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Undone science in climate interventions: Contrasting and contesting anticipatory assessments by expert networks

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ABSTRACT

In global climate governance, anticipatory assessments map future options and pathways, in light of prospective risks and uncertainties, to inform present-day planning. Using data from 125 interviews, we ask: How are foundational experts contesting the conduct of anticipatory assessment of carbon removal and solar geoengineering – as two emerging but controversial strategies for engaging with climate change and achieving Net Zero targets? We find that efforts at carbon removal and solar geoengineering assessment leverage and challenge systems modeling that has become dominant in mapping and communicating future climate impacts and mitigation strategies via IPCC reports. Both suites of climate intervention have become stress-tests for the capacity of modeling to assess socio-technical strategies with complex, systemic dimensions. Meanwhile, exploring societal dimensions demands new modes of disciplinary expertise, qualitative and deliberative practices, and stakeholder inclusion that modelling processes struggle to incorporate. Finally, we discuss how the patterns of expert contestation identified in our results speak to multiple fault-lines within ongoing debates on reforming global environmental assessments, and highlights key open questions to be addressed.

1. Introduction

In global climate governance, anticipatory practices in assessment map impacts and governance options that lie in the future, informing present-day planning in light of prospective trends, risks, and uncertainties (Muiderman et al., 2020). With practices that range from kinds of modelling, to analogies, to qualitative stakeholder engagements, assessments must not only explore concurrent issues, impacts, and interconnections – they must also anticipate latent and emergent ones. These practices are contained in a range of assessments, from the Assessment and Special Reports of the Intergovernmental Panel on Climate Change (IPCC) and other global environmental assessments (GEAs) to more national or sectoral assessments; they might be conducted by scientific, policy, business, and civic networks, or focus topically on environmental impacts and human vulnerability, mitigation and adaptation-based strategies, or adjoining issues in security or food systems. Deepening challenges confront such assessments. They build authoritative knowledge on complex, incoming socio-ecological problems – and increasingly, shape the space for solutions. At the same time, assessments must make sense of 'wicked' issues, navigate kinds of expertise, practices, and communities, and map strategies that eye different audiences in government, business, and civil society.

In this paper, we ask: How are foundational experts contesting the conduct of anticipatory assessment of *carbon removal* and *solar geoengineering* – as two emerging but controversial strategies for engaging with climate change and achieving Net Zero targets? We use data from 125 qualitative interviews with key experts and technologists in both suites, speaking to these research questions: the novel demands of anticipating the challenges and governance of carbon removal and/or solar geoengineering, the fit of those novel demands with dominant IPCC-facing assessment processes, and the supplements and reforms called for. Our intent is to evaluate the practice of anticipatory assessment related to these strategies, and discuss their implications for science-policy relations and for future climate and environmental governance.

Why is this important? Expert processes – particularly those leveraging the IPCC as an authoritative, public- and policy- facing global environmental assessment body– create foundational knowledge on carbon removal and solar geoengineering, and shape how wider audiences conceive of novel climate response strategies. We shed light on

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how different kinds and aims of assessment contest the knowledge base on which climate strategy in coming decades may be decided; we also question the shape of assessments needed. Our focus is therefore not on carbon removal or solar geoengineering in themselves (McNutt et al., 2015a, 2015b), nor on how dominant assessments have shaped our understandings of these proposals (Beck and Oomen, 2021; Low and Honegger, 2020; Stilgoe, 2015). Rather, we treat carbon removal or solar geoengineering as case studies that reflect new demands for anticipatory assessment in the climate regime, and for GEAs more broadly.

Our selection of these two suites of approaches from a larger range of potential climate response strategies is pragmatic. Our research is part of the European Research Council-funded 'GeoEngineering and NegatIve Emissions pathways in Europe (GENIE)' project, which aims at a multidisciplinary assessment of carbon removal and solar geoengineering in conversation with publics and policy-makers. The project reflects growing interest and concern over two of the most significant recent entrants to the formulation of future climate action – in concept, politics, infrastructure, and governance. Carbon removal describes the proposed development of a rapidly-growing space of engineered or biogenic sinks to sequester and store carbon; solar geoengineering would forestall warming by reflecting incoming sunlight via 'sunshades' of clouds or layers of sulphate aerosols. Both have a linked history as part of an intense period of scientific assessment in the 2000 s and 2010 s on 'climate geoengineering', or deliberate, large-scale climate interventions to manage a warming planet (Shepherd et al., 2009; Oomen and Meiske, 2021). In recent years, their paths have diverged. Assessment processes within and beyond the IPCC have normalized carbon removal, and spurred wider innovation and governance proposals in the Paris Agreement era. In contrast, solar geoengineering remains a controversial but resilient proposal for a 'cheap, fast, and imperfect' planetary sunshade, on the fringes of mainstream climate assessment.

Section 2 contains a literature review of different kinds of anticipatory assessment for climate strategies. Section 3 details our research design, grounded in expert interviews. Section 4 reports the data derived from our interviews. We observe two areas of activity in carbon removal and solar geoengineering built around systems-modelling that has become dominant in mapping and communicating future climate impacts and mitigation strategies via IPCC reports, and a third area emerging as challenges to systems-modeling with more qualitative, multidisciplinary, local, and actor-focused assessment. Section 5 zooms out to discuss how the patterns of expert contestation identified in our results speak to fault-lines within ongoing debates on reforming global environmental assessments, and highlights key open questions to be addressed.

2. Literature review: the anticipatory assessment challenge of climate interventions

We treat carbon removal and solar geoengineering less as individual technologies and innovation systems, and more as broad, unbounded, and evolving sociotechnical strategies for addressing climate change (Low and Boettcher, 2020) that have been made relevant through scientific assessment (McLaren and Markusson, 2020). There are voluminous literatures on their technical, environmental, socio-political, and ethical aspects – we give this a light treatment here, with a focus on the role of researchers and assessment.

In the 1990 s and early 2000 s, a network of earth systems scientists conceptualized both suites as forms of 'climate geoengineering', with an overlapping focus on management of the environment that was both intentional and large scale (Keith, 2000; Oomen and Meiske, 2021). The term experienced a heyday of attention in academic circles (Shepherd et al., 2009; Oldham et al., 2014; Irvine et al., 2016; Blackstock and Low, 2018, eds.; Sapinski et al., 2020, eds.), with media, NGO, and limited governmental attention (Morton, 2015; Jinnah and Nicholson, 2019). Solar geoengineering received the bulk of early attention as a comparatively high-leverage, low-cost option for managing global temperatures, and continues to receive attention in academia (Pasztor and Harrison, 2021) and high-level assessments, particularly via the US National Academies of Science (NASEM, 2021). But as a highly controversial option, solar geoengineering remains on the outskirts of formal IPCC assessment, with brief, precautionary mentions rather than a central role (IPCC, 2014a, 2022a, Chapter 16; IPCC, 2022b, Chapter 14). The most active and supportive research currently takes place in a fringe but highly vocal corner of climate modelling (MacMartin and Kravitz, 2019; Keith and Irvine, 2016; Zhang et al., 2022; Stilgoe, 2015; McLaren, 2018; Flegal, 2018; Oomen, 2021), with calls to escalate research (Aldy et al., 2021) balanced against efforts to highlight the widespread risks of raising it as a climate strategy (Biermann et al., 2022a).

Meanwhile, several landmark IPCC assessments (IPCC, 2014a; b; IPCC et al., 2018; IPCC, 2022a; b) have projected that carbon removal would be needed in vast amounts for ambitious climate targets to be reached by century's end. Incorporation into authoritative reports has driven attention for carbon removal across assessment (Waller et al., 2020), technology innovation (Nemet et al., 2018), forestry, agriculture, and marine-space management (European Commission, 2021; Boettcher et al., 2021), and policy proposals (Schenuit et al., 2021). Carbon removal, however, is represented in IPCC scenarios by immature approaches and speculative scales that may never exist as envisioned (Beck and Oomen, 2021). Moreover, these scenarios were largely driven by integrated assessment modelling (of techno-economic pathways). Besides entrenching carbon removal as a climate strategy, they have spurred reflection on and challenge to how techno-economic modelling could have so swiftly redefined climate action (Geden, 2016; Gambhir et al., 2019), and how assessment could better map the uncertainties and challenges surrounding carbon removal and other mitigation strategies (O'Neill et al., 2020; Schweizer et al., 2020).

We employ the phrase 'undone science' to capture the iterative, and often messy way, that integrated assessments and climate forecasting are done in practice. Focusing on the 'undone' element of scientific practice means emphasizing assumptions that are taken for granted, institutionalized, or invested with authority by different groups of people. These include an incomplete aspect (the 'undone' aspect) of how scientific knowledge is transmitted, achieves stability, processes that go into its creation and maintenance, and how it becomes organized and categorized into different spheres, or fails to do so (Collins, 1985; Bloor, 1991). The production of technological knowledge is fundamentally social because it is defined or constituted by practices of work, trust, methods of analysis, methods of interpretation, values, and institutional arrangements (Knorr-Cetina, 1999). When extended to climate science, practitioners will often develop their own distinct systems of knowledge, and that their research and language will be shaped by this system, even unconsciously.

Studies have captured the 'undone science' elements of citizen science or social movements (Frickel et al., 2010; Arancibia and Motta, 2019), but not within expert assessments and scenarios, nor within intergovernmental assessment bodies. The emergence of carbon removal in post-Paris governance, as well as contestation over how to escalate or dampen solar geoengineering research, have cast new scrutiny on the role of authoritative, highly visible scientific assessments in generating attention around new climate strategies. Some of this scrutiny has fallen on the IPCC, as an authoritative GEA that marshals scientific knowledge for informing publics and policy (Jabbour and Flachsland, 2017). Some, however, question the fitness of its assessment processes for mapping and appraising novel sociotechnical strategies in mitigation and adaptation (Beck and Oomen, 2021). There is much historic and ongoing work on the mandate, organization, and epistemologies (Miller, 2004; Mahony and Hulme, 2018) of the IPCC. More fine-grained literatures exist on the different assessment modes embodied by its three Working Groups – respectively, modelling of climatic processes (WG1, Heymann and Dahan Dalmedico, 2019; Edwards, 2010), diverse geographical methods for assessing impacts, vulnerability and adaptation (WG2, Berrang-Ford et al., 2021), and integrated assessment models that map mitigation options for (reducing) emissions (WG3, van Beek et al., 2020; Cointe et al., 2020). We draw upon these works as reflective of kinds of expertise, practice, and communities in climate assessment.

Moreover, there is a renewed focus on the particular role of anticipation across kinds of climate assessment – the use of appraisals and scenarios set in deeply uncertain and alternative futures as grounds for planning (Pulver and Vandeveer, 2009). Our analysis (Section 4) focuses first on two linked fields of assessment characterized by global systems modelling (Low and Honegger, 2020): earth systems and physical climate modelling approaches leveraged by key solar geoengineering research advocates (Keith and Irvine, 2016), and the integrated assessment modelling efforts that helped launch carbon removal and 'Net Zero' as an emerging strategy (van Beek et al., 2021). However, we widen our discussion beyond how these modelling methods are envisioned and used by expert communities, to how they are challenged with new modes of assessment. We build upon critiques of a techno-economic, solution-oriented mode of prioritizing mitigation options (Beck and Oomen, 2021; Cointe et al., 2020), and expand the implications beyond carbon removal to solar geoengineering (Gupta et al., 2020; McLaren and Markusson, 2020). We further connect systems modelling efforts to more deliberative, qualitative, and actor-facing modes (Stilgoe et al., 2013; Low and Buck, 2020; Chilvers and Kearnes, 2019), and widen the intent and scope of anticipatory assessments in climate governance (Muiderman et al., 2020) and global assessments more broadly (Castree et al., 2020; Pereira et al., 2021a; Muiderman et al., 2022).

