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Beyond climate stabilization: Exploring the perceived sociotechnical co-impacts of carbon removal and solar geoengineering

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ABSTRACT

The scientific literature on the co-impacts of low-carbon energy systems—positive and negative side effects—has focused intently on climate mitigation, or climate adaptation. It has not systematically examined the prospective co-impacts of carbon removal (or negative emissions) and solar geoengineering. Based on a large sample of diverse expert interviews ($N = 125$), and using a sociotechnical approach, in this study we identify 107 perceived co-impacts related to the deployment of carbon removal and solar geoengineering technologies. Slightly less than half (52) were identified as positive co-impacts (38 for carbon removal, 14 for solar geoengineering), whereas slightly more than half (55) were identified as negative co-impacts (31 for carbon removal, 24 for solar geoengineering). We then discuss 20 of these co-impacts in more depth, including positive co-impacts for nature-based protection, the expansion of industry, and reduction of poverty or heat stress as well as negative co-impacts for water insecurity, moral hazard, limited social acceptance and path dependence. After presenting this body of evidence, the paper then discusses and theorizes these co-impacts more deeply in terms of four areas: relationality and risk-risk trade-offs, co-deployment and coupling, intentional or unintentional implications, and expert consensus and dissensus. It concludes with more general insights for energy and climate research, and policy.

1. Introduction

Novel sociotechnical interventions are being considered in pursuit of net zero emissions and climate stabilization. A global strategy for *carbon removal* (or negative emissions) involves currently nascent approaches such as direct air capture, enhanced weathering, and bioenergy with carbon capture and storage. Carbon removal is currently envisioned as essential for reducing global temperate change or meeting the longer-term targets embedded in the Paris Agreement (IPCC, 2018). Meanwhile, *solar geoengineering* techniques such as stratospheric aerosol injection could serve as an emergency measure to ameliorate the risks of global warming, or create a stop-gap period of adjustment that gives countries time to adapt to the impacts of climate change (Barrett et al., 2014). Other options such as marine cloud brightening or cirrus cloud thinning are endorsed in the literature for being able to remediate the risks of regional "tipping points" in the climatic system (National Academies of Sciences, Engineering, and Medicine, 2021; Heutel et al., 2016), and to diversify the portfolio of options we have to slow or arrest suspected increases in temperature (Sovacool, 2021). But what are the possible intended, and unintended, co-impacts to these technologies? The term "co-impacts" is meant to capture the positive or negative side-effects that occur in addition to merely the provision of energy services or climate protection (Floater et al., 2016; Edenhofer et al., 2014; Sovacool et al., 2020; IPCC, 2022).

In this study, building on earlier work in this journal (Sovacool et al., 2020) and based on a rigorous and original sample of semi-structured expert interviews ($N = 125$), we explore the types of co-impacts associated with both negative emissions and solar geoengineering research and deployment. Using a sociotechnical approach that highlights the importance of a wider range of factors alongside the technical ones which have tended to receive most attention, we catalogue 107 prospective co-impacts across 20 different negative emissions and solar geoengineering options. These include 38 positive co-impacts for carbon removal along with 14 positive co-impacts for solar geoengineering. The list also includes 31 negative co-impacts for carbon removal as well as 24 for solar geoengineering. Tellingly, 25 of these positive co-impacts were

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identified as financial and economic in nature, followed by 18 socio-environmental positive co-impacts, 17 technical ones, and 9 political and institutional ones. Identified negative co-impacts however follow a different pattern, with 12 being socioenvironmental in nature, 10 in the financial and economic domain, 8 in the political and institutional domain, and 8 in the technical domain.

The primary contribution of the study is to offer a systematic, in-depth, and balanced assessment of risks and benefits using the more inclusive concept of "co-impacts", doing so across multiple carbon removal and solar geoengineering approaches, and drawing from an extensive original dataset containing the views of a large sample of experts ($N = 125$). We take our inspiration from Alan Robock's long-running and periodically updated list of "risks and benefits" surrounding solar geoengineering – which is functionally about one technology thought to be technically implementable but societally controversial: stratospheric aerosol injection (Robock, 2008; Robock, 2014; Robock, 2016; Robock, 2020). Indeed, we agree with Robock et al. (2009), who write that "evaluations of the benefits, risks, and uncertainties of various proposals should, in an ideal world, inform decisions about implementation of geoengineering". As of 2020, Robock's list has grown to 6 benefits and 28 risks, garnered through reviews of the scientific literature. Meanwhile, no studies have attempted a similar list for carbon removal, though such listings may exist for individual approaches. Certainly, the literature on carbon-removal feasibilities and impacts (Minx et al., 2018; Fuss et al., 2018; Nemet et al., 2018) is rapidly growing, but the suite of evidence may represent a much more heterogenous and expanding range of approaches that is more difficult to aggregate.

A more holistic and comparative assessment of carbon removal and solar geoengineering offers a compelling contribution to the ecological economics community. So far, papers have explored the narrative aspects such as discursive tensions (Heikkurinen et al., 2019), the potential risk of moral hazard, assessed through an experimental game approach (Andrews et al., 2022), or the decarbonization potential of various national energy scenarios (Mathy et al., 2018). Other studies have focused on the potential costs or benefits of deployment. For instance, Popp et al. (2012) offers a critical lifecycle assessment of prospective emissions from land-use change regarding bioenergy, while Pindilli et al. (2018) determines that sequestering CO2 has positive social benefits including the restoration of precious peatlands, and Henderson et al. (2020) argues in favor of a large potential market for pine forests in the United States to store carbon (Henderson et al., 2020). These studies, each offering welcome insights on the role of climate intervention options in avoiding the worst effects of climate change, tend to explore one technology at a time, e.g., by looking at bioenergy or afforestation or stratospheric aerosol injection, rather than portfolios of options together. Moreover, these studies often emphasize only one dimension of co-impact (positive or negative), such as the costs or harms (e.g., land-use emissions) or societal benefits (e.g., peatland restoration), but not both. There is added technological novelty to our study as well, with only one study (Andrews et al., 2022) looking at one form of solar geoengineering, stratospheric aerosol injection.

For all these reasons, this study makes a crucial contribution to the ongoing understanding of climate intervention options and, in particular, does so with the intent of motivating further discussion through the lens and tools of ecological economics. Indeed, many of the perceived co-impacts, as identified by our set of experts, correspond closely to those which have received attention in ecological economics (e.g., around food systems and land-use change, management of natural resources, and issues of justice more generally) and, what is more, underscore how the ultimate effectiveness and sustainability of these climate-intervention options, whether explored singly or in portfolio, will broadly depend on the contours of their relationship with economic activity and economic systems. In short, this study also serves as an invitation for further engagement from and the application of the unique insights and perspectives of the field of ecological economics.

This study is structured as follows. Section 2 defines and conceptualizes the notion of co-impacts and a sociotechnical approach useful for understanding them. It then justifies the focus on a mix of carbon removal (or negative emissions) and solar geoengineering (or solar radiation management) techniques. Section 3 presents 107 distinct potential co-impacts: organized in terms of positive versus negative co-impacts and in relation to the suites of carbon removal vis-a-vis solar geoengineering technologies. We go further into the top 5 positive and negative co-impacts for each of the two suites of technology, using rich quotes from our interview data. With this evidence presented, Section 4 discusses and theorizes the identified co-impacts in a more cross-cutting way, in terms of four areas: Relationality and risk-risk trade-offs; Co-deployment and coupling; Intentional or unintentional implications; and Degrees of expert consensus. Section 5 concludes with general insights for energy and climate research and policy.

2. Conceptual framework and research methods

This section defines co-impacts, explains our sociotechnical approach and introduces readers to our research design.

