which can in principle remove CO_2 via land-based sinks—such as afforestation or biochar—do not foreground carbon removal, for example, they may focus on conservation or agriculture. While excluding such studies limits the conceptual scope of this review, it does help to locate studies relevant to the establishment of carbon removal as a distinct focus for innovation.

The final corpus (Table 2) contains 49 studies, of which 21 have been conducted by researchers at UK institutions, and 9 of these are by the authors of this paper. The distinctive position of UK-based researchers in research on carbon removal has not gone unremarked (e.g., Low & Schaefer, 2020). In total, only seven studies in our corpus are conducted by researchers based outside of Europe and North America, and several of these involve collaborations with North American researchers. 19 studies were funded through dedicated geoengineering or carbon removal funding programs, like the German Research Council's (DFG) Climate Engineering priority program or the UK Research and Innovation (UKRI) Greenhouse Gas Removal program. Indeed, the present authors are participants in the latter program.

While research on perceptions has advanced social inquiry on the topic of carbon removal, in some cases it has clearly also played a role in performing public engagement with scientific programs of assessment and demonstration. The following sub-sections therefore examine the ways in which these studies conceptualize the public and the role perceptions play in relation to field trials and experiments of carbon removal methods. Moving beyond these top-level features of the literature, we now apply the four questions formulated in Section 2 to this corpus of 49 papers.

3.1 | To what extent is research on perceptions of carbon removal situated in, or in relation to, specific sites where trials or experiments are staged?

Thirty-three studies in the corpus discuss ongoing or future field trials and experiments of carbon removal methods. However, relatively few studies situate the study of perception in relation to specific sites where carbon removal is being undertaken or demonstrated. Across many of the studies, a few high-profile controversies over field experiments—including protests against CCS in Germany and the Haida Salmon Restoration Corporation's iron fertilization experiments—are referenced widely, often to illustrate the ways in which experimentation can generate public controversy. Yet despite this, few studies in the corpus address field experiments in specific places. Many focus on nationally-defined publics and where they do address location it is generally defined in terms of territorial nation states. A study focused on perceptions of afforestation among Australian landholders provides one example; analyzing diverse values and motivations for tree planting among individual owners of land within an administrative region (*40*). Yet defining location in administrative terms has limitations—for example, Gannon and Hulme (*25*) show that conflicts over ocean

fertilization in a First Nations village in British Columbia were situated by participants within wider histories of indigenous subjugation and long-standing conflict with the settler state. Such cultural relations to land are erased by approaches that treat location as primarily a technical or administrative category.

Of the studies situated by location, several address the ways in which proximity to sites of field experiments or proposed deployment relate to public perceptions. Feldpausch et al. (*22*) analyze coverage of both bioenergy and CCS, respectively, in newspapers local to sites of research and development. They find a link between a newspaper's proximity to research sites and the level of detail about a technology provided, arguing that local media express distinct perceptions of the issues, when contrasted with national news reporting. Proximity to sites of research and development has also operated as a sampling criterion in other studies. Thomas et al. (*44*), for example, situated their research on risk perceptions of bioenergy with carbon capture and storage (BECCS) in proximity to major electricity infrastructure where trials were taking place (a similar approach is taken in *36*). Connections between risk perceptions and sites of technology deployment may also take less direct forms, for example in Cox et al. (*19*) who show how analogies to controversies around fracking sites surfaced in public deliberations about carbon storage. They argue that such analogies can be seen to reflect deeper misgivings about the motivations of experts and policy-makers based on past experiences.

Such accounts highlight the challenge of conceptually bounding local sites of research and development on carbon removal. As Bellamy et al. (*5*) show, technical definitions of the spatial scale of field experiments are poor predictors of public concerns that may emerge, because "scale" and "location" often serve as proxies for the more capricious issue of "controllability." Indeed, as an early UK study titled *Experiment Earth* highlights, the imagined "global" scale of geoengineering has provided a guiding political rationale for many carbon removal field experiments (see discussion in Stilgoe, 2015). As Gannon and Hulme's (*25*) study shows, scientific accounts of the global scale of geoengineering may conflict with ideas about nature and human agency that are culturally and geographically specific to sites of experimentation. Taken together, these studies highlight that perceptions of experimental sites may often not be obtained through direct experience but rather mediated through, for example, institutional authorities, cultural practices, news and infrastructures.

3.2 | How are the identities of experts and other participants constructed in studies on perceptions of carbon removal?