3. Research design

We conducted semi-structured interviews with 125 experts on carbon removal, solar geoengineering, or both as forms of climate interventions (Annex 1). As a benchmark for recognized activity in assessment, technology development, or policy engagement, we solicited individuals with peer-reviewed publications or patents between 2011 and the present. Within these bounds, invited experts were further selected for diversity of scientific disciplines and sectors, as well as a mix of general and specific expertise on carbon removal and solar geoengineering approaches with strong visibility in current assessments. Although a plurality of experts discussed both sets of technological options, 33 focused only on carbon removal, 35 focused only on solar geoengineering. Overall, 90 engaged with carbon removal when answering at least one of the questions, and 92 with solar geoengineering.

The criterion demanding publications or patents does contain a selection bias against NGO representatives or activists who may not (be able to) prioritize such contributions. However, it ensures that the majority of interviewees participate in and have actively shaped anticipatory assessments within and surrounding the IPCC, via academic papers, modelling or multi-disciplinary research projects, and seminal 'grey literature' reports – which is key to the content of this paper. A demographic summary of our interview pool can be found in Annex 2.

Using a 'semi-structured' methodology (O'Sullivan et al., 2010), we engaged our interviewees on a wide range of subjects – from innovation and business models, to risks and governance, and dimensions of justice and sustainability. The full listing of seven question sets can be found in Annex 3. However, semi-structured interviews permit room to explore emergent questions on an ad hoc basis, beyond the original set. These included: How are assessments used or challenged on their capacities to assess complex, multidimensional topics within and beyond climate governance? How are research communities using kinds of assessment to instrumentally or functionally shape carbon removal or solar geoengineering? Conversely, how are they or refining and interrogating those assessments?

We therefore derive the data used in this paper from our interviewees' efforts to speak to the novel demands of anticipating the challenges and governance of carbon removal and/or solar geoengineering, the fit of those novel demands with dominant IPCC-facing assessment processes, and the need for supplements and reforms. Themes of analysis were distilled iteratively between the authors, using NVivo as a content-categorizing software. These form the basis of analysis, in the following Section 4.

4. Results and analysis

To convey our results and analysis, we combine tables (labelled 1–4) with contextualizing text. Each table identifies 'themes' (column 1) within which a number of respondents (column 2) conveyed similar concerns – supporting or challenging carbon removal or solar geoengineering, and the anticipatory assessments of these approaches. 'Statements of concern' are distilled from numerous longer quotes (column 3). To give some sense of the rich interview data, 'representative quotations' for each of the aggregated 'statements of concern' are included (column 3).

We then connect the themes of the tables to further analysis, as well as to surrounding literatures – such studies are noted in parentheses. We list all interviewees in Annex 1 – but preserve their anonymity in relation to specific statements, denoting each with a randomized respondent number (e.g. R10, N = 125).

4.1. Carbon removal assessment in integrated assessment models (IAMs)

Experts highlighted that carbon removal became entrenched as a strategy in the Paris Agreement era by being prominently featured in the pathways (emissions trajectories) of IPCC's Fifth Assessment Report (IPCC, 2014b) and Special Report on 1.5 C (IPCC, 2018). These pathways were generated by integrated assessment models (IAMs), which model big-picture changes to energy, technological, and land-use systems that correspond to global temperature targets. As the prospective scale of carbon removal in pathways became clear, critique on IAM practice grew.

Our experts echoed points (*Theme 1,* Table 1) from this literature: that IAM work balances between the historic IPCC imperative to be 'policy-relevant but not prescriptive' with a new, conflicting orientation toward generating solutions (Beck and Oomen, 2021); that the IAM community (Cointe et al., 2020) parlayed a perceived policy interest in the 2 C target into modeling speculative scales of carbon removal (Geden, 2016); that IAMs represent techno-economic modeling practices that functionally prioritize cost-benefit optimizing technological systems (van Beek et al., 2020); that IAMs are the IPCC reports' dominant means of mapping climate mitigation options through Working Group 3 (Corbera et al., 2016); and that carbon-removal-heavy pathways have already shaped political expectations that global emissions can 'overshoot' in the near-term and be compensated by increased carbon drawdown in late century (Beck and Oomen, 2021).

Experts followed with critiques on whether IAMs – as economic models coupled with comparatively limited representations of natural and societal systems – are capable of mapping emerging mitigation strategies that do not rely on global-level supply-side systems innovations (*Theme 2,* Table 1). Experts questioned whether IAMs can better represent regional scales, inequities and differences between geographies represented in modeling, novel options whose technical dimensions are unknown or exaggerated, and whose societal dimensions cannot be represented. These mirror external critique (Braunreiter et al., 2020) as well as reflection from within the IAM community (O'Neill et al., 2020; Gambhir et al., 2019a; Schweizer et al., 2020). Further questioning were raised on the capacities of IAMs to inform new intents and users, such as monitoring, reporting, and verification (MRV) of carbon removal, or for the emissions of full supply chains and life-cycles. Experts similarly voiced concerns over the capacity of IAMs to model new carbon removal approaches, beyond bioenergy CCS and forestry

Table 1
Carbon removal assessment in integrated assessment models.

Theme	Respondent	Statement of Concern and representative quotation
1. Critique of carbon removal in IPCC reports	R81, R84, R101	Cost-effective techno-economic modelling permitted carbon removal as a backstop for achieving ambitious targets. *"It's insane, this kind of social construction that has emerged in the IPCC, this overshoot… and all of a sudden it was established wisdom … Now all of a sudden we need to be by 2050 carbon neutral … Now we need the negative emissions. I mean, they have boxed policy makers into this kind of paradigm and now they say there is no escape, there is no alternative."* (R81)
	R81, R87, R101, R120	IAMs have an agenda-setting ability regarding mitigation options - despite the 'policy-relevant but not prescriptive formulation'. *"… carbon dioxide removal has been … featuring in IAMs, largely as a result of model assumptions rather than, let us say, guiding policy questions… And then, let us say, this is rather a policy-prescriptive move… We will be having a bit of a confused debate in the scientific community as a result. Some communities have moved ahead, assuming vast potentials or integrating this into some models. Other communities have been taken by surprise, trying to push back, trying to understand the system implications of what is coming their way."* (R101)
2. Challenges for representing novel mitigation and carbon removal options	R12, R40, R55, R82, R101	IAMs underplay differences between direct emissions reductions and carbon removal, as well as inequities in distribution and funding of diverse, distinct carbon removal approaches in different sectors and geographies. *"Well, I think when it comes to CDR, I think that the main question is surrounding, basically, the scenario design and pathway design… So we do know about CDR potential with regional applicability, different scales, and so on, but we do not have it represented in IAMs sufficiently well. So, let us say, the no-regret option mapping that we now have from bottom-up is more comprehensive than we had in terms of top-down representation."* (R101) *"But there is this kind of tunnel vision towards looking at just mitigation and the economic potential… that is marginalising all the other factors we should be taking into account when weighing different mitigation pathways or different technologies… Then the whole question of overshoot, I guess, just neglects so many different dimensions of the difference between direct emission reductions and CDR… That tends to lead to certain undesirable outcomes, like the outsourcing to the Global South…."* (R55)
	R12, R121	IAMs do not account well for complex life cycle assessments, supply chains, couplings, and trade-offs. *"At the end of the day, your (modelled) BECCS has done multiple objectives of providing an energy service, which is why it's so embedded in choices and pathways of decarbonisation… But it's not providing any of those potential other co-benefits that might actually bring society on board and might meet some of the other societal objectives around biodiversity, so resilience, flood mitigation… It also extends to the communities and livelihoods, right? I think there are lots of trade-offs and couplings there. Perhaps, capturing it all in an IAM is not the right way to go. Or it's not meaningful at that level. The IAM information needs to be paired together with other sets of information in a more nuanced view if you want to explore those trade-offs."* (R12)
	R41, R120	IAMs do not capture policy instruments well. *"What I'm personally really after are the policy instruments that actually make the deployment feasible. Currently, everything is, all of these technologies are, triggered in the model by carbon taxes. That's just too crude an off-policy approximation, especially for negative emission technologies, because a tax on a negative emission becomes a subsidy."* (R120)
	R36	IAM community incorporated bioenergy CCS because of path-dependence. *"They're based on economics. They liked bioenergy because it made sense economically within the models, and they basically couldn't do any of the ocean-based approaches. They didn't value other things as much as, like, restoring blue carbon, so those were left out."* (R36)
	R6, R12, R56, R36, R50, R121	Attention for new approaches is filling the gap left by questioning on bioenergy CCS' feasibility. IAMs have unclear constraints on these new approaches, and could deploy them as backstops by systematizing unrealistic assumptions on new approaches. *"But there's been a lot of progress claimed around direct air capture (DAC), in recent years. And so increasingly, it's starting to be incorporated into the body of modeling literature… Not just BECCS, and do a balance of a bunch of different things, to remove CO2, and maybe if the impacts of doing any one will be not untenable…. But*

(*continued on next page*)

Table 1 (*continued*)

Theme	Respondent	Statement of Concern and representative quotation
		with negative emissions, especially with DAC, that have no obvious constraints on their deployment. Again, what that allows you to do is keep pushing…" (R6) *… if you have a technology that has a fixed cost… what happens is they basically just turn out to be backstops. So, the models end up, at some point, just deciding, "Okay, I'm done doing anything else. I'm just going to use these CDR technologies." That's what the models will do, so that's a modelling challenge that comes up because you're just strictly doing this from an economic standpoint…"* (R121)
	R36, R50	IAMs have poor capacity to model ocean/marine dynamics and ecologies, and to assess marine CDR. *"… few IAMs have the ocean represented… there have been a lot of efforts in coupling the models with land-based models, but not with ocean, because they… only have a small ocean box for only surface and the lower ocean, and it's difficult to model, and many don't even have a box."* (R50)
	R12, R108	IAMs' techno-economic and carbon-emissions focus cannot account for biodiversity-, sustainability-, adaptation-oriented assessment. *"It's not just carbon stored. You're also thinking about many of the other Sustainable Development Goals around livelihoods. You're talking about biodiversity, you're talking about… resilience, with the climate change that's already baked in. Personally, it's not something that translates to an IAM and a cost function very well at all."* (R12)
3. What should IAMs be doing?	R18, R39, R107	IAM community should de-emphasize or nuance the scale of carbon removal in future pathways. There is evidence from recent Special and Assessment Reports that they are doing so. *"If IAMs have created a narrative which is that large-scale CDR isn't that hard to do and decarbonisation of some sectors is really hard to do, the only role for IAMs, I think, is to flip that on its head and show that, actually, decarbonisation is a lot cheaper than we thought and CDR is a lot more risky than we thought."* (R18)
	R18, R82	IAMs should contain more detailed energy system models – e.g. assessing particularly what sectors most need offsets. *"I think there's a role for more detailed energy system models, maybe at a national level to think about what forms of CDR, in that more limited role, fit in to those systems., [examining] these are the limited sectors where maybe there's offsets for CDR. Or equally, actually, this CDR has not been used to offset other emissions, it's been used to do… hedge against climate uncertainties or just provide additional drawdown."* (R18)
	R18, R39, R59, R63	IAMs should be paired with more deliberative and bottom-up methods, especially on topics and dimensions in which IAMs have less capacity. *"I very much agree with … making the scenario-production process more deliberate and participatory… And I think that is a space that is rapidly evolving. Whether or not this directly feeds into the ways that IAMs function I am not sure, because of course IAMs really represent that top-down approach… So I think with alternative conceptions of the future that [IAMs] will be seen as more relative than it was so far. But it is an industry in and of itself. The IAM community has the ears of research funders very directly. That is just a fact. So it will not fundamentally change its ways from one day to another."* (R39)
	R61, R84	Instead of allowing IAMs to reify immature technologies, multi-dimensional appraisal should precede modeling. *"We're used to the concept of an integrated assessment model to compare mitigation strategies, but I'm not sure that we have an IAM type of thinking when it comes to research-and-development prioritisation."* (R61) *"… the mode of thinking that exists under integrated assessment models [is] very left-to-right thinking. 'We have a bunch of techniques. How are we going to fit them in the models? What does that tell us?' We need more right to left, which is, 'What do good solutions look like?'… You really need to think, 'What can work in this multi-dimensional way? What can work socially, technically, economically, environmentally?', and then put it in the models, if it can work."* (R84)

Source: Authors

and land-use management. The latter had originally dominated ambitious IPCC pathways because they are more readily modellable. But early attention on large-scale terrestrial carbon removal has since been balanced by multidisciplinary critique on how IAMs simplified their supply chains and impacts (see also Clery et al., 2020), and on whether these are feasible beyond how they are depicted in models (see also Jewell and Cherp, 2019).