2.1. Conceptual framework: co-impacts through a sociotechnical lens

The term "co-impacts", in the context of low-carbon transitions, refer in the broadest and simplest sense to "the positive and negative side effects of mitigation policies and technologies" (Ürge-Vorsatz et al., 2014). In their more recent and synthetic review of the literature for the most recent Intergovernmental Panel on Climate Change (IPCC) report, Babiker et al., 2022 note that the understanding of co-impacts has come to capture both positive benefits and adverse side effects of climate action. This framing captures multiple objectives, where climate policy or emissions reduction is placed alongside other policy and political objectives. They note that attempts at identifying and assessing co-benefits and co-impacts can serve a multitude of social and political functions, including using them as leverage to enable financial support for climate action; helping justify actions which provide a balance of net benefits or a mix of short and longer-term benefits; and obtaining support from a greater number of stakeholders. The identification and assessment of negative co-impacts has been particularly helpful at trying to avoid them and providing policymakers and decision-makers with more complete information by which they can understand and even preempt tradeoffs between climate action and other social objectives.

Our definition of co-impacts is broad and includes environmental, energy, social, political, and environmental dimensions, rather than focusing only on one dimension; it includes intended and unintended co-impacts; and it occurs direct and indirect co-benefits. There are more than 20 different terms used to describe co-impacts or co-benefits, often imprecisely (e.g., "win-win situations," "life-cycle benefits," and "synergistic objectives"), and often with confusing and overlapping terms (Floater et al., 2016). The ecological economics community has often used terminology such as "co-benefits" (Chabba et al., 2022; Kragt et al., 2016), positive "externalities" (Moretti and Vanschoenwinkel, 2021), or "spillovers" (Stergiou and Kounetas, 2022; Leimbach and Baumstark, 2010) in their published studies, although these tend to focus only on positive aspects, and not negative ones.

To offer a more balanced and complete conceptualization, we rely on the synthetic definition offered by Ürge-Vorsatz et al. as "positive and negative side effects." This reflects recent advancements in the co-benefits and co-impacts literature emphasizing social and political dimensions alongside technical, environmental, or public health dimensions. Social issues of acceptability and legitimacy are treated as falling within the notion of a co-impact given that they, too, are mentioned in the literature as "social" or "public" co-benefits. For example, Ürge-Vorsatz et al. (2014) argue that the term encompasses positive spillovers (co-benefits) such as improved user behavior in buildings, enhanced productivity of workers, or negative co-impacts such as social opposition to reduced visual amenities or increased noise (e.g., from wind power). Edenhofer et al. (2014) also classify a social dimension to co-benefits to include improvements in individual behavior or practice, the attainment of more equitable outcomes, enhancing access to particular forms of energy systems, assisting with reductions in poverty, as well as time savings, new business opportunities, enhanced safety, better working conditions and job satisfaction, and reduced local conflicts over resource extraction. We extend this to include positive or negative perceptions of political and social support as well as social acceptability, or the lack thereof. In this study, we extend and apply such a definition beyond the domain of climate mitigation to also consider 20 specific options across carbon removal and solar geoengineering, discussed in detail in Annex 2 (see especially Table A1).

A second novelty of the study is that we apply and utilize a sociotechnical lens to examine co-impacts. In the ecological economics community, sociotechnical research has revealed the intersections between dominant regimes that can shape technology deployment and innovation but also social aspects such as behavior and practice; both technical and social change can lead to lock-in and the resistance of change (Seyfang and Gilbert-Squires, 2019). Sareen and Wolf (2021) add that a sociotechnical lens has become widely adopted over the past fifteen years to better appreciate the social aspects of technology development and social change, including patterns of knowledge generation, investment, research, and deployment. They helpfully chart four dominant concepts and heuristics at use within the sociotechnical field: transition management and strategic niche management, which are about how actors can purposively shape and engage with transitions, and the multi-level perspective on sustainability transitions and technological innovation systems, which attempt to map and reveal the influence of their systems-level dynamics and features.

A sociotechnical approach means that we not only investigate the technical aspects related to the kinds of technology, infrastructure, and hardware involved in climate protection, but also the financial and economic, socioenvironmental, and political and institutional dimensions summarized by Fig. 1. As Sovacool (2021) writes, "the idea of a sociotechnical system helps reveal that technologies must be understood in their societal context, and that the different values expressed by inventors, managers, and consumers shape technological change." Such "systems thinking" reveals the different elements necessary for a new technology to achieve widespread use, elements (shown in Fig. 1) which furthermore interlink and also coevolve together. We will return to these sociotechnical dimensions in Section 4 of the paper.

2.2. Data collection: semi-structured expert research interviews

Our research design centered on original data collected from 125 semi-structured interviews with established experts and practitioners. Our recruitment and sampling of experts focused on a mix of advocates and critics of both negative emissions technologies and solar geoengineering options. We invited only those who have published high-quality peer-reviewed research papers on the topic, or published patents and intellectual property, within the past ten years (from 2011 to 2020). There was a systematic search utilized to select our experts, with Scopus used for academic articles and Lexis Nexus used for patents. We approached 206 experts and 125 agreed to participate, making our acceptance rate 60.7%.

Through the interviews, which were conducted over the course of May to August 2021, we explicitly invited insights and discussion on, inter alia, the risks and benefits of deploying carbon removal or solar geoengineering technologies, with Annex 1 showing our full interview question set and guidebook. Informants were asked only about their self-declared areas of expertise, meaning many did not discuss each and

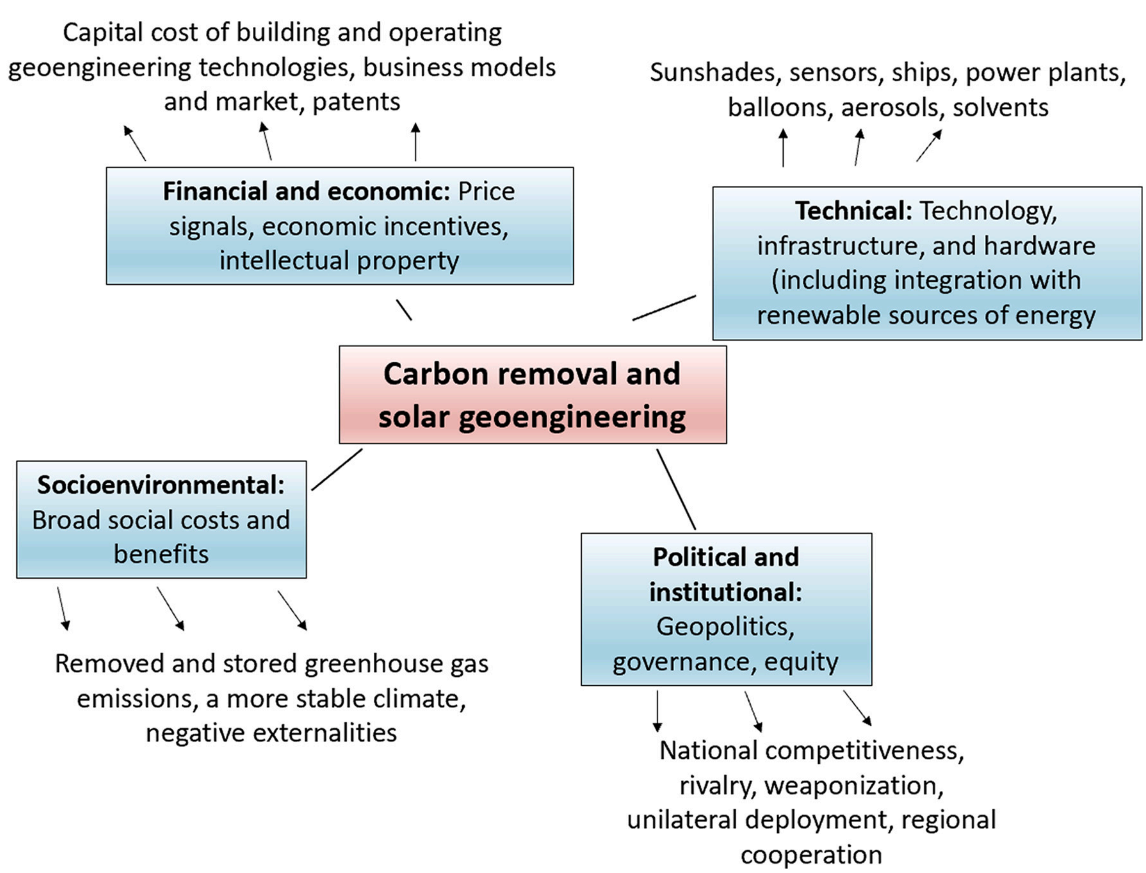

Fig. 1. Visualizing carbon removal and solar geoengineering as a sociotechnical system.
Source: Authors, inspired from Sovacool (2021).