Participant identities in large-n survey studies are widely characterized as national citizens or members of national publics (20 studies), almost all deploying demographic categories of age, gender and education, and weighted according to census data to construct nationally-representative samples. Representation of the public in these surveys is therefore based on statistical formalism rather than social and political theories of the public. Social and political theories do figure (although not necessarily prominently) in studies involving interviews, focus groups and deliberative methods, sometimes combining demographic categories with identities of concerned groups, political persuasion or views on climate change (*15*; *47*) or socio-cultural groups (*5*).

Most studies distinguish expert and stakeholder identities, on the one hand, from the "lay public," on the other. They differ, however, in the degree to which these distinctions are treated as fixed or provisional. There are, for instance, some clear differences in how the authority of carbon removal experts is conceptualized. Some studies in the corpus draw comparisons between carbon removal and other controversial technologies (such as fracking or GMOs) (*19*) or question the basis of policy consensus among stakeholders and experts (*33*, *35*). In other studies, it is easy to detect more traditionally technocratic concerns relating to the scientific literacy of the general public (*11*). Although scientific literacy is not an explicit concern of most studies, expert authority is often deferred to rather than interrogated. Information provided to participants—often a condition for eliciting perceptions of carbon removal (38 studies)—is often validated by experts who are taken to be authoritative (e.g., *18*, *30*) or is based on technological descriptions from reports of scientific bodies like the UK's Royal Society or the US's National Academies of Science (e.g., *1*). Yet such expert actors are often not characterized as "participants" in these studies and are therefore excluded from many researchers' representations of the public.

3.3 | What roles are attributed to media in studies on perceptions of carbon removal?

Media are rarely an empirical focus of perceptions research on carbon removal. Where media are foregrounded, it is typically in relation to news and the communication of science through news media. However, looked at another way,

we find that media-technologies often play a central *methodological* role in researchers' attempts to turn carbon removal into visual and textual representations that can elicit responses from participants. Although this often goes under the banner of "information provision," analysis of supplementary materials reveals a much richer trove of multi-media presentation formats that imply interactions between experts, artists and designers. From this perspective, around 20 studies in the corpus give a significant methodological role to media-technologies in eliciting perceptions of carbon removal.[3] The limited space given to such work in the main body of the research articles signals the low epistemological status accorded to media in research on perceptions. Before attending to this we first examine the more explicit treatments of news media in these studies.

Two studies in the corpus deploy news media analysis to analyze perceptions. In one, news media are treated as settings of public discourse and a means of "gauging public perceptions about technologies" (*22*). The other focuses on science communication of carbon removal, examining competing expert narratives about BECCS across a variety of news media (*27*). In both studies news media are considered as shaping the formation of public perceptions and opinion, albeit not necessarily in a linear fashion.

News media also comprise a focus for several psychologically-oriented studies that test the effect of different information framings on participants. A study by Wolske et al. (*48*) examines the effects of "nature"-related framings of carbon removal using made-up Associate Press news articles given to survey participants, and find that support for different carbon removal technologies is related to how much they are perceived to tamper with nature. Made-up news articles (publication unspecified) also feature in a survey conducted by Bolsen et al. (*8*) who experiment with the effects of political partisanship and conspiracy theories on support for the direct air capture. While the methods deployed in these studies suggest news media play a role in the elicitation of perceptions, they do not discuss the specific significance of news media in relation to the topic of carbon removal nor distinctions between news and other media.

Uses of media to provide research participants with "information" vary between those designed around narrow cognitive aims and those more open to interpretation. In some cases, media presentations are described pedagogically, for instance one study characterizes materials given to participants as "tutorials" (*26*). But, in many instances the information provided to participants is designed to generate multiple and competing interpretations of carbon removal. A wide variety of visual media—including videos and films, diagrams, posters, concept boards and animated "infographics"—are used to convey technological concepts to participants alongside textual explanations, scenarios, quotes from different actors, verbal presentations and a "debate website." Several studies (e.g., *13*) describe steps taken to ensure such materials avoid introducing "framing effects" to the research, for example running pilot studies (*29*), or, conversely, to test the effects of particular framings (*46*). With respect to the latter, Corner and Pidgeon (*16*) introduce "natural" analogies for carbon removal and solar radiation management in factsheets, associated with a fake website (climateinfo.org), given to participants as an experimental condition compared with a control group.[4] Others note that the materials are checked by experts, although none specify which kinds of experts were consulted or how the process of validation worked in practice (e.g., *9*). Such materials highlight the pervasive roles that media-technologies and media practices play in making carbon removal into visual and textual representations that researchers deploy to elicit "lay" perceptions. Yet, the very limited critical discussion accorded to such work also arguably obscures the artistic and design work involved in representing carbon removal to research participants.