Experts argue that assessment of new carbon removal approaches must learn lessons from the simplification of bioenergy CCS within IAMs (*Theme 2,* Table 1). Increasing attention in innovation is being paid to new approaches: direct air CCS (Nemet et al., 2018) and marine or ocean-based carbon removal (Boettcher et al., 2020; GESAMP, 2019). The former is also receiving more attention within IAM work (Realmonte et al., 2019; Fuhrman et al., 2021). According, some experts warn that IAM work should not understate modelling constraints placed on direct air CCS and allow it to become another backstop (see also Fuhrman et al., 2021). Others question the capacities of IAMs to map the physical and biogenic dimensions of marine-based approaches (see also Boettcher et al., 2020). Still others ask if IAMs are capable of mapping dimensions relevant to biodiversity or food systems governance, which are implicated in carbon removal approaches based in natural systems.

Experts also noted that there has been a reaction to critique from within the IAM community, who have been de-emphasizing or nuancing carbon removal in subsequent pathways (*Theme 3,* Table 1). Indeed, deliberate efforts were made in SR1.5 to create a 'heroic' pathway that does not rely on carbon removal (IPCC, 2018), and pathways in the Sixth Assessment Report further nuance the expansion of carbon removal and limit temperature overshoot (IPCC, 2022; Drouet et al., 2021; Riahi et al., 2021). Experts questioned if this may reflect an adjustment of intent in IAM work – recognizing how a simplified portrayal of carbon removal in AR5 generated unexpectedly strong attention from innovation and policy users. These perspectives also echo uncertainty over the capacity of IAMs to appraise complex climatic, technical, and societal dimensions of new climate strategies.

Experts accordingly pointed out that the current mode of IAM-driven assessment needs to include new kinds of knowledge and practices of appraisal for novel mitigation options catered more to societal dimensions at bottom-up, local-to-regional scales (*Theme 3,* Table 1). Still, there is a spread of opinions on precisely how to supplement IAMs. Some note that techno-economic dimensions of different options and sectors focused on by IAMs can already be improved, providing updated information on: life cycle emissions and constraints posed to diffusion and distribution; what sectors have hard-to-abate emissions and may require offsets; or the 'gap' that carbon removal must fill, given ongoing renewable energy innovations. Others pointed out that new appraisal practices are needed to gauge the multi-dimensional feasibility of new mitigation options *before* they should be included in IAM work.

4.2. Carbon removal assessment in multi-scale environmental modeling

In Table 2, experts reflected that carbon removal is increasingly assessed by environmental process modeling at multiple scales. First are the global-scale earth systems models (ESMs) that feed into the IPCC's Working Group 1 on physical science and impacts. New carbon removal approaches are being assessed in ESMs through the Carbon Dioxide Removal Model Intercomparison Project, or CDR-MIP (Keller et al., 2018), expanded from what had been included in IAM work in AR5 and the Special Report on 1.5 C (Section 4.1). CDR-MIP's ESM-driven work is being fed back into IAMs, informing the constraints that bound how significant these carbon removal approaches become in mitigation pathways (CDR-MIA, n.d.).

Experts raised concerns about the fit of ESM work for mapping processes and impacts (*Theme 1,* Table 2). This work is firstly driven by scientific intent: exaggerated scales of carbon removal deployment that allow for greater signal-to-noise in modelling the implications for earth systems. While these provide a clearer picture of physical processes, they do not reflect politically realistic scenarios of deployment and distribution. Experts also point out shortfalls: ESMs operate at the planetary level, and mapping granular physical risks requires downscaling, or engaging regional and local process and impacts models.

But ESM work on carbon removal draws on antecedent work in solar geoengineering modeling (see Section 4.3). We will examine solar geoengineering assessment later; for now, we note two implications. First, this interaction shows a resonance of the historic discourse on climate geoengineering (see Section 2) that included both solar geoengineering and carbon removal, with exchanges between researcher communities and practices driven by systems-modeling, and are less capable of capturing politically-grounded schemes, motives, and impacts. Secondly, carbon removal and solar geoengineering are being filtered through the same kinds of systems-level assessment that are

Table 2
Carbon removal assessment in multi-scale environmental modelling.

Theme	Respondent	Thematic concern and representative quotation
1. Challenges for earth systems models representing carbon removal	R36, R38	ESM work does not produce politically realistic deployment scenarios. Scientific relevance demands studies structured around unrealistically extreme perturbations to earth systems to permit clearer results. This bears comparison with solar geoengineering modeling. *"I always worry that they're being misused or interpreted incorrectly by others to say, "This is how CDR is going to be deployed in the future," which is not how these scenarios were designed. They were designed to really hit the climate system hard and see how the Earth system responds to CDR, but they're not to say, 'This is how we think future deployment will happen,' or anything like that."* (R36) *"… I think, [this] is in stark contrast as to what is going to happen when we actually deploy these measures, because I do not think we are going to go to the Southern Ocean on a regular basis to spread either iron or alkaline substances. Yes, and the same goes for solar radiation management, in most cases."* (R38)
	R4	Local environmental processes are not captured in ESMs; ESMs need to be downscaled to local levels to be made meaningful. *"If we're going to do large scale geoengineering, in whatever form it is, and we're going to get some sense on, "What's the potential risk to ecosystem services?" Food production and others, for example. We've got to be realistic about the biophysical constraints, and we've got to be realistic about what that means for places where we live at scales we live at? … We've just skipped and we've assumed that 100 km by 100 km grid box is an acceptable level to actually say something about the whole system."* (R4)
2. Local-to-regional modeling for monitoring, reporting, and verification	R36, R40, R55, R61, R65	Analysis of local impacts and MRV for carbon accreditation requires a combination of on-ground engagement, remote sensing and spatial analysis, and earth observation – mixed methods and modeling and multiple scales. *"And I can tell you that we have not done anything around inventing new sensors… And then it's modelling, and I think the modelling is really important. There's, of course, process-based modelling, and then there's practice-based modelling… And because it's a distributed issue, there's a lot of remote-sensing and spatial-analysis needs and big-data-handling needs. And not all the hands that need to be on deck are necessarily on deck on this."* (R61)
	R36, R38, R60	

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Table 2 (*continued*)

Theme	Respondent	Thematic concern and representative quotation
		MRV can be harder in marine spaces than on land. *"I think one of the big differences, probably, with the marine ones is the issue of monitoring and verification is much more of a challenge than it is on land… For something like ocean fertilisation… you've got to prove it in the first place before you can allow modelling to just determine what would be counted as verification, particularly if you're claiming carbon credits for it. [Meanwhile, for] things like blue carbon … that would be pretty similar to the terrestrial ones, effectively."* (R60)
	R60	If MRV stretched beyond carbon management to co-benefits, calculation becomes much more complex. *"The co-benefits for many of them, really, goes back to what I said earlier: that we don't really know enough about some of these things to be able to get a really good handle on what are the actual issues, the impacts. If you don't know enough about the impacts, you really can't quantify the potential co-benefits."* (R60)
	R50, R107	There is a mismatch between the agendas of global modelers vs innovators of novel CDR approaches and carbon credit sellers. *"[There were] two companies' claims of how much afforestation they were doing [that] would take up about 12% of the entire supply of afforestation that we think is out there. So once 500 companies are making those claims, there is not going to be enough to meet it in that sector. Do they really know how much they are going to get in 20 years from enhanced mineral weathering, assuming they even know what the [expletive] that is?"* (R107)

Source: Authors

prominently included in IPCC reports.

Experts at the same time called for regional environmental process modeling to aid an emerging set of intents and users: e.g. monitoring, reporting, and verification (MRV) for carbon accreditation (*Theme 2,* Table 2). This is a different range of models to global-level ESMs – greater in number, more varied, and fine-tuned to particular regions, geographies, and environmental dimensions. Experts point out that improving MRV and understanding local conditions and side-effects requires granular, real-time, applied assessment practices that combine physical and remote observation, data-handling, and modeling – different to the long-duration prospections of sociotechnical and climatic systems calculated by IAMs and ESMs.

Experts (*Theme 2,* Table 2) pointed out that global-level models produce misleading implications for MRV. ESMs seek to capture earth systems processes, and IAMs top capture mitigation landscapes and trajectories; but innovators of novel carbon removal approaches and credit buyers and sellers want to measure the carbon that can be sold. This may be particularly true for some marine-based approaches, as the ocean's simplified representation in IAMs creates the misleading impression of a massive carbon reservoir (Boettcher et al., 2021). Multiscale environmental modelling could fill in gaps on the storage lengths and capacities of different kinds of carbon removal in different geographies (see also Carton et al., 2021), and on life cycle assessments and supply chains (see also Clery et al., 2021). However, experts questioned if environmental modeling can be stretched beyond MRV and carbon management to assessments of societal, multi-dimensional impacts and co-benefits.

4.3. Solar geoengineering in earth systems models

Unlike carbon removal, the assessment of solar geoengineering is dominated by a single, planetary approach: stratospheric aerosol injections. Moreover, while carbon removal approaches are well-incorporated into IPCC assessments, solar geoengineering receives light and precautionary attention in IPCC processes and outputs (e.g. IPCC, 2014a; IPCC, 2022a, Chapter 16; IPCC, 2022b, Chapter 14). However, the ESMs that underpin WG1's study of the physical science of climate change have been re-purposed for modeling solar geoengineering. ESMs therefore represent a key practice for generating scenarios of deployment, and gauging high-level effects for precipitation and reducing temperature rise.

Certain experts see the use of ESMs as part of assessment that should influence governmental decision-making, by developing scenarios that will inform the strategic use of – and ideally, incentivize international cooperation regarding – stratospheric aerosol injection to buy time for mitigation (*Theme 1 and 2,* Table 3). This policy-orientation is coupled with a pivot towards a 'design'-driven perspective: modeling deployment schemes that are 'optimised' to achieve tailored sets of climate objectives deemed desirable. This 'mission-driven' intent is a reaction to previous and ongoing work conducted by the Geoengineering Model Intercomparison Project (GeoMIP), which some experts characterized as driven by self-regarding imperatives that prioritize earth system knowledge, derived from scenarios whose modelled deployments are too blunt and extreme to provide guidance for real-world deployment. Some of these mirror arguments made in Keith (2017), Keith and Irvine (2016), MacMartin and Kravitz (2019), and Kravitz and MacMartin (2020).

However, the same experts voiced concerns over trade-offs between the use of ESMs for understanding climatic processes and informing (perceived) strategic decision-making (*Theme 1 and 2,* Table 3). ESMs – crucially – are a tool repurposed from a much wider realm of climate science, where solar geoengineering modelling is an upstart. Furthermore, there is an unclear fit between the demands of mainstream ESM work and that of solar geoengineering: Experts pointed out that not all politically realistic scenarios can be modelled, while those attempting to do so may not produce results that climate science journals deem relevant. Experts also highlighted that these dimensions also apply to more recent earth system modeling of carbon removal approaches (*Theme 1,* Table 2).

These experts also reflected on the fitness of ESM-derived scenarios for assessing the political implications of deployment, and suggested avenues for improvement (*Theme 2,* Table 3). A first effort must be to model a more realistic space of geopolitics. Much ESM assessment relies on design-driven scenarios that presume perfect political cooperation and technical feasibility. Experts argued that scenarios now need to examine conflicting deployments between global powers and delayed timelines. A second avenue would seek couplings to other modeling suites: a diverse range of fit-to-region impact models for granular risk assessment, or agent-based models for dynamically simulating strategic actions. Indeed, some called for incorporating solar geoengineering into IAM practice and outputs, and for integrated strategy formulation with carbon removal and other mitigation and adaptation actions in emissions pathways (see also NCAR, 2021). At the same time, experts note that attempts to do so have been halting, given the variety and existing

Table 3
Solar geoengineering in earth systems models and integrated assessment models.