every one of the 20 techniques, and although most focused on both classes of technologies, some focused only on one (e.g., biochar, or direct air capture, or stratospheric aerosol injection). Fig. 2 shows an overview of the demographics of our sample, and Annex 2 presents details of all 125 experts who participated. Although we did secure interviews with members of civil society and nongovernmental organizations, governments, and commercial entities in the private sector, the sample is strongly concentrated towards experts at universities and research institutes. That said, the sample does include scholars from more than 30 disciplines as well as a dozen participants from the Global South, here determined by either the country of origin of the participant and/or their current location. Given that interviewees were speaking on their own behalf, and also given the sensitivity of the topic, the data from these interviews is presented here as anonymous with a generic respondent number (e.g., R10 for respondent 10, or R110 for respondent 110). Annex 2 also provides further information on our expert-interview sample.

2.3. Data analysis and coding

The interviews were semi-structured, meaning that, in every interview, all central questions were asked but, depending on the expert's answers and how the discussion evolved, not all sub-questions were necessarily asked; these were asked only when relevant and only when they fit into the conversational flow of the interview (see Annex 3). This semi-structured approach conforms to standard qualitative research methodology.

All interviews were recorded, fully transcribed, and then coded via NVivo. Given that interviews were completed over a three-month period, blocks of interviews were sent to a professional transcription service as they were completed. Upon being returned, all transcripts were then cleaned by the authors before being entered in the qualitative data-analysis program NVivo, where transcripts of all 125 interviews were coded. Using this program, new nodes (and sub-nodes) were iteratively created in order to capture the diverse perspectives of the expert sample, including, for instance, to reflect where different understandings of specific aspects of policies or issues arose. All interviewee statements were triple-coded: once relating to the particular question they answered, one relating to emergent themes that began to emerge based on the data (i.e., co-benefits, co-costs or externalities, innovation, social acceptance, governance), and one relating to the specific technology being discussed. This enabled the research team to assess and analyze the qualitative data by question, theme, and technology.

The resulting dataset thus represents a structured coding of the interview data, which can be simultaneously utilized to explore both consensus views across experts and significant differences of opinion or perspective. In total, the analysis is thus thematic and inductive, with perceptions of co-impacts coded and recoded iteratively within the research team.

2.4. Limitations

As the discussion on climate-intervention strategies has evolved, focusing simultaneously on both negative emissions and solar geoengineering is becoming controversial in some circles. This includes the argument that "lumping" them together obscures critical differences between such options and tends to neglect certain salient risks and challenges (Jinnah and Nicholson, 2019). Pamplany et al. (2020) even write that: "A major structural handicap of the debate seems to be the tendency to ignore the distinction between various technologies and to lump everything under the umbrella label of geoengineering." Other academics have objected entirely to the notion of studying solar geoengineering techniques on the grounds that they are too risky, calling for a treaty of non-use that would prohibit most research and deployment (Biermann et al., 2022).

That being said, there is a case to be made for looking at them comprehensively, as some studies have done (Delina, 2021). In particular, there is growing appreciation of the need for "all hands on deck" thinking about how to avoid the worst impacts of climate change, in view of both the drastic consequences that are already taking place and the insufficient pace of climate mitigation. As a result, what is urgently needed now is a comparative analysis of the potential roles of all sorts of technologies in this context, that is, all to be given consideration though by no means equally weighted or prioritized. To this end, we argue that is necessary to look at both carbon dioxide removal (CDR) and solar radiation management (SRM) together, rather than one or the other, in order to, inter alia, investigate the full portfolio of climate protection and geoengineering pathways, without bias or predetermined conclusions about them. Indeed, undertaking a more comprehensive evaluation of climate-intervention options together could offer a stronger lens for researchers, policymakers, and the general public, and indeed anyone wishing to understand and wrestle with the implications of employing climate-intervention technologies.

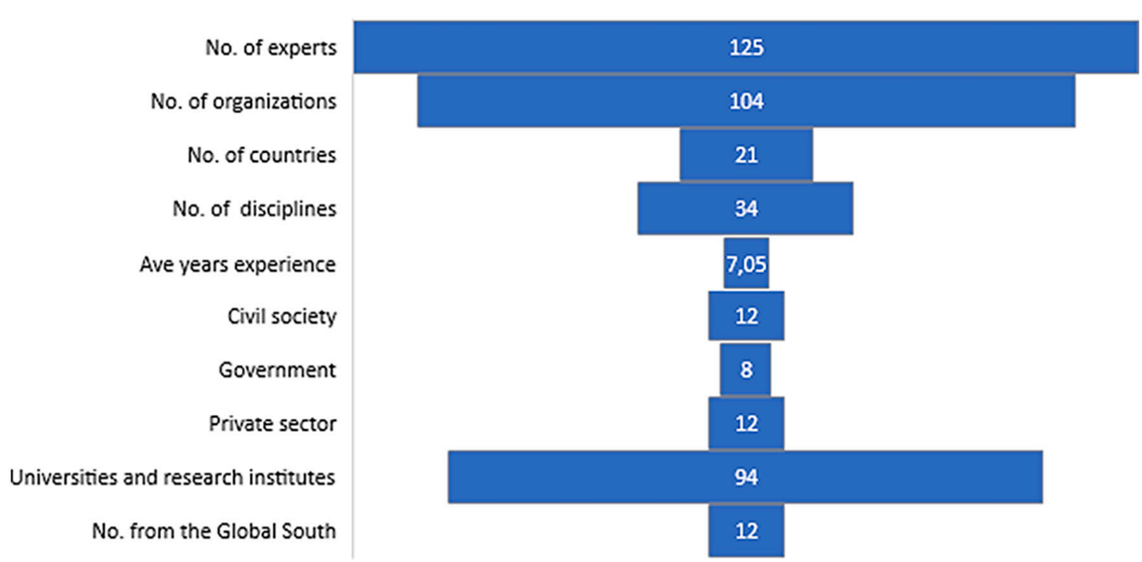

Fig. 2. Summary of the demographics of experts who took part in our study.
(Source: Authors. Note: The sum equals 126 due to the dual affiliation of one of our experts.)

In turn, our orienting approach that comprehensively entertains all negative emissions and solar geoengineering technologies is matched to our data collection techniques, wherein we asked respondents about all options (although they could narrow their focus as they saw fit, we neither prompted nor forced them to do so). Moreover, our project adheres to the matching principle from environmental justice, which suggests that the scale of a solution ought to match the scope of the problem. There is therefore an urgent need to examine trade-offs between and within multiple options and across the various prospective pathways. Lastly, our approach of investigating both suites of climate-intervention technologies together has strong relevance to policy recommendations, as it mirrors the policymaking dilemma of choosing options, and cultivating pathways, with limited resources and uncertainty. In the words of one of our respondents, "nothing is more important for climate policy" than understanding how the full range of CDR and SRM options might work together, or not, to help avoid the worst impacts of climate change.