3.4 | What kind of instruments are referred to, used or relied on in studies on perceptions of carbon removal?

References to instruments in the reviewed studies mainly address the research tools used to elicit and analyze perceptions of carbon removal, rather than instruments deployed in the staging of field trials and experiments. Nonetheless, the former is characterized in very different ways across the corpus. Over half of the corpus deploy survey instruments to elicit perceptions, of which 14 characterize their methodology as experimental (several deliberative research designs are also characterized as experimental, such as deliberative mapping and Q-Methodology). Methodological individualism—that is, the individual as the unit of analysis—predominates in survey-based studies (comprising roughly half the corpus) which deploy devices and theories from experimental psychology, including using cognitive tests as part of their research design (*1*, *9*). These studies often compare responses of a control group against those of other groups who have been provided treatments (as in framing studies). As highlighted above, the information about carbon removal provided to participants in such studies tends to be validated by experts or deferring to expert bodies such as the IPCC, offering few opportunities for participants to contest scientific framings of carbon removal.

A more general deference to science-led framings of carbon removal is arguably detectable in the shifting problem definitions between studies undertaken before and after the 2015 Paris Agreement. In studies conducted before 2015, carbon removal is predominantly linked to geoengineering discourses, and roles for technologies are examined broadly in relation to their potential for "addressing climate change" (*39*), with the UK's Royal Society (2009) report as a common reference. In 19 studies, perceptions of carbon removal methods are combined with those of solar radiation management, such as stratospheric aerosol injection. In post-2015 studies meanwhile, 23 studies cite the Paris Agreement and relate the problem of carbon removal to temperature targets. BECCS—the most prominent carbon removal approach in the IPCC's Fifth Assessment—predominates in the post-2015 studies.

Deliberative studies, of which there are seven in the corpus, do provide examples where scientific authority and framings of carbon removal are questioned by participants. While deliberative studies are all workshop-based, they vary greatly in approach: some draw on methodologically individualist approaches from psychology while others situate deliberation within social interaction and wider discourses. For example, Bellamy et al.'s (*5*) study experimented with response to framings of carbon removal under distinct "social atmospheres" of deliberation, manipulating the physical set-up and style of deliberation to compare perceptions and participant interactions. In an example of scenario-based deliberation, McLaren et al. challenged participants to situate carbon removal within political economies of climate change, as a means of exploring the widespread concern that researching carbon removal could deter emissions reductions (33). By experimenting with the devices and protocols of small-group deliberation, these two studies, in particular, show how deliberative instruments can be used to interrogate interactions between social and epistemic authority.

Our analysis of this corpus of 49 studies makes clear that perceptions of carbon removal can be produced in very different ways, depending on the research practices designed to elicit, record, measure and analyze them. This does not mean that perceptions of carbon removal are a mere artifact of research practices with no independent reality (cf. Osborne & Rose, 1999). Rather, our approach highlights that epistemological questions about how researchers study perceptions of different methods and their relative risks are inseparable from ontological questions about the social reality of carbon removal. Many researchers position their studies as "upstream" of demonstration, aiming to assess the social acceptability of future field trials and experiments (evident to differing degrees in 31 studies, see Table 2). The focus on future social acceptance means that few studies in the corpus attend empirically to the ways that demonstrations can generate problems of perception (as discussed in Section 2). Indeed, in some studies social acceptance is conceptualized in such a way that the technical demonstration of carbon removal methods appears almost a *fait accompli*, with practices of presentation or display reduced to procedures that have little or no bearing on the technical content of an experiment. We now discuss why too strong an emphasis on the social acceptance of field trials and experiments may prevent the study of perceptions from attending to conflicting expectations about what carbon removal projects will demonstrate.