Theme	Respondent	Thematic concern and representative quotation
1. Earth systems modeling of planetary solar geoengineering (stratospheric aerosol injection, SAI) on the fringes of mainstream IPCC assessment	R28, R33, R105	ESM work on SAI has an aspirational direction-of-travel: from curiosity-driven and science-oriented scenarios, to 'optimised' scenarios for informing policy, to further assessment aimed at reducing fundamental uncertainties. *"GeoMIP is an earth system model and a comparison exercise. And earth system models do specific things on specific scales. If nobody were doing that work, I would be very alarmed. But, in my opinion, it's less cutting edge than it used to be… where I think the field really needs to go is we need to understand what are the high priority research questions? … people have their lists of priorities… but that's a curiosity driven model, it's not aimed at reducing fundamental uncertainties in the field."* (R28)
	R28, R33, R64, R97, R105	Optimised schemes usefully show where relative winners and losers are, and create best-case scenarios for guiding cooperative planning, rather than entrench rationales for brinksmanship. *"With modelling especially – we can give policymakers a set of realistic options. What could this really do in a way that wouldn't be wild, or totally irresponsible, or would lead to conflict? … I think has this sort of disciplining effect on the policy community going forward and would ensure that discussions [are] based in the science … that, 'Of course, if you are going to do it, it has to be coordinated or collaborative,' because the alternative is a non-starter."* (R33)
	R28, R33, R84, R105	There are trade-offs between using ESMs for scientific and geopolitical inquiry. *"Every time someone says, "Well we need a more realistic experiment, let's put in a more realistic experiment", and then you end up compromising because you have to say, "Okay, well what's realistic that the models can also actually do?" And then you get this sort of weird hybrid of sort of world relevant, sort of scientifically valuable, and then you mix it all together, it's like, 'Okay, well I guess we can get a paper out of this, sort of. We don't really know what's going on.' It takes a lot of effort and a lot of really careful thought to come up with something that is both highly scientifically and politically relevant."* (R28)
	R28, R33, R105	

Table 3 (*continued*)

Theme	Respondent	Thematic concern and representative quotation
2. Proposed directions for modeling solar geoengineering		A wider range of more 'realistic' scenarios must be considered, but these have limits. *"Sure, you can look at equatorial injection, but don't only look at equatorial injection, because we know that that's probably not the right way to do it … What we [also] need to be thinking about are, if we wind up in a world that's more like 2.5–3°, does it make sense to cool it back down? So, we need them to be scenarios that are more moderate. We need to even get basic stuff right, like not starting deployment in 2020, which has been true in every single climate model simulation that has ever been conducted of geoengineering."* (R105) *"… you can model two coalitions or blocks and generate some very basic patterns that are likely to take hold. And those are useful as sort of guard rails to illustrate major risks and hurdles and what is to be avoided. But it can't give you detailed information about what that party is going to do, what they are going to do, the cycle of action, reaction."* (R33)
	R28, R84, R101, R105	ESMs can only produce high-level aggregated depictions of temperature and precipitation. Further assessment should engage with impacts modeling and other modelling suites. *"So, an earth system model can spit out temperature, precipitation, sea ice, so what? I care about food security and water security and how all of those interact with the transportation sector; supply and demand, things like that. I mean this is getting into the realm of impacts modelling and integrated assessment modelling."* (R28)
	R33, R105	IAMs could integrate SAI with carbon removal and mitigation approaches - sequence of deployment in an integrated strategy. *"And the critical window of opportunity for SAI to deliver the benefits that it could deliver would be in that 20, 30-year window between now, say, and the existence of CDR technologies… And that is an idea, it is a hypothesis, but I think it is probably worth looking at that, at the sequencing, and that would involve tying it up to economic models as well to look through the development cycle of these, say, CDR technologies and what the real constraints are in the real world in terms of getting a critical mass to make a difference in terms of atmosphere concentrations."* (R33)

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Table 3 (*continued*)

Theme	Respondent	Thematic concern and representative quotation
3. Challenges for representing solar geoengineering in earth systems models	R20, R44, R84, R101, R103	Optimised scenarios represent an unrealistic fine-tuning of climatic dimensions. *"If you look at IPCC reports, even with just greenhouse gas warming, we do see a lot of deviations between climate models in their ability to represent regional circulations and so on, and this is only doubled with SRM."* (R101) *"It doesn't matter that you can model an SRM application that is optimum, that improves everyone's well-being. If it changes people's well-being relatively, that is still going to impact in security terms and when – to get a model that says, "You can do all this perfectly" – you have to have a highly controlled, modulated system of delivering feedback that does not exist. [A prominent research advocate confirms this] in the papers, but then he goes on writing, churning out papers about cybernetic control. It's imaginary, piled on imaginary. Then these best outcomes are floated as, 'This is what SRM can do for us.' It just is so detached from reality that I don't know how to deal with these people."* (R103)
	R84, R101	ESMs do not have a wider context of life cycle assessment of SAI deployment and phase out. *"… in the wider context, a whole life cycle assessment of, actually, how do you look at scenarios of SRM deployment and phase-out and the global implications of those is something that is currently absent from the literature."* (R101)
	R25, R33, R73, R84	ESMs cannot capture social and political conditions, interpretations of risk, and (geo)political priorities. *"I don't think assessment's done anything wrong so much as that it is incomplete. I think … computer models, need to really be thinking about how their results are going to fit into modern international relations. How does this fit into the modern sovereignty and security landscape in the world? I just read one paper about injecting sulphur along various latitudes… But they weren't really thinking about it in terms of the nations that are along those latitudes…. in which case are you just soaking up money with your model to try to build a library of best-case scenarios? That's not going to help actual decision-makers."* (R73) *"I have been thinking recently about just geoengineering as a kind of political issue rather than the deployment schemes in models, and how that could be used to buttress other agendas- and so on and so forth, in the way that isn't related to climate, or maybe that is a different thing… It is going to plop down in the middle of this ongoing strategic rivalry, these great forces having to do with trade, economics, finance, history, past humiliations, prestige, technology… It gets swept up in the megaproject prestige leadership issues that take place within the US and China, and will even more so."* (R33)
	R12, R33	ESMs cannot capture dynamics around delaying decarbonization; modelling idealized solar geoengineering could reinforce it. *"So, I find that there's a lot of enthusiasm within current political – well, government – spheres for direct air capture [DACCS, carbon removal]. That's what they're really focused on: "How much DACCS can we get? How fast can we get how much DACCS?" because it's read as, "Then I don't have to do difficult stuff. I don't have to make people make changes." That, for me, is the real-time functioning of mitigation deterrence. So, all the idealised stuff about SRM, about, "We'll definitely do it like this," you should spend much more time looking at, effectively, the stupid use of it, because that's more likely to happen if you go down that route, personally, is my experience of how the difference is between idealised theoretical modelling and what you see happening on the ground."* (R12)
	R47, R78	Models cannot capture unknowns – which is obvious – but these can be profound. *"SRM, that's the fundamental risk, because we simply just don't understand it… some of the major effects of nuclear weapons we learned about by accident. So when we set the first hydrogen bomb off in the atmosphere, we learned about EMP. It was, 'Oops'."* (R47).
	R25, R78	Least developed countries in the global South prioritize adaptation, development and poverty alleviation, health and agriculture - SRM does not combine straightforwardly with their competencies and limited capacities. *"We don't have the expertise basically to do this modelling, this legal risk assessment… also not much funding. So, that's another challenge, and of course there is just no support from governments. I mean national governments from our region, because I think the*

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Table 3 (*continued*)

Theme	Respondent	Thematic concern and representative quotation
		focus has always been on adaptation. And little by little mitigation - mitigation always depends upon availability of international support, right? So, adaptation has always been the concern, so when we were there, we were discussing, 'Do we really need extra effort to study geoengineering, or shall we just focus on climate adaptation and of course climate mitigation?'" (R25)
	R78	Assessment in the global South has to navigate scarce funding, and power dynamics imposed by funders. This can involve being locked out of Western funding, but also intra-South power dynamics. *"A rich country can do that. Maybe, sometimes, you can collaborate, or our guys can apply for a grant and do research with western countries, like this kind of model, but I don't think completely local resources will be given to understand SRM from a national scale. For SRM, no, but climate adaptation, I see there are a lot of… I see India-Bangladesh joint research on the Ganges River. Yes, so that kind of [collaborative] research is there, but I wouldn't say this is really a massive scale. There is still a lot of mistrust and competition. Because India is a big brother. You know? … I think power plays a bigger role."* (R78)
	R33, R44, R107	Scenarios meant to incentivize cooperation can also generate incentives for national experts/governments to develop perverse rationales and deployment schemes. *"Remember the CIA funded the first NAS study on geoengineering. I get this call that says, "[Redacted], this is somebody with the Central Intelligence Agency," which you never want to hear. (Laughter). Yes, the CIA calls, but they wanted to meet because they were funding this NAS study. What they said – you know, take them at their word – was that they were afraid that other countries were going to try to weaponize solar radiation management approaches. That is all they were looking at the time. So I was like, 'Okay, well, are you guys trying to weaponize them or somebody else?'"* (R107)
4. Challenges for representing solar geoengineering in integrated assessment models	R121	IAMs are getting better at representing climate and linking to climate models, but it is unclear how regionally- or nationally- specific modelling can be. *"…integrated assessment models are getting increasingly good at – they're still bad because they're so hard – but increasingly good at representing more granular effects on things like temperature or precipitation than they did before, so not just at a national level but gridded scale, linking with climate models and so forth."* (R121)
	R28, R36, R38, R40, R101, R121	IAMs as cost-optimizing economic models are misleading for SAI assessment – this requires a risk assessment framework with climatic and political dimensions, which IAMs cannot provide. *"The energy consequences of SRM might be interesting to explore a bit more, but my first guess is it's not 10% of the energy supply, or much less. And therefore, still not the biggest concern that you would have with respect to the decision, whether you want this technology or not. So, I think 90% of this discussion, 95% of the discussion, do I want SRM or not, would be simply about what are the risks of applying this technology in terms of for the climate system? And what could I avoid?"* (R40) *"[Putting SAI in IAMs] sounds really important to do, because this is, you know, potentially a game changing technology that I honestly believe we will use, at some point. The problem is, if you put in a model that is fundamentally based on economics, the model will choose it every time, because it's just so cheap and there are no downsides within the modelling framework."* (R28)
	R89, R101	Systems models – ESMs and IAMs – represent platforms with which to raise solar geoengineering's profile and credibility. *"I think it is fine to do research, but I think it would be important to reflect on the culture of research that we do in the context of SRM, because, let us say, we tend to be driven by – particularly in climate research – a bit of a media hype, directly single paper-to-policy kind of process. This, of course, in the context of SRM, is a big risk because there is a direct policy agenda that is related to this issue, and every single publication might already resonate there. This does not necessarily align well with, let us say, also reporting mis-findings or un-findings, and so on."* (R101)

Source: Authors

priorities of these other modeling communities, with unclear avenues for repurposing them towards solar geoengineering.

These suggestions are contested by multidisciplinary critique of model-driven assessment practices (*Theme 3,* Table 3). First, understandings of the climate system are argued to be insufficient, as are modeling capacities to simulate them – repurposing them for solar geoengineering piles uncertainties on uncertainties. Secondly, ESMs are used to create idealized scenarios that emphasize relative improvements in environmental impacts and conditions, assume stable politics, and elide deep political uncertainties (see also Low and Honegger, 2020; McLaren and Corry, 2021). While research advocates readily admit this, critics emphasize that such scenarios produce a discussion of risk for decision-makers that ignores complex unknowns, and narrows risk to what can be simulated by ESMs in optimised scenarios. Such scenarios may even create insular, security-driven incentives, rather than cooperation over climate protection. This critique also reflects how IAMs may have mismanaged the rise of carbon removal as a strategy – shaping initial perceptions of viability and necessity, through idealised modeling, that are now under fire. Thirdly, critics challenge the role and capacity of the IPCC assessment structures and practices to take on stratospheric aerosol injection, focusing on imbalances between the interests, funding, and participation of research communities between the global North and South.