Additionally, although we believe our large and diverse sample of expert interviews facilitates triangulation and has methodological merit, our research design does have shortcomings. One is that there could be both selection and confirmation bias within the experts that accepted our invitation to be interviewed: e.g., they agreed only because their views may not be representative, and they may have participated to emphasize information already consistent with their worldview.

Another limitation is that our sample *is* limited to only experts. Our study did not attempt to confirm the generalizability of these views through other forms of data collection such as household surveys, community interviews, or site visits – such a task, admittedly worthy, is intended for future research. We nevertheless believed the topic best suited to expert interviews given that general knowledge of geoengineering among the lay public is quite low as well as malleable to the framing and presentation of information (Burns et al., 2016; Cox et al., 2020; Jobin and Siegrist, 2020; Merk et al., 2019; Raimi, 2021). This signals that attitudes may not yet be stable or well-formed.

Even though we targeted those with expertise in one or several of these technologies, the knowledge of interviewees in general is necessarily limited, and our semi-structured approach may have encouraged them to comment outside of their experience or knowledge. That said, we also wanted to avoid imposing our own views regarding the expertise and experience of our respondents, and to avoid artificially forcing them to only comment on those areas where *we* deemed them competent, instead of deferring to where they *themselves* determined their own competency.

Finally, we took an ethnographic approach that did not correct or problematize responses, so we present the data in an unfiltered way, even if our respondents may have had misperceptions on specific points. We thus frame our study as offering perceptions of prospective co-impacts rather than as definitive evidence of actual co-impacts in practice.

3. Results: expert perceptions of positive and negative co-impacts for climate stabilization

This section presents our core results, with a focus on both the full list of identified co-impacts (107, positive and negative) as well as the most frequently identified co-impacts by our expert respondents (the top 5 positive and negative co-impacts for both carbon removal and solar geoengineering, respectively). We place each of the co-benefits in a "primary dimension" of a sociotechnical system, e.g., socio-environmental, technical, financial and economic, or political and institutional, in a mutually exclusive manner. We did this based on what we perceived as the best fit for a dimension of the system, realizing that in many cases particular co-benefits straddle many (if not all) such dimensions. Although some of our co-impacts interconnect (i.e., moral hazard could shape patterns of offsetting, and patterns of offsetting can germinate further moral hazard), we still treated them as analytically distinct and mutually exclusive for the purposes of classification, as well as to more closely examine the range of co-impacts identified by our set of experts. Furthermore, some co-impacts (like equity) cut across both CDR and SRM, and some co-impacts relate specifically to a particular technology (like biochar helping substitute for concrete in nuclear reactor designs) whereas others relate to climate protection in general, independent of whether it is achieved by a particular carbon removal option.

3.1. Positive co-impacts of carbon removal

As Table 1 summarizes, our expert interview data reveal a prodigious number of prospective positive co-impacts for CDR. Such positive co-impacts span many different clusters of technologies, some being specific to one (e.g., DACCS or biochar) and with others being more about carbon dioxide removal as a whole. Despite this long inventory of co-impacts, five recur with the most frequency among the experts, signifying some degree of consensus: protection of life above land, positive coupling with solar energy, innovation and industrialization, decent work and employment, and the expansion of bio-economies. We will discuss each of these "top five" co-impacts in turn.

3.1.1. Nature-based carbon removal can enhance protection of life above land

The most frequent positive co-impact identified by our experts related to the ability for some forms of carbon removal (especially nature-based or natural solutions) to protect "*life above land*" such as biodiversity, forests, habitats, and soils (Buck et al., 2020; Fuss et al., 2018). R015 spoke about how such carbon-removal actions can "*improve crop production and improve soil*," whereas R059 mentioned "*better management of things like water supplies, irrigation systems, land use, and synergistic afforestation processes that would obviously really help meet or help to push forward the life on land sustainable development goal*." R062 agreed and argued that "*if you do carbon sequestering well, then you will actually be enhancing biodiversity, you might even slow down species loss*."

Some respondents spoke not about CDR as a whole, but specific applications of it. R072 said that "*integration of enhanced weathering with land-based management practices … can prevent desertification, minimize soil erosion, and protect, restore, and promote sustainable land use*." R019 noted positive co-impacts to biochar, going on to say "*my little slogan is that biochar is safe, scalable and shovel ready, and it's durable … it can help reforesting efforts, it can help maintaining forests, it can keep forests healthy and reduce bio risks*." R096 spoke about the links between afforestation and reforestation and the creation of "*sustainable and biodiverse forests that will hopefully stand the test of time and be able to survive climate change*."

We will explore another side of this co-impact when we discuss negative synergies in terms of land in Section 3.3.3.

3.1.2. Has strong positive couplings with solar energy

Another frequently mentioned co-impact was positive couplings with renewable energy, in particular between direct air capture and solar energy. R005 framed this by noting that "*because solar power is very cheap, especially in deserts, it makes good sense to run DACCS on it*." R010 identified "*a positive potential synergy between DAC and solar energy, given DAC could create demand for solar even more*." R051 also concurred that "*solar … is the cheapest form of energy that can be used to power future DAC facilities, and solar thermal in particular could provide water at 100 degrees Celsius and offers a very low-carbon, economic solution*." R056 even quantified the prospective benefits, arguing that:

electricity costs with solar PV are super competitive, it will be worth their while (the DAC industry) to deploy it with solar energy because electricity costs could be a cent per kilowatt hour … DAC can be easily coupled with, and powered by, the lowest renewable electricity cost in the world, which is solar energy.

Table 1
Expert perceptions of the positive co-impacts of carbon removal."