4 | BRINGING PERCEPTIONS RESEARCH CLOSER TO DEMONSTRATIONS

The analysis above suggests that many elements found in linear models of innovation can be detected in studies on perceptions of carbon removal. As indicated by the *State of Carbon Dioxide Removal* report (Smith et al., 2023), linear models provide a powerful way of linking the science of carbon removal with industry and policy, visualizing the field in a way that distinguishes the position of such actors from the public. As highlighted earlier, the model proposes that demonstrations play a crucial role in reconciling competing expectations that may be held between different groups and progressing to the scale-up phase of technology development. Linear models imply that it is relatively straightforward to divide out the issues concerning groups with expertise in carbon removal from those without. While there are many ways to draw expert/non-expert distinctions, precedents in research on perceptions have often centered around "deficit" theories of the public that link literacy in science and technology with the capacity to participate in their governance (Chilvers & Kearnes, 2015; Wynne, 2015). While it is now not uncommon for perceptions researchers to critique deficit models of the public, studies reviewed above nonetheless often invoke (or defer to) an expert consensus about carbon removal. In doing so, they suggest (in line with linear models) that scientific controversies about carbon removal are, in principle at least, resolvable within expert communities and that boundaries between the social and technical dimensions of carbon removal demonstrations are politically uncontentious.

Such assumptions have provided the target for a variety of social critiques of carbon removal that, in different ways, show how competing expectations may reveal less harmonious relations between experts across science, policy and industry. Critical perspectives on political economy, for example, highlight the threat posed by climate change to capital

accumulation and asset values in fossil fuel industries, and argue that the promise of future carbon removal may provide scientific justifications for delaying (otherwise urgent) climate mitigation policies (Carton, 2019; Markusson et al., 2018). While experts involved in researching, developing and commercializing carbon removal do not necessarily deny the potential risk of "mitigation deterrence," deliberations point toward a variety of political and economic mechanisms that can lead to the exaggeration of experts' expectations and their rationalization in policy (McLaren et al., 2021). It is also evident that selectively promoting carbon removal methods can be a form of activism—for example, environmental activists promoting tree planting as a method as a "natural" solution in contrast to "engineered" carbon removal like BECCS—suggesting that scientific controversies are bound up with struggles over the expertise to define carbon removal as a policy issue (Waller et al., 2023). Linear models that insulate expert debate and responses to demonstration projects from the public might therefore be seen not only to reflect the interests of some actors but also the marginalization of certain kinds of expertise. Approached in this way, it is the perception (and maintenance) of expert consensus around carbon removal projects that is in need of social explanation as much as the appearance of "opposition" to their social acceptance (a similar argument from the field of synthetic biology is made by Marris, 2015).

The relevance of contestations over expertise to the ways demonstrations of carbon removal are perceived can be seen in an analysis of climate interventions by Low et al. (2022). They show how scientific controversies are highly visible in struggles that emerge around carbon removal experiments, despite often being represented as external "opposition" to research and development. They highlight that these struggles often center around how questions of scale and uncertainty are represented in practical interventions, and caution experiment planners to be mindful of the tactics some actors use to obscure such questions. By invoking expert consensus about future carbon removal, perceptions researchers may therefore (inadvertently perhaps) de-politicize conflicting expectations that surface around demonstrations and struggles over the expertise to settle them.

In different ways, these latter studies make clear why bringing perceptions research closer to demonstrations requires developing research strategies that attend to conflicting expectations about carbon removal. In addition to the forums where experiments are planned, the framework we developed in Section 2 points toward a wider range of situations where demonstrators may address problems of perception and engage with conflicting expectations. In concluding, we reflect on the value of the framework developed here for research on perceptions.

5 | CONCLUSION

In setting expectations about future carbon removal, demonstration projects must contend with questions about how "real-world" field trials and experiments are publicly perceived. As made clear in Section 2, problems of perception are latent in practices of demonstration and generated in the staging of experimental presentations and displays; they are rarely reducible to "deficits" (cognitive or otherwise) in external audiences. We have therefore argued that problems of perception can be *valued* as occasions to interrogate competing expectations about a field trial or experiment, and to study the collectives that emerge when expectations conflict.

Using the concept of "performativity," we have drawn attention to the ways in which practices of demonstration bring emergent publics into being. Emergent publics are obscured by linear models of innovation that distance the public from the scene of demonstration. In foregrounding the performativity of demonstrations, the framework outlined in Section 2 points toward strategies for bringing perceptions research closer to field trials and experiments than linear models permit.

The framework presented is designed to bring into focus several practical dilemmas with which demonstrators of carbon removal projects will likely contend, foregrounding: (1) The *Sites* where trials and experiments are staged; (2) The *Identities* of experts and other participants; (3) The role played by *Media*; and (4) The *Instruments* used or relied upon. While the framework is intended as a contribution to the toolbox of research on perceptions of carbon removal, it also draws attention to a potentially wider range of social research approaches that might be deployed (not only by academic social scientists) to identify and make visible publics that emerge around demonstration projects.