Similarly, experts contested proposals to incorporate solar geoengineering into IAM practice and IPCC mitigation pathways (*Theme 4,* Table 3). Some, in favour, argued for policy-informing imperatives: integrating solar geoengineering into IAM assessment allows for a more complete portfolio mapping of climate options, as well as for gauging the trade-offs between these different options. Others, against, countered that the physical risks of stratospheric aerosol injections need to be more granularly mapped first, and that IAMs have an especially poor fit for capturing physical impacts. Others questioned whether cost-benefit-optimizing IAMs would simply use stratospheric aerosol injection as a backstop akin to bioenergy CCS, and if the logic of deliberately optimised deployment schemes in ESMs – in one expert's words, "creating the impression of fine-tuning temperature and precipitation everywhere" [R101] – would be amplified in IAMs. Still others argued that systems modelling – e.g. IAMs and IPCC pathways – represent highly visible, policy-facing platforms with which advocates hope to raise solar geoengineering's profile.

4.4. Generalizable gaps and new anticipation tools

Calls for new assessment practices in carbon removal and solar geoengineering, represent three generalizable themes across systems modeling (*Theme 1,* Table 4). First, experts questioned 'disciplinary bounding', and the capacity of practices and researcher communities grounded in the physical sciences or techno-economic analysis to fully assess novel climate strategies with complex political motives and dimensions. This is compounded by the deployment of these practices in controversial solar geoengineering approaches. Second, experts called for a stronger focus on society-facing appraisal and incentivization of climate action, to supplement a historic focus on technological solutions and innovation in model-driven work. Crucially, this calls for assessments beyond a 'cockpit' focus on global systems and decades-to-centuries timelines, and for the incorporation of the missing local-to-region, actor-oriented detail that would make climate strategies meaningful and actionable. This would require not only new methods of assessment and engagement, but local, traditional knowledge that are marginalized within scientific self-conceptions of proper expertise. Third, experts called for a move beyond strict focus on climate per se through carbon emissions or temperature management, to multi-issue governance that reflects connections with food systems, biodiversity, marine governance, security, and others.

Experts then suggested a number of qualitative methods to anticipate novel strategies, abrupt and changing timelines, political actors and

Table 4
Assessment gaps and new anticipatory tools.

Theme	Respondent	Thematic concern and representative quotation
1. Generalizable assessment gaps across carbon removal and solar geoengineering	R41	Models – and many other approaches – are scientifically driven and disciplinarily bounded in design, and need to be part of a wider ecosystem of approaches and open to a robust range of uses. *"… you cannot model a transition with an equilibrium model because transition is, by definition, an equilibrium-changing process. I have the impression it's like a watchmaker having only a hammer as the only tool and then hoping to repair your watch. [We need] interaction of different kinds of knowledge in a knowledge society, where no discipline or no actor can any longer play a monopoly position…"* (R41)
	R116	Novel technologies reflect the biases of their advocates. *"I hang around with people who think in the future, and I know that that's a luxury. People who live in the future are comfortable in the present. You hardly find a futurist who's hungry."* (R116)
	R89, R116	There is more focus on technological innovation than on societal appraisal. *"It's a systemic problem that we have. We have this tendency to focus on the technological innovation and dismiss, under-invest, under-consider, under-model or under-analyse, the social implications or social constructs leading up to the physical technology."* (R89) *"Am I saying basically, 'It's okay to do technical fixes, so long as you're carrying people along and carrying society along?' That's probably where I'm at because I'm not a critic of technology. What I'm a critic of, is not building society at the same time. Or thinking that because we've got the technology we're saving the world."* (R116)
	R102	Assessments need to focus on detail meaningful to actors, instead of overhead concepts, targets, and methods (e.g. justice, nature, sustainability, overshoot, 1.5 C, optimized scenarios). *"I think the most important thing to be is clear about the concept [underpinning assessments]. Really precisely… we call it 'thick and thin concepts.' So a 'thin' concept is one that everyone likes the idea of. Like 'justice' or 'nature'. The details aren't really filled out. It is actually filling out these details of the technology and filling out the details of these kind of concepts that is going to be key, I think."* (R102)

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Table 4 (*continued*)

Theme	Respondent	Thematic concern and representative quotation
	R49, R55, R83, R89	Models focus on carbon emissions or temperature management; assessment must reflect and incentivize more issue-cross-cutting challenges and governance. *"I think the Sustainable Development Goals are a perfect guiding framework for how to do CDR or what CDR should do. In a similar way [that] we tried to use biodiversity as that guiding framework, the SDGs are more comprehensive and deal with more issues… Making those distinctions is really important when you're talking about the land sector because [what] always happens in papers and in IAM models and stuff is not what happens on the ground."* (R49)
2. New anticipatory tools and purposes	R63	Assessment should expand relevance to decision-making by going beyond cost-benefit analyses. *"Obviously, we have a cost-benefit-analysis paradigm [in IAMs]. There is some heterodox work around real options and in academia there is some stuff around studying optionality, impossible futures, and creating more robust options. That sits at many levels, and it's … a nested hierarchy of priorities, societal buy-in, institutional architectures, the decision incentives within those institutional architectures, the right decision support tools… under uncertainty [and] the role of participatory processes in doing that at a number of levels."* (R63)
	R94	Assessment should be society-facing: Broad principles for guiding more tailored action; individual analyses, stage gates, catering to local contexts, couplings, values, and sustainability intersections. "*Assessment is a three-part process for us. It's about broad principles. It's about the risks and opportunities, which may be associated with individual technologies, which you obviously have to control through the RD&D process, maybe through 'stage gates' which have been used on a number of UK projects…Then – and in my mind, crucially – it's about where these technologies are going to be employed or what countries they're going to affect, what the local priorities are, the relationship with development politics and with the SDGs in general, and what kinds of values and concepts and issues are raised in that process of interaction with those policies."* (R94)
	R76	Agent-based models and network models can provide more dynamic strategy modeling. *"… we really need to have more of these agent-type models, as opposed to either dynamic systems models that most of the IAMs are, because on the social and governance side, it's really important for the actors to see themselves represented more directly in the models… you can sort of use the IAMs and other models like that to say, "Well, we need to make these changes in our social-technical systems", but those models aren't so good about, "How do we actually affect that kind of change?" So, a better understanding of the interaction between social actors, individuals, governments, businesses,* etc.*"* (R76)
	R17, R20, R76, R106	Fiction is a resonant qualitative mapping of actors and contingencies. *"… it might be very possible that SRM can end up just perpetrating the structural inequalities. I always like to give the analogy of the Snowpiercer movie… it's creating the escape from the disaster caused by failed geoengineering, but within the eternal engine train, there's no ideal, equal society they build. They still build a class-divided society, and that's human history. So, when we think about the opposite way, even if SRM is successfully deployed, I think it might be easy to end up perpetrating a systemic inequality rather than resolving inequality."* (R17) *"This, for me, is, let's say, a real 'so what?' And if one reads [Ministry of the Future], of course one gets into interesting things like climate terrorism and unilateral action. I liked the description of the Indian heatwave and then how they put SAI. That is exactly the point. If you suffer directly from climate change impacts and you have a policy option at your disposal, then you don't care whether the international community actually will accept it or not, unless you get, of course, a retaliation threat and so on. So, overall, I would say one needs to have a very open dialogue with all stakeholders about the potential risks."* (R106)

Source: Authors

projects, and qualitative, stochastic challenges that cannot be mapped by systems modelling (*Theme 2,* Table 4). Again, these applied to both carbon removal and solar geoengineering: supplementing systems modeling with bottom-up and user-specific practices that include qualitative stakeholder engagement, scenario-construction, case-studies, agent-based and network modelling to provide more dynamic strategy formation. Fiction was noted by several as culturally-resonant depictions of future climate action: the film *Snowpiercer* as a reflection of structural conditions that shape human responses to a changing climate, and the novel *Ministry of the Future* as a gameplan for developing disruptive climate strategies in the context of overt and clandestine geopolitical agendas.

These suggestions mirror a literature emerging throughout climate and global environmental assessment on the need for new modes of research. This development is central to our paper, and we discuss it at length throughout Section 5. For now, we turn to a synthesis of the different kinds of assessments and research communities present in carbon removal and solar geoengineering.

4.5. Synthesis: contrasting anticipatory assessments in carbon removal and solar geoengineering

To recall: we see carbon removal and solar geoengineering as evolving products of researcher communities with different intents, practices, intended audiences, and outputs. These shape our conceptions of novel strategies, and how they are to be governed. In this sense, carbon removal and solar geoengineering are becoming stress-tests for dominant modeling practices that feed – or are designed to feed – into IPCC reports. We synthesize the insights of Section 4 here, and furthermore in Table 5.

We observe two areas of activity in our data that are built around modelling (Table 5, columns 'Carbon removal' and 'Solar geoengineering'): an established community of research groups using IAMs to map mitigation options in IPCC processes, including carbon removal (van Beek et al., 2020; O'Neill et al., 2020); and a smaller, looser network primarily (though not exclusively) using ESMs to map solar geoengineering schemes (MacMartin and Kravitz, 2019; Aldy et al., 2021), and aspiring to greater visibility (Oomen, 2021) in the face of considerable critique (Biermann et al., 2022b).

But we can also see a third, less coherent area of activity, as a range of experts challenge systems-modeling on the need for more qualitative, multidisciplinary, local, and actor-focused assessment (Table 5, column 'Societal appraisal'). The key critique is that ESMs and IAMs are repurposed tools that are unfit for the purposes to which they are inertially or inadvertently turned. Neither are designed to incorporate or assess granular, localized physical or societal dimensions; neither are designed as tools of risk analysis; neither are tools from which to prioritize the research and development of novel technologies. Crucially, they elide (geo)political motives and implications in an increasingly polarized world, by being unable to incorporate them. In doing so, they create and entrench partial pictures of risk, optimized schemes and intents, technocratic modes of inclusion, and exclude societal expertise. Meanwhile, systems models are functionally used to construct best-case, idealised scenarios: long-term and uncontested deployment schemes tailored to particular climate goals. Ideally, these scenarios and pathways create a basis for cooperation or further refinement; but plausibly, they reinforce the promise of silver bullets.

Still, if many experts agree that technical tools of systems-assessment have been mis-purposed, they are not united on the scale of reform, nor on the intent of assessment. In solar geoengineering, there is emerging agreement on assessing the politics underpinning research and deployment (Table 3). Some do so within a 'mission-oriented' mode that seeks greater policy relevance, calling for social science to map the political dimensions of international deployment and ideally, cooperation (Table 3, see also Reynolds and Horton, 2020; Parson and Reynolds, 2021; Aldy et al., 2021). Others call for the same practices, but with the aim of open-ended, critical assessment that caters more towards publics and marginalized voices than towards strategic policy-making (Tables 3 and 4, see also McLaren and Corry, 2021; Low and Buck, 2020). Most are agreed on the need to involve researchers, decision-makers, and publics from the global South (Rahman et al., 2018; Biermann et al., 2022b; Táíwò and Talati, 2020). The battle here is not on whether the shape and scope of assessment needs to be widened, but on whether the intent of

Table 5
Contrasting anticipatory assessments in carbon removal and solar geoengineering.