No.	Technology	Perceived positive co-impact	Primary Dimension	Frequency (N = 125)	%
1	CDR (as a whole)	Nature-based carbon removal can enhance protection of life above land	Socioenvironmental	40	32.0%
2	DACCS	Has strong positive couplings with solar energy	Technical	29	23.2%
3	CDR (as a whole)	Carbon removal can promote innovation and more sustainable industrialization	Socioenvironmental	26	20.8%
4	CDR (as a whole)	Could contribute to decent work, local economic development and job growth	Socioenvironmental	24	19.2%
5	BECCS	Creates expansion of bioenergy and bioprospecting systems	Financial and economic	22	17.6%
6	Enhanced weathering, biochar, BECCS, DAC	Can be strongly coupled with hydrogen energy systems	Technical	19	15.2%
7	CDR (as a whole)	Germinates green entrepreneurism	Financial and economic	18	14.4%
8	Ecosystem restoration, soil management, afforestation	Can replenish and revitalize habitats and ecosystems	Socioenvironmental	17	13.6%
9	Biochar, CCUS	Enables net-zero or more sustainable concrete and cement production	Technical	16	12.8%
10	DACCS	Could produce positive couplings to wind energy	Technical	15	12.0%
11	CDR (as a whole)	Climate stability can reduce inequality	Political and institutional	15	12.0%
12	DACCS	Produces synergistic couplings to nuclear power	Technical	14	11.2%
13	DACCS	Learning by doing leads to enhanced innovation patterns	Technical	12	9.6%
14	CDR (as a whole)	Would contribute to the creation of local marine economies	Financial and economic	12	9.6%
15	CDR (as a whole)	Climate protection can help reduce poverty	Political and institutional	12	9.6%
16	DACCS	Could create extra incentives to invest in geothermal energy	Financial and economic	10	8.0%
17	CCUS	Can catalyze synthetic fuels (synfuels) markets	Financial and economic	9	7.2%
18	BECCS	Leads to sustainable forestry practices and markets	Financial and economic	9	7.2%
19	CCUS, DACCS, BECCS	Creates path dependence for low-carbon infrastructure	Financial and economic	8	6.4%
20	BECCS	Supports a future decentralized electricity grid	Technical	8	6.4%
21	CCUS	Will enhance the shipping industry	Financial and economic	8	6.4%
22	Enhanced weathering, biochar	Leads to enhanced building structures and designs	Technical	6	4.8%
23	CDR (as a whole)	Nature-based options can be coupled to gender empowerment and training	Political and institutional	6	4.8%
24	DACCS	Generates strong couplings to hydropower development	Technical	5	4.0%
25	DACCS	Facilitates waste heat storage or networks and district heating	Technical	5	4.0%
26	DACCS	Offers near-term benefits to the chemicals industry	Financial and economic	3	2.4%
27	CDR (as a whole)	Can protect and enhance the automotive industry	Financial and economic	3	2.4%
28	Ecosystem restoration, soil management, afforestation, biochar	Could cultivate the rural bioeconomy	Financial and economic	2	1.6%
29	Biochar	Can result in "green coal" when co-fired	Socioenvironmental	2	1.6%
30	CCUS	Could enhance the steel industry	Financial and economic	2	1.6%
31	BECCS, afforestation, biochar	Cheaper enzymes and design purpose crops enhance biofuel capacity	Financial and economic	1	0.8%
32	DACCS, CCUS	Enhances the paper and pulp industry	Financial and economic	1	0.8%
33	DACCS, CCUS	Enhances the glass industry	Financial and economic	1	0.8%
34	DACCS, CCUS	Enhances the plastics industry	Financial and economic	1	0.8%
35	BECCS	Promotes hydrogen shipping networks for the marine freight industry	Financial and economic	1	0.8%
36	Biochar	Can be used in more sustainable nuclear reactor designs	Technical	1	0.8%
37	CCUS	Needed to decarbonize the sugar industry	Financial and economic	1	0.8%
38	Ecosystem restoration	Contributes to tourism	Financial and economic	1	0.8%

Source: Authors. Note: CDR = carbon dioxide removal. DACCS = direct air capture with carbon storage. BECCS = bioenergy with carbon capture and storage. CCUS = carbon capture utilization and storage. Note: This section presents expert quotations only for the top five positive co-impacts, rather than for all of them, for reasons of length.

3.1.3. Carbon removal can promote innovation and more sustainable industrialization

A third recurring co-impact occurs at the macroeconomic scale, involving the furthering of innovation and promotion of more sustainable forms of industrial growth and development. R010 spoke about how "*carbon removal can catalyze the development of technological capabilities; it can positively impact innovation patterns*." R096 stated that afforestation could promote "*good co-benefits such as improvements to local incomes, tourism, and industrialization … it has the potential for massive co-benefits*." R059 even quantified such prospective economic value, noting that it could exceed *trillions* of dollars. As they remarked:

the market for CDR or DAC could be huge, they can couple nicely with higher process-heat industrial manufacturing, and thus provide economic growth and jobs … if the business models for carbon removal take off, they could create a multi-trillion dollar-value sequestration market, with consequent transformations in economic-growth and national effects from that.

3.1.4. Could contribute to decent work, local economic development and jobs

The fourth-most frequently mentioned co-impact also relates to the economy, but more focused at the microeconomic scale on "decent work" and "local jobs." R018 spoke about how "*CDR opportunities can provide employment opportunities for work in areas that otherwise won't get them … with really big benefits and economic opportunities, and revenues, for local communities*." R041 spoke about afforestation and reforestation benefitting in particular "*farms via agrofarming, with better soil storage and better soils for agriculture and smallholder farmers*." R013 agreed and noted that "*there are going to be exciting synergies between CDR and with livelihoods and jobs, there are going to be millions of job opportunities*." R072 stated their belief that carbon removal would "*bring jobs to communities, especially with things involving mineral extraction like enhanced weathering or planting trees or erecting tree plantations, all would help end poverty in all of its forms*."

3.1.5. Creates expansion of bioenergy and bioprospecting systems

A final frequently mentioned co-impact connected to the expansion of bioenergy and bioprospecting systems in particular. R037 mentioned how:

CDR has positive synergies with bioenergy, where we need low-carbon energy to drive the processes needed for CDR … direct air capture has a very large energy requirement and it could need both land and renewable energy, and bioenergy could be the perfect fit.

R055 spoke about how "*obviously, BECCS needs massive upscaling of the bioeconomy, and it could revolutionize the biofuel, biomass, and biogas markets, along with transport networks and supply chains connected to them*."

R120 also spoke about how CDR can benefit "the entire bioeconomy" and in particular how it can result in "biomass cascades" and "large amounts of carbon recycling and storage," leading to a more sustainable, strategic use of biomaterials in the economy that could see the eventual replacement of plastics or steel with biomass. R061 similarly described the potential bioprospecting opportunities:

I see the greatest co-benefit in terms of biodiversity and nature-based CDR. The soil harbors the greatest biodiversity on Earth, the greatest that has not been explored. It has biomedical implications. Our antibiotics come from the soil: streptomycin was isolated from soils. So, bioprospecting could be a huge co-benefit. Before we have a mass extinction of microorganisms in soils, we need to make sure that we know what we're losing and hopefully by managing soils appropriately - and organic matter is the key for that. So, nature-based CDR could literally help prevent mass extinction of microorganisms and therefore preserve that biodiversity that has numerous benefits, but just one is probably human health. Bioprospecting has immense implications.

Their statement also notes that CDR could even prevent species extinction, and has strong synergies with the positive co-impacts for protection of life on land discussed above in Section 3.1.1.

3.2. Positive co-impacts of solar geoengineering

Our expert interview data also reveal a diversity of positive co-impacts of solar geoengineering, summarized by Table 2. These, similar to the carbon-removal options, involve some very specific options such as stratospheric aerosol injection as well as solar radiation management techniques in general. As the Table indicates, 14 prospective co-impacts could occur in total. The top five most mentioned co-impacts include a boost to the aerospace and defense industries, reduction of inequality and poverty, the protection of ecosystems for the future, reduced heat stress, and enhanced crop production and agriculture. We will discuss each of these in turn.

3.2.1. Provides a boost to the aerospace, defense, and technology industries

The most frequently identified positive co-impact to solar geoengineering was the enhancement of aerospace and defense capabilities among those nations or communities adopting these technologies or engaged in their development. R024 spoke about how investing in solar radiation management could enable "*a broader selection of people representing all nations*" to become involved in "*the expansion of humanity into space and aerospace*." R105 added that "*stratospheric aerosol injection in particular would benefit the aerospace and military defense supply chain, with significant investments required in aircraft design as well as fueling those aircraft and monitoring results*." R117 concurred when they remarked that:

I see an entire new business model for Boeing or Airbus to design special higher altitude aircraft to deliver cloud thinning or stratospheric aerosol injection …they would need to design big aerial tankers that can operate at the altitudes at which the highest spy planes operate today, carrying the high payloads required, and that plane just doesn't exist. But it doesn't exist not because it can't exist, it is just there is no customer who has ever needed that mission.