In reviewing the existing research on perceptions of carbon removal, we also draw attention to the critical role that *expectations* will play in demonstrations of carbon removal methods. In many cases, demonstration projects will be demonstrating the "promise" of a method for future carbon removal. While field trials and experiments may provide the center piece of demonstrators' "theater of proof," the conflicts they spark may bring into view wider controversies over how expectations about future carbon removal are devised (e.g., Beck & Mahony, 2018; Carton et al., 2020). That

the future promise of carbon removal is at stake in the field trials and experiments makes all the more clear why demonstrators are not only innovators of specific methods: they are also in the business of making carbon removal public.

AUTHOR CONTRIBUTIONS

Laurie Waller: Conceptualization (lead); formal analysis (lead); investigation (lead); methodology (lead); writing – original draft (lead); writing – review and editing (lead). **Emily Cox:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Rob Bellamy:** Conceptualization (supporting); formal analysis (supporting); funding acquisition (lead); investigation (supporting); methodology (supporting); project administration (lead); supervision (lead); writing – original draft (supporting); writing – review and editing (supporting).

ACKNOWLEDGMENTS

The authors thank the editors and two anonymous reviewers for their comments that have helped clarify the analysis presented in the paper.

FUNDING INFORMATION

The authors gratefully acknowledge research funding from the Natural Research Environment Council for the project: "The UK GGR Directorate Hub." Grant number: NE/V013106/1.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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ENDNOTES

[1] The Intergovernmental Panel on Climate Change (IPCC) defines carbon dioxide removal as: "Anthropogenic activities removing carbon dioxide (CO_2) from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products." The phrase carbon removal and acronym CDR are used interchangeably throughout the IPCC. See the Glossary at: https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_AnnexVII.pdf (accessed 22/02/2023).

[2] For example, the Frontier fund for carbon removal projects requires applicants to detail their "public engagement" plans. See the project application template at: https://github.com/frontierclimate/carbon-removal-source-materials/blob/main/TEMPLATE%20Project%20Application/2022_08%20(fall)/Prepurchase%20Application%20Template.pdf (accessed 25/01/2023).

[3] This number would increase if we included those survey studies that use digital media to recruit participants (one study, e.g., uses Facebook ads) and distribute questionnaires. Although one study claims (without evidence) that digital surveys "eliminate interviewer bias," for the most part the medium goes unremarked.

[4] The findings of Corner and Pidgeon (*14*) highlight the potential for natural framings to increase support for proposed innovations and interventions and are widely referenced in the corpus.

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How to cite this article: Waller, L., Cox, E., & Bellamy, R. (2023). Carbon removal demonstrations and problems of public perception. *WIREs Climate Change*, e857. https://doi.org/10.1002/wcc.857

APPENDIX

QUERY TERMS AND FULL REFERENCES FOR PERCEPTIONS STUDIES

Query object	Query terms
Carbon removal (general)	"carbon dioxide removal" OR (cdr AND (co2 OR carbon*)) OR "negative emission*" OR "negative carbon dioxide emission*" OR "negative CO2 emission*" OR "negative GHG emission*" OR "negative greenhouse gas emission*" OR (geoengineer* OR geo-engineer* OR "climate engineer*") OR "greenhouse gas removal" OR (ggr AND (co2 OR carbon*)) OR ((ghg OR "greenhouse gas*") NEAR/2 removal))
Specific carbon removal techniques	("direct air capture" OR DACCS OR "bioenergy" AND "carbon capture and storage" OR BECCS OR "Soil carbon sequestration" OR "Ocean fertilization" OR Biochar OR "Enhanced weathering" OR Afforestation OR Reforestation OR "building with biomass" OR "wood in construction" OR "habitat restoration" OR "ecosystem restoration" OR "peatland restoration" OR "carbon negative concrete" OR "mineral carbonation" OR "ocean alkalinity")
Perceptions (filter)	(perception* OR attitude* OR opinion* OR deliberation OR deliberative)

Source	
1	Amelung, D. and Funke, J. (2015). Laypeople's risky decisions in the climate change context: Climate engineering as a risk-defusing strategy? *Human and Ecological Risk Assessment: An International Journal*. 21(2), pp. 533–559. https://doi.org/10.1080/10807039.2014.932203
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4	Bellamy, R. and Lezaun, J. (2017). Crafting a public for geoengineering. *Public Understanding of Science*. 26(4), pp. 402–417. https://doi.org/10.1177/0963662515600965
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