	Solar geoengineering via earth systems models	Carbon removal via integrated assessment models	Societal appraisal and multi-scale assessment
Intent: Mandate or raison d'etre of assessment	'Mission-oriented' assessment, ideally for incentivizing cooperative strategic policy; Implicitly to bring solar geoengineering to greater prominence as backstop for ambitious targets	'Policy-relevant but not policy-prescriptive' assessment of mitigation options; Functionally prescriptive of carbon removal as backstop for ambitious targets	Varied: Highlight local-to-regional socio-political implications; Inclusive and deliberative participation; Introduce new intents to assessment (eg. MRV, security, food)
Researchers: Expert networks and communities based around practices, topic or agenda	Network of research advocates; ESM-use predominant but not exclusive	IAM community of IPCC Working Group 3	Looser networks, interdisciplinary social science, typically but not exclusively critical of climate interventions
Users: Real and perceived audiences targeted by or further using assessment outputs	Policy-makers (implicitly, national governments)	Policy-makers (through IPCC mandate); functionally	Varied: Local-to-regional demographics; Galvanizing new assessment communities; Decision-makers at multiple levels
Practices: Methods and epistemologies of assessment; kinds of expertise and knowledge prioritized	Earth systems modeling on high-level impacts	Techno-economic modeling of mitigation options	Multi-scale, mixed-methods, actor/user-focused assessments that nuance systems modeling
Outputs: Products of assessment	Deployment schemes depicting high-level benefits / risks	IPCC mitigation pathways; 'Matrix architecture' including Shared Socioeconomic Pathways framework	Frameworks and studies emerging at various global assessments or at sub-state level
Shortcomings of current work	Mis-purposed as a tool for risk and impact assessment; Creates optimized schemes that emphasize relative climate improvements and elide perverse geopolitical agendas	Mis-purposed as a tool for risk and impact assessment and technology prioritization; Creates optimized schemes based on cost-benefit efficiency and unclear criteria for novel technologies	Unclear overall intent when taking a bird's eye view over solar geoengineering and carbon removal assessment, or climate and global environmental assessment broadly
Proposed direction-of-travel towards societal appraisal	Model more geopolitically-realistic scenarios; Expand to local-to-regional impacts models; Expand to qualitative scenarios for political agendas; Expand	De-emphasize carbon removal in favor of alternative pathways to stringent mitigation; Expand communication and use of IAM pathways and frameworks;	Nuance endemic technocratic, global-systems-oriented assessment; Greater integration or at least coordination between methods, research communities, and assessments

(continued on next page)

Table 5 (*continued*)

	Solar geoengineering via earth systems models	Carbon removal via integrated assessment models	Societal appraisal and multi-scale assessment
	to IAMs and IPCC pathways	Greater interdisciplinary and stakeholder collaborations	
Uncertainties over future work	Given desire to bring solar geoengineering to greater prominence, how instrumental will further work be?	Given dominance of IAM pathways and practice, how tractable are calls for societal appraisal?	Comparatively low resources and visibility. How to coordinate diverse intents and methods, spread across (siloed) levels, polities, and global assessment regimes?

The elements of intent, researchers, users, practices, and outputs (column 1) are pragmatically conceived and defined, and have parallels throughout surrounding literatures. Studies of scientific assessment make use of an ecosystem of overlapping terms fit-to-purpose – Leonelli and Ankeny (2015) refer to 'norms, infrastructures, procedures and resources'; Macnaghten and Chilvers (2014) to 'products, processes, and purposes'.
Source: Authors

those doing the assessment functionally normalizes solar geoengineering.

Carbon removal is more normalized as an incoming strategy. But conversations are expanding beyond the bounds of initial IAM-driven mappings into a much wider range of approaches spread across industrial, terrestrial, and marine environments, and at local-to-regional rather than global or macro-regional scales. The diversity of applications demands a more imaginative, locality- and actor-driven approach to anticipation (Tables 1, 2, *and 4*; see also Markusson et al., 2020; Cox et al., 2021). Exploring the impacts of different carbon removal distributions will require combinations of earth systems models, impacts models, and qualitative case studies. Expanding MRV for carbon accreditation to a wider understanding of co-benefits and risks across local contexts and longer supply chains will require industry and public engagement, multi-scale modeling, and novel monitoring systems (Tables 2 and 4). Incoming frameworks also expand carbon removal assessment beyond management of carbon emissions. Buck et al. (2020) invents plausible carbon removal projects to flesh out details on which to base governance in the context of adaptation; Dooley et al. (2020) derives a 'threat identification' framework in the context of biodiversity governance.

5. Discussion

We now move from an in-depth treatment of carbon removal and solar geoengineering assessments and communities/networks to reflect on a more generalizable paradox. On one hand, these approaches have been made relevant to incoming climate strategy and policy through scientific assessments. At the same time, these same mainstream assessments are unable to provide adequate understanding of these strategies, their limitations, and their implications to relevant audiences. Carbon removal and solar geoengineering are case studies that show how mainstream assessment bodies and practices may need to be reformed to deal with increasingly complex climate and environmental futures.

In what follows, we map 5 overlapping fault-lines in anticipatory practice that surfaced through our expert interviews. Through these, we discuss interplays between how key experts envision the anticipatory assessment of carbon removal and solar geoengineering, and highlight key questions that these pose in the wider debate on reforming global environmental assessments (GEAs).

5.1. Simplification vs. Comprehensiveness

All anticipatory assessment asks: What phenomena (impacts, risks, courses of action, background contexts) are we trying to capture in or about the future? This necessitates concrete choices, narrowing down what is or can be accessed from an otherwise limitless array of inputs and outputs in systemic issues. Another way of phrasing this is the attempt to obtain signals against noise.

This is endemic. One interviewed modeler (R28) cited the well-used adage that "All models are wrong, but some are useful" – one must choose parameters that balance between trying to attain useful simplification fit for purpose, while navigating a complex system. This is reflected in surrounding literature: MacMartin and Kravitz (2019) on modeling solar geoengineering, and Low and Schäfer (2020) on modeling carbon removal (see also Heymann and Dahan Dalmedico, 2019 on ESMs, or van Beek et al., 2020 on IAMs). It is also true of qualitative, deliberative futuring – foresight seeks to amplify 'weak signals', or making abstract possibilities about the future 'thick' and actionable with politically-relevant detail (Parson and Reynolds, and Low, 2021, 2017 on solar geoengineering; Buck et al., 2020 on carbon removal; Gambhir et al., 2019b in general).

But there are shortfalls to all such simplifications. A topical or technological focus can become myopic. Studies might over-assume the importance of solar geoengineering or carbon removal, and project political scenarios formed wholly around them – rather than investigate how these still-immature climate response proposals might be altered or ignored by existing contexts and interests. The feasibility and risks of carbon removal and solar geoengineering approaches can also be filtered imperfectly though the epistemologies of different assessment practices (Section 5.4). For understanding emerging technologies and adjoining challenges, obtaining clear 'signals' emphasizes initial concepts of benefit and risk – but also narrows and even entrenches them.

This invites us to consider: What are the purposes behind the choices that balance between simplicity vs. *comprehensiveness in various assessments? More importantly, what do they accomplish, and what do they elide?* If the objective behind optimized solar geoengineering scenarios is to present best-case scenarios to inform international policy coordination, or if IAMs optimize mitigation strategies around cost-effectiveness, what does this perversely simplify in political motives and impacts? If critical stakeholder engagements pose corrective functions by introducing (geo) political imperatives and concerns, what dimensions of risk or benefit are they in turn emphasizing to the detriment of others?

5.2. Explorative vs. Solutions-oriented assessment

This relates to a tension between explorative and solutions-oriented assessment – and significantly, researchers differ on the meaning of these terms in characterizing their efforts. Kowarsch et al. (2017) reflect on a move towards problem-solving research in the face of grand challenges in GEAs – going beyond assessment of problems to "integrated, contextualized evaluation of different environment-related policies and their complex effects" (p.586). Here, solution-oriented work is thought of as 'explorative' – in that it does not predict or prescribe particular courses of (policy, technology-development) action, but maps them under different conditions. This is a resilient conception of solution-oriented assessment, reflecting the IPCC's 'policy-relevant, but not policy-prescriptive' mandate. IAM pathways, for example, are described as a cartography (Edenhofer and Kowarsch, 2015).

Others contest the conflation of explorative and solutions-oriented work, arguing that 'mapped' solutions are still filtered through modeling paradigms. Orienting solutions towards particular (temperature) targets, when coupled to epistemologies that focus on earth systems or techno-economic variables, narrows what solutions become thinkable and practicable (Beck et al., 2022; Boettcher, 2020). Aiming at 'policy-relevance', meanwhile, becomes a tool to gain or maintain scientific authority, and 'not prescriptive' becomes a defence mechanism against critique (Hansson et al., 2019).

For example: 'mission-oriented' SAI modeling is functionally prescriptive towards policy-planning, creating best-case scenarios for deployment according to idealized climatic criteria. IAM work maps combinations of mitigation approaches across an ever-expanding array of conditions and scenarios – but while purporting to be informative but not prescriptive towards climate strategy, IAM pathways have functionally focused climate governance on a techno-economic evaluation of carbon removal necessary for reaching ambitious temperature targets.

This invites us to consider: When is solution-oriented assessment in particular GEAs trapped within particular methodologies, organizing frameworks, and pathways, such that it is no longer explorative but prescriptive? Can greater stakeholder inclusion offer increased perspectives? And if technocratic assessments in GEAs must be opened up, at what point can these be considered 'closed' enough to act upon?

Critics of this inadvertent narrowing of the solutions space have an additional conception of 'explorative' assessment – forestalling a premature closing down towards expert-driven solutions by opening up research to participation from stakeholders, embracing a greater degree of local knowledge, complexity, and uncertainty in assessment, being catered to on-the-ground context and concerns, and plotting strategies that would be 'robust' or workable across a large range of different stakeholder interests and future contingencies (e.g. Beck et al., 2022). These are directly connected with the discussions of all the following sections.

5.3. Research vs. user priorities

Assessments purport to orient themselves towards particular audiences or 'users' in policy-making, business, civic organizations, and other actors thought relevant to the operationalization of climate and sustainability goals. At the same time, assessments can be research community-centric, and prone to epistemological or issue-based siloing and myopia. Findlater et al. (2021) recently argues that the field of climate services, explicitly set up to bridge the operationalization gap between climate information and decision-making, has become dominated by the priorities of researchers themselves. Plainly put, researchers can become their own users, in a self-perpetuating cycle.

There are parallels in carbon removal and solar geoengineering assessments, where researchers arguably do not engage with real, situated decision-makers as much as broad, self-derived conceptions of decision-makers and their imagined demands (see Geden, 2016 for carbon removal; McLaren and Corry, 2020 for solar geoengineering). Much input from our expert interviews bears this out – priorities of ESMs are central to ongoing research into stratospheric aerosol deployment schemes, and that of IAMs for the earlier phases of carbon removal research. Such arrangements can become inertial.

This invites us to consider: How can we incorporate new intents, researchers, users, practices, and outputs into existing modes of assessment? Society-facing assessments, left to technocracy, can become self-regarding and display gate-keeping characteristics. When coupled to a solutions-orientation, such assessment unduly narrows how it is possible to think about future climate strategy (Section 5.2).

Others explore a different dimension: Assessments do serve users beyond researchers themselves – although perhaps not all users, and nor is service evenly distributed. Montana (2020) points out that GEAs cater more to developing the authority of scientific bodies, reports, procedures and communities than to bottom-up engagement – but the top-down mode has benefits as a centralized input to high-level, intergovernmental agenda setting. Maas et al. (2021) go further, mapping how different processes and sub-groups that make up an assessment – from scoping, to production, to use – empower different actors at multiple levels, but not evenly. *This invites us to consider: How can we expand the range of audiences recognized within assessments, without eliminating the connections already made?*

5.4. Systems modeling vs. societal appraisal

Much research on the impacts or mitigation of climate change uses systems modeling, and many works trace how the dominance of these modes have been cemented over time for their respective and joint tasks (Edwards, 2010; Heymann and Dahan Dalmedico, 2019; Grundmann and Rödder, 2019; Beck and Oomen, 2021; Cointe et al., 2020; van Beek et al., 2020). Heymann and Dahan Dalmedico (2019) note that a "modeling paradigm has become an agent of change in its own right" in the "social task of producing policy relevant predictive knowledge" (p.1139).

At the same time, in carbon removal and solar geoengineering assessments, these global-scale modelling tools prioritized by IPCC processes are re-purposed, and arguably stretched beyond their strengths to account for new questions and challenges under conditions of deep uncertainty. ESMs and IAMs are mediums that shape the message: solar geoengineering and carbon removal are made feasible through constrained modes of assessment based around modelling radiative forcing or techno-economic criteria.

This invites us to consider: What assessment practices could supplement systems modeling? Critique of top-down, technical perspectives in assessments – resonantly described by Hulme (2010) as an abstract "view from everywhere" – connects to debates about how to make the design and conduct of participatory, society-facing assessments that are inclusive of, meaningful to, and usable by the stakeholders who would need to put them into action. These are longstanding conversations (Pulver and Vandeveer, 2009; Stirling, 2008; Salter et al., 2010; Rothman et al., 2009), and are recently gaining in strength, including frameworks for novel fields of techno-science (Guston, 2014; Stilgoe et al., 2013; Chilvers and Kearnes, 2019), or for the IPCC (Standring and Lidskog, 2021) and climate governance (Muiderman et al., 2020), or GEAs in general (Castree et al., 2020; Biermann, 2021; Pereira et al., 2021a; Turnhout and Lahsen, 2022; Beck et al., 2022).