The potential advantages of such business models, and thus capacity needed for this infrastructure, could be significant, benefitting a large community of locations with diversified economies and political structures. As R117 continued:

For true climate protection using solar radiation management, you would need to deploy both northern and southern hemisphere in roughly equivalent amounts. You would vary your deployment seasonally because there is more sun in the northern summer in the summer and less in the southern hemisphere at that time and vice versa. *You would vary things latitudinally so you would have some bases at say 15° north and south and some at 30° north and south. And you would vary the deployment amounts among those places, again seasonally. You would seek to have a network of bases in lots of longitudes, so many countries will benefit. Not because you need that physically but because you want political diversification so that if Iran's government decides to shut down their deployment base that the world has located there, you have also got deployment bases in China and Mexico that can pick up that deployment. You need a system that is operationally robust from weather, from airplane accidents, from political decisions. So, you need to disperse the bases around the world … I see the future here not of rockets, balloons, guns, or tethered hoses. If we are only talking about 20 km, 66,000 ft in altitude, airplanes can do that. And airplanes would be far cheaper than any of the other technologies that currently exist.*

R116 expanded this thinking as follows:

If you're talking about aerospace companies, they have immense opportunities to capture value from solar geoengineering. They are already are constantly in the space of, like, "What is the next thing that we have to get on top of to keep us relevant?" What are the next technologies that your average Joe wouldn't be able to develop? Working on geoengineering stuff takes a big

Table 2
Expert perceptions of the positive co-impacts of solar geoengineering.

No.	Technology	Perceived positive co-impact	Dimension	Frequency (N = 125)	%
1	SRM (as a whole)	Provides a boost to the aerospace, defense, and technology industries	Financial and economic	18	14.4%
2	SRM (as a whole)	Climate protection can reduce inequality or poverty	Political and institutional	16	12.8%
3	SRM (as a whole)	Climate stabilization helps protect ecosystems for future generations	Political and institutional	13	10.4%
4	SRM (as a whole)	Reducing heat stress and heat waves	Socioenvironmental	11	8.8%
5	SAI	Enhanced crop production and agriculture in the northern latitudes	Socioenvironmental	11	8.8%
6	SRM (as a whole)	Can protect and prolong fossil fuel assets and thus jobs and just transitions	Financial and economic	7	5.6%
7	Space mirrors	Facilitates advancements in space exploration and the moon economy	Financial and economic	6	4.8%
8	SRM (as a whole)	Enhances military capabilities and defense contracting	Technical	6	4.8%
9	Space mirrors	Offers a more controllable and reversible form of climate protection	Technical	5	4.0%
10	Space mirrors	Can more cost-effectively reduce global temperature than mitigation efforts	Financial and economic	3	2.4%
11	SRM (as a whole)	Can facilitate technological leapfrogging	Technical	2	1.6%
12	SRM (as a whole)	Would generate new forms of insurance business	Financial and economic	2	1.6%
13	SAI	Can change weather patterns for the better	Socioenvironmental	1	0.8%
14	SRM (as a whole)	Expanded trade from targeted ice melting	Financial and economic	1	0.8%

Source: Authors. Note: SRM = solar radiation management. SAI = stratospheric aerosol injection. Note: This section presents expert quotations only for the top five positive co-impacts, rather than for all of them, for reasons of length.

company. It takes big resources and things like that. So, it's an easy way to stay ahead of the game.

As R116 concluded, the market could be so large for such deployment, "*it could even be the future of the aerospace and aviation industry*."

3.2.2. Climate protection can reduce inequality or poverty

The second-most mentioned positive co-impact entailed the reduced social inequality or poverty that could result from expanded temperature reduction or climate protection offered by solar geoengineering. R024 framed this in terms of solar geoengineering's ability to "*minimize the damage of climate change and to thus generally increase wealth, taking pressure off of people that feel they have to exploit limited natural resources*." R001 added that:

from a critical justice perspective, the argument in favor of solar radiation management is that it will help those currently most vulnerable to climate change and it will protect them from the harms of climate change; it will protect the Global South from storm damage and sea level rise, it will protect farmers in Africa who are facing increased drought, because it reduces the risk of dangerous climate change, which already disproportionally effects the most vulnerable.

R045 added that:

Of course, the Sustainable Development Goals are jeopardized by a warming climate, which makes poverty eradication more difficult – if crops are failing or fisheries are disappearing because of warming seas. That, of course, adds weight to the arguments of those who say, "We're not going to limit warming without SRM of some kind."

R003 added that other techniques such as marine cloud brightening or cirrus cloud thinning can better enhance the protection of coral reefs, which in turn can provide "*a beneficial albedo effect*" that sees "*phytoplankton*" grow, beaches and reefs recover and stabilize, and small island states begin "*triple revenues*" from "*healthy fishing and leasing out ocean areas to provide global climate protection*."

3.2.3. Climate stabilization helps protect ecosystems for future generations

This third class of positive co-impact concerns ecosystem protection more broadly. R057 noted that "*my most likely projection is that stratospheric aerosol injection will have no serious direct environment health or safety risks, and instead it will be benign or at least it will be better than alternative pathways on pretty much every dimension*." This makes it the "*least risky*" option for climate protection, as well as one that is "*crucial towards avoiding a more grimly climate future than otherwise*." R057 later added that "*solar geoengineering is mostly positive and I think would have unrecognized beneficial effects on preserving species and biodiversity and ecosystems for the future*." R020 also added that "*solar geoengineering offers a degree of climate justice vis-à-vis future generations, it minimizes the ability for climate change to mess with the life of future generations and the climate stability they deserve and ought to enjoy*." Others spoke about the specific preservation of ecosystems in the polar regions. As R008 put it,

I'm really skeptical that society could preserve the poles, the Arctic and later Antarctica, the ice sheets, without the assistance of SRM. These systems are very crucial for our environment, for our biodiversity; a lot of species use it as a nutrition ground. If you really want to have an environment and biodiversity like, I'm not saying pre-industrial, but like in the 1980s or 1960s, I do not see how we could achieve that without SRM.

3.2.4. Reducing heat stress and heat waves

A fourth positive co-impact relates to the human-health benefits of solar geoengineering and its ability to reduce heat stress and heat waves. R003 articulated this co-impact as follows:

Heat stress is a major thing. I think heat stress is mentioned in the SDGs. At the moment we're getting close to having wet bulb temperatures which make it that no person can survive outside in daytime in some summers. No person can work outside without air conditioning in summer. We're getting close to that now. If that happens then we've got an awful lot of people who are going to die in rather unpleasant circumstances by simply having it over 35 °C and around about 95% humidity during the middle of the day, that kills people. It kills you within a few hours. Targeted, sustained solar geoengineering can directly address this.

R025 offered further support for such a claim, by noting that "*I do see the potential for solar radiation management to help some people with disabilities or aged people [the elderly], as it can directly reduce the risk of heat waves*."

3.2.5. Enhanced crop production and agriculture, at higher latitudes

A final frequently mentioned positive co-impact connects with positive synergies with enhanced crop management and agricultural productivity. As R123 explained,

for SAI, if you're imitating a volcanic eruption, that means reduced insulation and possible impacts also on agriculture … it could help agriculture by complementing soil fertility, and helping pollination, that sort of stuff, especially at higher latitudes.

R100 added that SRM and various types of albedo management via clouds could alter water and river flows in ways that enhance irrigation potential for farmland, because "*we can produce more energy and move more water in the future if SRM is implemented … which could be a boon for hydropower or irrigation provision*." This co-impact has been mentioned in multiple studies that offer various forms of supporting evidence (Kala and Hirsch, 2020; Fan et al., 2021; Kravitz, 2021).

3.3. Negative co-impacts of carbon removal

The positive co-impacts of carbon removal enumerated in Section 3.1 do not exist in a vacuum; they are also counterbalanced against the collection of 31 prospective negative co-impacts summarized by Table 3. The five most recurring negative co-impacts mentioned by our experts were degraded water security, moral hazard with climate mitigation, disruption of food production, dangerous carbon offsetting, and high rates of energy consumption. We address each in detail in this subsection.

3.3.1. May interfere with water security and scarcity

The most consistently mentioned negative co-impact with carbon removal was interference with water security or aggravating water scarcity. R043 put this into context when discussing afforestation:

If implemented not wisely and only with a carbon focus, you can do a lot of bad for sure with carbon removal. I mean, even if you plant trees, which everybody likes, you can for instance use up a lot of water that's then not available anymore downstream where a farmer is trying to feed the village. Definitely in order for those positive synergies to materialize you have to have not only the carbon lens, you have to have a bigger lens there.

R093 added that BECCS would "*need land and huge amounts of water*," and R124 warned that "*rivers could run dry with widespread deployment of BECCS*." R010 supposed that even direct air capture "uses water because you have to keep replenishing cooling systems" and then continued by noting that:

If you scale up at a large scale, then the consumption of water becomes really large. It may not be as large as BECCS and things like that, but it's fairly large. Then that could affect negatively water security around the world.

3.3.2. Creates a moral hazard and mitigation deterrence

A second recurring concern with carbon removal was the perceived negative co-impact of "moral hazard" and "mitigation deterrence", themes also evident in the literature (Anderson and Peters, 2016; McLaren, 2020). R026 explained this as follows:

Let's suppose the mitigation-deterrence argument is right, then you are short-changing future generations because you're not getting on with the game that you really should be getting on with, which is dealing with the overconsumption and the overuse of energy or the high use of energy, let's put it that way … You're depending on a unicorn and that short-changes future generations because it leaves them with the problem of cleaning up the mess, assuming they can even clear up the mess.

Table 3
Expert perceptions of the negative co-impacts of carbon removal.

No.	Technology	Perceived negative co-impact	Dimension	Frequency (N = 125)	%
1	CDR (as a whole)	May interfere with water security and scarcity	Socioenvironmental	76	60.8%
2	CDR (as a whole)	Creates moral hazard and mitigation deterrence	Political and institutional	65	52.0%
3	CDR (as a whole)	Could disrupt food production or land use	Socioenvironmental	59	47.2%
4	CDR (as a whole)	Leads to dangerous patterns of carbon offsetting	Socioenvironmental	58	46.4%
5	CDR (as a whole)	Strong energy penalties or need for energy consumption	Technical	55	44.0%
6	CDR (as a whole)	Lacks adequate monitoring, verification and enforcement	Political and institutional	53	42.4%
7	CDR (as a whole)	Technologies are insufficient or too immature to fully address climate change	Technical	40	32.0%
8	CDR (as a whole)	Impermanence and leakage concerns	Technical	35	28.0%
9	CDR (as a whole)	Limited social acceptance and legitimacy (including NIMBY)	Socioenvironmental	32	25.6%
10	CDR (as a whole)	Marine-based carbon removal destroys life below water	Socioenvironmental	32	25.6%
11	CDR (as a whole)	Creates trade-offs and reduces incentives to invest in renewable energy	Financial and economic	31	24.8%
12	CDR (as a whole)	Will require extremely large amounts of financing	Financial and economic	28	22.4%
13	CDR (as a whole)	Difficulty in scaling or reaching commercialization	Technical	26	20.8%
14	DACCS	Results in enhanced oil recovery in the near term	Socioenvironmental	26	20.8%
15	Ocean fertilisation, ocean alkalinity, enhanced weathering, afforestation	Will result in severe ecosystem impacts	Socioenvironmental	22	17.6%
16	CCUS, DACCS, BECCS	Creates synergies with and extensions of oil and gas use	Financial and economic	21	16.8%
17	Enhanced weathering, DACCS, ocean alkalization	Material-intensive and will require large supply chains	Technical	12	9.6%
18	BECCS, afforestation, biochar	Land dispossession can severely and negatively impact smallholder farmers	Socioenvironmental	11	8.8%
19	CDR (as a whole)	Permits excessive consumption and high-consumption lifestyles	Socioenvironmental	9	7.2%
20	CDR (as a whole)	Significant capital and investment costs	Financial and economic	8	6.4%
21	CDR (as a whole)	Does little to address ocean acidification	Socioenvironmental	7	5.6%
22	CCUS	Uncertain liability issues surrounding carbon dioxide storage or accidents	Political and institutional	5	4.0%
23	CCUS	Relies on chemicals and can exacerbate pollution	Socioenvironmental	5	4.0%
24	CDR (as a whole)	Exacerbates the risks of stranded assets	Financial and economic	5	4.0%
25	CDR (as a whole)	Could erode local culture and rural identities	Socioenvironmental	5	4.0%
26	CDR (as a whole)	May exhibit "first mover disadvantage" where early entrants go bankrupt	Financial and economic	4	3.2%
27	CDR (as a whole)	Could lead to green "cartels" like the Organization of Petroleum Exporting Countries	Political and institutional	3	2.4%
28	BECCS, afforestation, biochar	Will particularly threaten indigenous groups via land use or pollution	Political and institutional	3	2.4%
29	CCUS	Can lead to accidents and serious earthquakes near storage sites	Technical	2	1.6%
30	CDR (as a whole)	Will create uneven development and human "sacrifice zones"	Political and institutional	2	1.6%
31	BECCS, afforestation, biochar	Physical space for biomass results in trade-offs with land for advanced biofuels	Socioenvironmental	1	0.8%

Source: Authors. Note: CDR = carbon dioxide removal. DACCS = direct air capture with carbon storage. BECCS = bioenergy with carbon capture and storage. CCUS = carbon capture utilization and storage. Note: This section presents expert quotations only for the top five negative co-impacts, rather than for all of them, for reasons of length.

R109 agreed and added that:

Mitigation deterrence is often the main point that's raised, and I think that's quite an important point … Mitigation deterrence often actually prevents NGOs or civil society more broadly from engaging on a topic, because they might think that "Ah, because Company A is talking about negative emissions, that means that they're going to just use it to offset their emissions, but not actually reduce the emissions." And so that's one of the largest political risks, that nobody does climate mitigation if they think they can depend on carbon removal.

R084 spoke about "*the real danger of moral hazard in action*" because companies are saying "*we're going to be net zero by planning trees somewhere" and then using that as a justification to exploit tar sands in Canada.*"

3.3.3. Could disrupt food production or land use

The third-most commonly mentioned negative co-impact was disruption of food production and land use. R002 spoke about how most CDR options have "*a very large land footprint*" and that they will have "*some of the biggest direct tradeoffs with agriculture and land use.*" R037 articulated that "*large-scale BECCS and afforestation will negatively affect food security, because you are taking land out of production, and negatively affecting the ability for land to be used for poverty reduction or farming.*" R042 termed this as follows:

I see the highest risk of carbon removal with impacts on land use. And land use is the main driver of anthropogenic mass extinction that we are currently witnessing which is arguably at the same level and scale as climate change … If there are mass plantations and they are historically known to actually be led to land capture and land enclosures from societies that have traditional property rights on land, I'm skeptical that carbon removal will be able to deliver without hurting food production or agriculture.

R121 added that another dimension to this co-impact involved the pollution flows at the backend, which could also negatively impact land. As they noted: "*growing all of these bioenergy crops will generate large amounts of pollution, which could limit access to food or at least safe and healthy food.*"

3.3.4. Leads to dangerous patterns of carbon offsetting

A fourth kind of negative co-impact connects with moral hazard and mitigation deterrence (Section 3.3.2), but more explicitly emphasized and examined the dangerous patterns of carbon offsetting that could eventuate. R096 underscored that:

The main risk of CDR … is that companies will claim they are net-zero, that they have carbon neutrality, and will claim all of the benefits of carbon removal, when they are still burning carbon and emitting greenhouse gases out of their smokestacks. They're just abusing the CDR from another player to offset their own issues, with no net reduction of climate change. Offsetting through CDR is the last thing we should actually be allowing.