Given that systems modelling is endemic in global assessment, one pragmatic area of reform seeks to improve modeling inputs: for example, the integration of multi-disciplinary, local-to-regional criteria for examining the feasibility of carbon removal approaches (Jewell and Cherp, 2019; Rickels et al., 2019; Thoni et al., 2020; Waller et al., 2020).

Others envision a wider ecosystem of practices, with three principles to differentiate them from a top-down, systems perspective. They should be *'situated' or actor-focused* instead of taking a 'global cockpit' lens – accounting for the interests and contexts of particular industries, local communities, or national and regional polities (Pereira et al., 2021c); Viner and Howarth (2014)) calling for new epistemologies and engagement practices that incorporate localized communities and forms of knowledge (Mistry and Berardi, 2016; Norström et al., 2020). Accordingly, assessments should embrace *mixed methods* fit to purpose for particular objectives – marrying qualitative engagements, modelling suites, and practical observation (Muiderman et al., 2020 and 2022; Workman et al., 2020; Vervoort et al., 2022). Finally, they should keep any eye to *multiple scales*, understanding not only how assessments work for actors at local, regional, or global scales, but how they might link activity and knowledge across them (Biggs et al., 2007; Shaw et al., 2009; Rosa et al., 2017; Kadebe et al., 2018).

Proposals with these principles exist for reforming integrated assessment into a less global-aggregation and modeling dependent mode (Mach and Field, 2017; Gambhir et al., 2019; Braunreiter et al., 2021) – for carbon removal assessment (Markusson et al., 2020; McLaren et al., 2021) as well as for solar geoengineering assessment (Pereira et al., 2021b; Aldy et al., 2021; McLaren and Corry, 2021). Further studies tease out aspects of small-scale demonstrations (Low et al., 2022), ethics (Lenzi et al., 2021), and climate justice (Batres et al., 2021).

The conversation on how to develop multi-dimensional societal appraisals at these regimes of assessment and governance – and many others – are still nascent. Efforts can be seen particularly in biodiversity conversations contrasting themselves with the IPCC (Borie et al., 2021; Gustafsson, 2021), bearing fruit at the GEA level within IPBES (the science advisory body of the biodiversity regime) through its Nature Futures Framework (Diaz et al., 2015; Lundquist et al., 2021) and commitments to inclusivity, local knowledge, and alternative values towards nature. Similar efforts are emerging at the Global Environmental Outlook (GEO, 2019, Chapter 23). Still, efforts at multi-scale and mixed-methods assessment are largely cornered in proceedings dominated by technical science (Pereira et al., 2021a; Jacob and Ekins, 2020).

5.5. Coordination vs. siloing

Carbon removal and solar geoengineering assessment point to a need to further integrate or coordinate between global (environmental) assessments. Experts pointed out the systemic, or 'wicked' and multidimensional nature of both suites. Solar geoengineering was linked to human and state security through the geopolitics of deployment – and furthermore, as an intervention with potentially considerable leverage on the global climate, projected to indeterminately affect most (environmental) governance issues. Experts more concretely connected a diverse range of carbon removal approaches to energy and industry, agriculture, forestry, and aquaculture systems, and wider issues of urban, terrestrial, and marine space management. In surrounding literatures, experts are deriving assessment frameworks linking carbon removal to biodiversity (Dooley et al., 2020) and adaptation (Buck et al., 2020). Both suites are also being evaluated in light of the Sustainable Development Goals (Honegger et al., 2021a, 2021b).

These dimensions implicate assessments in climate security (Hardt and Viehoff, 2020 on the UN Security Council), biodiversity and eco-systems services (IPBES, 2019, the Convention on Biological Diversity), food (FAO et al., 2021, Food and Agriculture Organization), marine pollution (GESAMP, 2019, the London Convention and Protocol), and environmental issues (GEO, 2019, UN Environment Programme). A sub-group of GESAMP, the London Conventional and Protocol's technical advisory body, is the only body to look at both solar geoengineering and carbon removal as forms of 'marine geoengineering' (GESAMP, 2019). In this vein, experts also noted efforts to develop a new instrument on Marine Biodiversity of Areas Beyond National Jurisdiction (BBNJ), which could be made relevant to marine-based approaches. But this re-raises longstanding questions about how to integrate or coordinate between GEAs (Nilsson and Persson, 2012; Tengö et al., 2017; Biermann and Kim, 2020, eds; Visseren-Hamakers, 2018). GEA processes remain largely siloed – even the landmark Sustainable Development Goals have had a muted coordinating impact (Biermann et al., 2022a). It is unclear how the assessment and governance of carbon removal and solar geoengineering will filter into this fragmented landscape.

This invites us to consider: What starting points exist to strengthen areas – concepts, processes, and outputs – for strategic collaboration between GEAs, or the (expert) communities contributing to them? Within global climate assessment, one could seek greater integration or coordination between the Working Groups of the IPCC. There are efforts to expand and link the assessment processes marshalled by the IPCC Working Groups (e.g. IPCC, 2022's Cross Working Group boxes) However, none of our engaged experts spoke concretely to Working Group 2 activities on adaptation, impacts, and vulnerability, which is expanding inquiry into terrestrial carbon removal, while precautionarily touching upon solar geoengineering (IPCC, 2022a). Working Group 2 is a comparatively interdisciplinary and mixed-methods area of assessment that caters increasingly to the areas neglected by the systems-modeling dominant in the other Working Groups: the societal conditions that create resilience or deepen vulnerability to physical impacts (Adger et al., 2018) and diverse geographical and engagement methods for assessing local-to-regional contexts and implications (Beck, 2011; Eriksen et al., 2015; Klenk et al., 2017; Berrang-Ford et al., 2021). Vulnerability, resilience, and local development have been noted for their capacity to bridge the efforts of multiple assessment regimes (Peters et al., 2016; Kelman, 2015; Munera-Roldan et al., 2022).

Similarly, the IPCC Special Report on Climate Change and Land (SRCCL, IPCC, 2019) was little touched upon. SRCCL takes a broad scope of the land sector, and began to make crucial connections between carbon removal, adaptation, food security, climate justice, and developing countries for whom the agrarian sector is more relevant. Moreover, SRCCL was the first IPCC special report produced by all three Working Groups, with input from the assessment bodies of the UN biodiversity, desertification, and food and agriculture regimes – this could serve as a template for collaboration.

6. Conclusion

In this paper, we engage with key experts in carbon removal and solar geoengineering, treating these twinned fields as case studies that reflect new demands for anticipatory assessment. We observe three communities or networks embodying different intents, practices, outputs, and perceived users for anticipating challenges surrounding novel sociotechnical strategies. Two are built around systems modelling processes dominant at the IPCC: an IAM community seeking to nuance its initial overestimations of carbon removal in previous IPCC pathways, and a network of research advocates seeking to bring solar geoengineering to greater prominence through ESMs, and much more nascently, IAMs, impacts models, and qualitative work. A final one, much looser in coherence and critical in intent, is built around societal appraisal as a collective of frameworks and practices for making technocratic, high-level governance participatory and inclusive at multiple levels. All three contest the shape of assessments (intended to become) resonant through IPCC processes in the climate regime, but have implications for the shape of global environmental assessments more broadly.

What does this mean for anticipatory assessment at various levels – in solar engineering and carbon removal, at the IPCC or in climate assessment, or in global environmental assessment? We can see that there are calls to expand or nuance modelling practices to more mixed-methods, qualitative work catered to different kinds of knowledge and users – some highly critical of these evolving strategies, and some operating in a more solution- or mission- oriented mode that seeks to find options for climate policy. At the same time, we can question the fit of certain IPCC practices and processes – at least, the model-driven Working Groups I (physical science) and III (mitigation options) – and the capacities of their traditional modes to act in new capacities as tools for the anticipation and appraisal of new climate technologies. There is no clear fit between these systems modelling modes and how carbon removal and solar geoengineering should be more comprehensively assessed as immature or hypothetical sociotechnical systems, or critically interrogated as the products of advocacy, or by partial means of assessment. How well might these processes be expanded to assess an ever-increasing, multi-disciplinary and -sectoral range of issues, stakeholders, and climate actions (Pihl et al., 2021; Sovacool et al., 2020)?

Moreover, our study speaks to numerous linked fault-lines that apply beyond the assessment of novel climate action into the general conduct of future-oriented global environmental assessments. We have highlighted multiple degrees of 'undone science' within expert assessments – i.e. by showing epistemic gaps that are growing as well as potential bridges towards connecting them, thereby revealing core challenges for reforming anticipatory assessment. We recall these in Table 6.

If there is a broad sense that the current shape of anticipatory assessment in carbon removal and solar geoengineering is inadequate, the direction-of-travel for reform is uncertain – given that such reform must navigate equally shifting terrain in climate and global assessment. All this signals a need to better grapple with plural but converging trends: from siloing to integration of social, environmental, development dimensions, and from technocratic and technical earth system or

Table 6
Fault-lines and key questions.

Fault-line	Key questions
5.1 Simplification* vs. *Comprehensiveness	*What are the purposes behind the choices that balance between simplicity* vs. *comprehensiveness in various assessments? More importantly, what do they accomplish, and what do they elide?*
5.2 Explorative* vs. *Solutions-oriented assessment	*When is solution-oriented assessment in particular GEAs trapped within particular methodologies, organizing frameworks, and pathways, such that it is no longer explorative but prescriptive?*
5.3 Research* vs. *User priorities	*How can we incorporate new intents, researchers, users, practices, and outputs into existing modes of assessment? How can we expand the range of audiences recognized within assessments, without eliminating the connections already made?*
5.4 Systems modeling* vs. *Societal appraisal	*What mixed-methods, multi-scale, and actor-focused assessment practices could supplement systems modeling?*
5.5 Coordination* vs. *Siloing	*What starting points exist to strengthen areas – concepts, processes, and outputs – for strategic collaboration between GEAs, or the (expert) communities contributing to them?*

Source: Authors.

economic sciences to plural societal collaborations, in term calling for some horizontal integration across issues, regimes, and sectors and vertical integration across scales and levels. In this sense, the travails and shortfalls of assessment of carbon removal and solar geoengineering are but one part of a much larger picture in global environmental assessment and governance.

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CRediT authorship contribution statement

Sean Low: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Chad M. Baum**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – review & editing. **Benjamin K. Sovacool:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

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Data Availability

The data that has been used is confidential.

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Annex 1. . List of 125 semi-structured expert interview respondents

Name	Actor Type	Gender	Country	Institution
[Anonymous Aerospace Engineer]	Private Sector + Industrial Associations	Male	Germany	[Aerospace and space systems company focusing on integrated spacecraft]
Aganaba, Timiebi	Universities + Research Institutes	Female	USA	Arizona State University
Asayama, Shinichiro	Government + Intergovernmental Organizations	Male	Japan	National Institute for Environmental Studies
Bauer, Christopher Dean 'Casey'	Private Sector + Industrial Associations	Male	USA	Raytheon Space and Defense
Bazilian, Morgan	Universities + Research Institutes	Male	USA	Colorado School of Mines
Bellamy, Rob	Universities + Research Institutes	Male	United Kingdom	University of Manchester
Beuttler, Christoph	Private Sector + Industrial Associations	Male	Switzerland	Climeworks
Biermann, Frank	Universities + Research Institutes	Male	Netherlands	Utrecht University
Boettcher, Miranda	Universities + Research Institutes	Female	Germany	Stiftung Wissenschaft und Politik
Brauer, Uwe	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshade Foundation
Brickett, Lynn	Government + Intergovernmental Organizations	Female	United States	Department of Energy, USA
Briggs, Chad	Universities + Research Institutes	Male	USA	University of Alaska, Anchorage
Brown, Marilyn	Universities + Research Institutes	Female	USA	Georgia Institute of Technology
Bruce, John	Private Sector + Industrial Associations	Male	Canada	Carbon Engineering
Buck, Holly Jean	Universities + Research Institutes	Female	USA	University at Buffalo
Burns, Wil	Universities + Research Institutes	Male	USA	American University
Caldeira, Ken	Universities + Research Institutes	Male	USA	Breakthrough Energy, Carnegie Institution for Sciences, and Stanford University, and Stanford University
Camilloni, Ines	Universities + Research Institutes	Female	Argentina	University of Buenos Aires (and Harvard University)
Carton, Wim	Universities + Research Institutes	Male	Sweden	Lund University
Centers, Ross	Private Sector + Industrial Associations	Male	Germany	Planetary Sunshades
Chalecki, Beth	Universities + Research Institutes	Female	USA	University of Nebraska Omaha
Chavez, Anthony E.	Universities + Research Institutes	Male	USA	Northern Kentucky University
Clarke, Leon	Universities + Research Institutes	Male	USA	University of Maryland
Clarke, William S. (Sev)	Private Sector + Industrial Associations	Male	Australia	Winwick Business Solutions
Cobo Gutiérrez, Selene	Universities + Research Institutes	Female	Switzerland	ETH Zurich
Cox, Emily	Universities + Research Institutes	Female	United Kingdom	Cardiff University
Creutzig, Felix	Universities + Research Institutes	Male	Germany	

(continued on next page)

(*continued*)

Name	Actor Type	Gender	Country	Institution
				Mercator Research Institute on Global Commons and Climate Change (MCC)
Delina, Laurence	Universities + Research Institutes	Male	Hong Kong	Hong Kong University of Science and Technology
Di Marco, Leon	Private Sector + Industrial Associations	Male	United Kingdom	FSK Technology Research - Consultant
Dooley, Kate	Universities + Research Institutes	Female	Australia	University of Melbourne
Draper, Kathleen	Civil Society	Female	USA	International Biochar Initiative
Elliott, David	Universities + Research Institutes	Male	UK	The Open University
Erbay, Yorukcan	Private Sector + Industrial Associations	Male	United Kingdom	Element Energy
Felgenhauer, Tyler	Universities + Research Institutes	Male	USA	Duke University
Florin, Marie-Valentine	Universities + Research Institutes	Female	Switzerland	EPFL International Risk Governance Center (IRGC)
Forster, Piers	Universities + Research Institutes	Male	United Kingdom	University of Leeds
Frumhoff, Peter	Civil Society	Male	USA	Union of Concerned Scientists
Fuhrman, Jay	Government + Intergovernmental Organizations	Male	United States	Pacific Northwest National Laboratory (PNNL)
Fuss, Sabine	Universities + Research Institutes	Female	Germany	Mercator Research Institute on Global Commons and Climate Change (MCC)
Gambhir, Ajay	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Geden, Oliver	Government + Intergovernmental Organizations	Male	Germany	German Institute for International and Security Affairs (SWP)
Ghosh, Arunabha	Civil Society	Male	India	Council on Energy, Environment and Water (CEEW)
Grant, Neil	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Gruebler, Arnulf	Universities + Research Institutes	Male	Austria	International Institute for Applied Systems Analysis (IIASA)
Guillen Gosalbez, Gonzalo	Universities + Research Institutes	Male	Switzerland	ETH Zurich
Haberl, Helmut	Universities + Research Institutes	Male	Germany	BOKU Vienna
Haigh, Joanna	Universities + Research Institutes	Female	United Kingdom	Imperial College London / Grantham Institute
Hamilton, Clive	Universities + Research Institutes	Male	Australia	Charles Stewart University
Hartmann, Jens	Universities + Research Institutes	Male	Germany	University of Hamburg
Hawkes, Adam D.	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Healey, Peter	Universities + Research Institutes	Male	United Kingdom	Oxford University
Heap, Richard	Civil Society	Male	United Kingdom	Carbon Removal Centre, Foresight Transitions
Hepburn, Cameron	Universities + Research Institutes	Male	United Kingdom	Oxford University
Herzog, Howard	Universities + Research Institutes	Male	United States	MIT
Heyen, Daniel	Universities + Research Institutes	Male	Germany	TU Kaiserslautern
Heyward, Clare	Universities + Research Institutes	Female	Norway	UiT - the Arctic University of Tromso
Honegger, Matthias	Universities + Research Institutes	Male	Germany	Perspectives Climate Group
Horton, Joshua B.	Universities + Research Institutes	Male	USA	Harvard University
Irvine, Pete	Universities + Research Institutes	Male	United Kingdom	University College London
Jinnah, Sikina	Universities + Research Institutes	Female	USA	UC Santa Cruz
Johnson, Les	Government + Intergovernmental Organizations	Male	USA	NASA Marshall Space Flight Center
Kammen, Daniel	Universities + Research Institutes	Male	USA	UC Berkeley
Karami, Khalil	Universities + Research Institutes	Male	Slovenia/ Germany	University of Ljubljana/University of Leipzig
Karlsberg Schaffer, Madeleine	Civil Society	Female	USA	SilverLining
Keller, David	Universities + Research Institutes	Male	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Keller, Klaus	Universities + Research Institutes	Male	USA	Penn State University
Kravitz, Ben	Universities + Research Institutes	Male	USA	Indiana University
Kruger, Tim	Private Sector + Industrial Associations	Male	UK	Origen Power
Kuswanto, Heri	Universities + Research Institutes	Male	Indonesia	Institut Teknologi Sepuluh Nopember
Lawrence, Mark	Universities + Research Institutes	Male	Germany	Institute for Advanced Sustainability Studies
Lehmann, Johannes	Universities + Research Institutes	Male	USA	Cornell University
Lenton, Andrew	Government + Intergovernmental Organizations	Male	Australia	CSIRO
Lin, Albert	Universities + Research Institutes	Male	USA	UC Davis
MacMartin, Doug	Universities + Research Institutes	Male	USA	Cornell University
Mahajan, Aseem	Universities + Research Institutes	Male	United States	Harvard University
Malik, Abdul	Universities + Research Institutes	Male	Saudi Arabia	King Abdullah University of Science and Technology (formerly Grantham Institute)
McLaren, Duncan	Universities + Research Institutes	Male	United Kingdom	Lancaster University
Mengis, Nadine	Universities + Research Institutes	Female	Germany	GEOMAR - Helmholtz Centre for Ocean Research Kiel
Merk, Christine	Universities + Research Institutes	Female	Germany	Kiel Institute for the World Economy
Michaelowa, Axel	Universities + Research Institutes / Private Sector + Industrial Associations	Male	Switzerland	University of Zurich / Perspectives Climate Group
Montserrat, Francesc	Universities + Research Institutes	Male	Netherlands	Project Vesta, Royal Boskalis Westminster N.V.
Moore, John	Universities + Research Institutes	Male	Finland	University of Lapland / Arctic Centre
Moreno-Cruz, Juan	Universities + Research Institutes	Male	Canada	University of Waterloo

(*continued on next page*)

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Name	Actor Type	Gender	Country	Institution
Morrow, David	Universities + Research Institutes	Male	USA	American University
Muri, Helene	Universities + Research Institutes	Female	Norway	Norwegian University of Science and Technology (NTNU)
Obersteiner, Michael	Universities + Research Institutes	Male	United Kingdom	Oxford University
Odoulami, Romaric	Universities + Research Institutes	Male	South Africa	University of Cape Town
Parker, Andy	Civil Society	Male	UK	SRM Governance initiative
Parson, Edward 'Ted' A.	Universities + Research Institutes	Male	USA	UCLA
Pasztor, Janos	Civil Society	Male	Switzerland	Carnegie Climate Governance Initiative
Pidgeon, Nick	Universities + Research Institutes	Male	United Kingdom	Cardiff University
Pinto, Izidine	Universities + Research Institutes	Male	South Africa	University of Cape Town
Pongratz, Julia	Universities + Research Institutes	Female	Germany	University of Munich
Preston Aragonès, Mark	Civil Society	Male	Norway	Bellona Foundation
Rahman, Mohammed Mofizur	Universities + Research Institutes	Male	Germany	TH Cologne - University of Applied Sciences
Raimi, Kaitlin T.	Universities + Research Institutes	Female	United States	University Michigan
Reiner, David	Universities + Research Institutes	Male	United Kingdom	Cambridge University
Renforth, Phil	Universities + Research Institutes	Male	United Kingdom	Heriot-Watt University
Reynolds, Jesse	Universities + Research Institutes	Male	USA/ Netherlands	UCLA/Independent Consultant
Rickels, Wilfried	Universities + Research Institutes	Male	Germany	Kiel Institute
Robock, Alan	Universities + Research Institutes	Male	USA	Rutgers University
Rothman, Dale	Universities + Research Institutes	Male	USA	University of Denver
Rouse, Paul	Universities + Research Institutes	Male	United Kingdom	University of Southampton
Schleussner, Carl	Civil Society	Male	USA	Climate Analytics
Schmidt, Joern	Universities + Research Institutes	Male	Germany	Kiel Institute
Schneider, Linda	Civil Society	Female	Germany	Heinrich Boell Foundation
Scott, Vivian	Universities + Research Institutes	Male	United Kingdom	Edinburgh University
Simonelli, Lucia	Civil Society	Female	United States	Carbon 180
Smith, Pete	Universities + Research Institutes	Male	United Kingdom	University of Aberdeen
Smith, Steve	Universities + Research Institutes	Male	United Kingdom	Oxford University
Smith, Wake	Universities + Research Institutes	Male	USA	Harvard University
Spangenberg, Joachim	Universities + Research Institutes	Male	Germany	Sustainable Europe Research Institute SERI Germany
Stephens, Jennie	Universities + Research Institutes	Female	USA	Northeastern University
Stoefs, Wijnand	Civil Society	Male	Belgium	Carbon Market Watch
Sugiyama, Masahiro	Universities + Research Institutes	Male	Japan	University Tokyo
Sunny, Nixon	Universities + Research Institutes	Male	United Kingdom	Imperial College London
Surprise, Kevin	Universities + Research Institutes	Male	USA	Mount Holyoke College
van Vuuren, Detlef	Government + Intergovernmental Organizations	Male	Netherlands	PBL Netherlands Environmental Assessment Agency
Vaughan, Nem	Universities + Research Institutes	Female	United Kingdom	University of East Anglia
Victor, David	Universities + Research Institutes	Male	USA	UC San Diego
Vivian, Chris	Government + Intergovernmental Organizations	Male	UK	GESAMP
Wagner, Gernot	Universities + Research Institutes	Male	USA	NYU
Wolske, Kimberly S.	Universities + Research Institutes	Female	United States	University Chicago
Wood, Robert	Universities + Research Institutes	Male	USA	University of Washington
Workman, Mark	Universities + Research Institutes	Male	UK	Energy Futures Lab, Imperial College London

Source: Authors

Annex 2. . Demographic characteristics of experts

Summary information	*No.*
No. of experts	125
No. of organizations represented	104
No. of countries represented	21
No. of academic disciplines represented	34
Cumulative years spent in industry or research community in solar geoengineering, carbon removal, or both	881
Average years spent in industry or research community in solar geoengineering, carbon removal, or both	7.8
No. of experts whose current position falls into the following areas:	
Civil society and nongovernmental organizations	12
Government and intergovernmental organizations	8
Private sector and industrial associations	12
Universities and research institutes	94
No. of experts from the Global South	12

Source: Authors

Annex 3. . Interview question sets

1. Innovation	Which options have high or low innovation potential in technical, communication, societal appraisal, and policy dimensions?
2. Coupling	What energy systems or other sociotechnical systems could or should be coupled with geoengineering and negative-emissions technologies?
3. Business models	What business models and markets could be created or disrupted?
4. Risks	Which serious risks (social, political, military, ethical, environmental) may arise?
5. Sustainability	What are the synergies and trade-offs of deployment for the Sustainable Development Goals and other societal objectives?
6. Justice	What vulnerable groups could be affected, positively or negatively?
7. Actors	Who are the most relevant (or important) actors (or: stakeholders and networks), e.g., for commercialization, development, and acceptability?

Source: Authors

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