Other experts spoke about some of the opportunity costs and lifetime extension issues which were bound up with offsetting. R104 said that:

The biggest risk of carbon capture in all of its industrial forms is the opportunity cost. Its funds are not devoted to the clean energy transition, but instead fossil fuels … The second biggest risk, beyond the opportunity cost of not investing in clean technologies, unfortunately, is the lifetime extension for the fossil fuel infrastructure, which has a very large, additional list of downsides, many of which we don't quantify today. These sorts of games, and reliance on offsets, could prevent true climate action.

R039 agreed and noted that "*one of the biggest challenges with offsets and the monitoring of CDR is the huge uncertainty we have to what is actually happening with carbon, land, and soils*." They continued with particular reference to biochar: "*We have voluntary carbon market actors paying producers of biochar just for the production of biochar and for selling it, with entire disregard for whatever happens with it afterwards*."

3.3.5. Strong energy penalties or need for energy consumption

The final negative co-impact identified frequently by our experts concerned the large amounts of energy use needed to run and maintain carbon removal technologies. R002 stressed that "*most if not all of the CDR techniques have very heavy coupling to energy consumption because they involve such large amounts of mass, large amounts of land or water, large amounts of natural resources, and very large amounts of energy*." They noted that these dimensions "*weigh down*" the ability to scale up carbon removal options quickly and sustainably. R103 even attempted to quantify how much energy use could be needed for some options, and calculated that BECCS alone could need *nine times* the energy consumption of India:

To me, BECCS is an energy cost, not a source. I did some rough calculation, because everyone likes saying, "BECCS, yes, we can do it," but the numbers add up to something like nine times the primary energy use of India, so, yes, a future world with BECCS uses a lot of energy.

R004 argued that enhanced weathering and the resultant crushing of rocks "*have a very high energy demand*" and that calling these "*low-carbon*" options was "*disingenuous*." Regarding direct air capture, R119 went so far as to argue that high energy penalties made such options "*useless*." In specific, they criticized that:

if you're getting the energy to run these energy-intensive machines from coal power plants or gas power plants or anything else like that then you're just putting pollution in upstream and taking it out downstream. There's one other huge infrastructure need that goes around direct air capture … but thermodynamically they're useless.

3.4. Negative co-impacts of solar geoengineering

As Table 4 reveals, our experts identified 24 prospective negative co-impacts of solar geoengineering. The top five of these, which we will explore in turn, relate to limited social acceptance, undesirable associations with weather modification, difficulties in commercialization, termination shock, and dependence on governments and financing.

3.4.1. Limited social acceptance, public support, and legitimacy

The most commonly mentioned negative co-impact for solar geoengineering was its lack of social acceptability, public support, or social legitimacy. R027 mentioned how:

Lack of a social license is a real risk for many techniques. A lot of solar radiation management ones would definitely fall into that category … We know that people get really uncomfortable with the idea of interfering with the upper atmosphere and with the idea of interfering with the open ocean … As soon as you scale it up to the point where you are actually trying to achieve these kind of things, that's when these unintended consequences might emerge. More importantly, and I think this is the point that the public pick up on really astutely, is that we might not even know that these knock-on consequences are happening because the systems are so complex and so interconnected. We still don't fully understand how they work.

R057 concurred and stated that "*the lack of social legitimacy and adequate governance … is the entire reason for the intensity of opposition*

Table 4
Expert perceptions of the negative co-impacts of solar geoengineering.

No.	Technology	Perceived negative co-impact	Dimension	Frequency (N = 125)	%
1	SRM (as a whole)	Limited social acceptance, public support, and legitimacy	Socioenvironmental	64	51.2%
2	SRM (as a whole)	(Un)intentional consequences for and associations with regional weather modification	Technical	54	43.2%
3	SRM (as a whole)	Difficulty in scaling and commercialization	Technical	46	36.8%
4	SRM (as a whole)	Path dependence and the risk of "termination shock"	Technical	26	20.8%
5	SRM (as a whole)	Will require government intervention and financing	Financial and economic	20	16.0%
6	SRM (as a whole)	Passes on climate risks to future generations	Political and institutional	19	15.2%
7	SAI	Aerosol injection could interfere with monsoons	Socioenvironmental	18	14.4%
8	SAI, MCB, CCT	Could have negative effects on ozone protection	Socioenvironmental	10	8.0%
9	SRM (as a whole)	Unequal or unfair involvement in decision-making and planning	Political and institutional	9	7.2%
10	SRM (as a whole)	Geopolitical conflict and military instability	Political and institutional	9	7.2%
11	SRM (as a whole)	Will face innovation gap and commercialization problems	Financial and economic	8	6.4%
12	SAI	Requires very sophisticated waste management systems	Technical	6	4.8%
13	SRM (as a whole)	Does little to address ocean acidification	Socioenvironmental	5	4.0%
14	SAI	Risk of attack by rogue nation or terrorism	Political and institutional	5	4.0%
15	SRM (as a whole)	Potential for "green finger" deployment	Political and institutional	5	4.0%
16	SAI	Will increase air pollution and acid rain	Socioenvironmental	4	3.2%
17	SRM (as a whole)	Results in uncontrollable counter geo-engineering research	Political and institutional	4	3.2%
18	SRM (as a whole)	May confront significant intellectual property barriers	Financial and economic	3	2.4%
19	SRM (as a whole)	Could trade-off with climate adaptation	Socioenvironmental	3	2.4%
20	SRM (as a whole)	Aesthetic effects including changes to the colour of sunsets	Socioenvironmental	3	2.4%
21	SAI, MCB, CCT	Could worsen patterns of commercial control	Financial and economic	3	2.4%
22	SAI	Will trade off with solar energy production	Technical	3	2.4%
23	SRM (as a whole)	Entrenches patriarchy and a "boys with their toys" masculine attitude about nature	Socioenvironmental	3	2.4%
24	SAI, MCB, CCT	Can lead to nutrient robbing	Socioenvironmental	1	0.8%

Source: Authors. Note: SRM = solar radiation management. SAI = stratospheric aerosol injection. MCB = marine cloud brightening. CCT = cirrus cloud thinning. Note: This section presents expert quotations only for the top five negative co-impacts, rather than for all of them, for reasons of length.

against proposed research on solar geo right now." R064 believed that: "*there are large-scale ethical concerns people have about tampering with nature, about doing versus allowing climate harms, which are more nebulous, but they're there, and they drive a lot of people's negative reactions to solar geoengineering*." R100 added that even in the Global South, "*there are strong ecological movements against SRM … they don't see SRM as a possible solution at all*."

3.4.2. (Un)intentional consequences for and associations with regional weather modification

A second concern pointed to by our experts related to the ability for solar geoengineering techniques to be used as weather modification, something both constrained under international law and also connected to the point about declining social legitimacy (Section 3.4.1). R002 explained it as follows:

Many people and even policymakers view SRM as a form of weather control … It's not being quantified yet, we don't know exactly it would work that well but given that you could turn it off and on, on a shorter timescale that we're able to make accurate weather forecasts, it means you've got the choice between at least "on" and "off" as your weather forecast and so you get to pick between those two. I think that's potentially a little worrying about those ideas, is that weather control or weather influence potential. I think all of them have the security issue … marine cloud brightening, cirrus cloud thinning, and stratospheric aerosol geoengineering would potentially create these military targets if you decide to take it as a military threat. And as you would want to maintain deployment you would have these things that would effectively become key infrastructure, like GPS satellites and power lines and so on, that you'd need to protect and look after … so solar geoengineering quickly becomes militarized.

R119 also believed that solar geoengineering is intimately connected to:

…trying to deliberately control the weather, to encourage increased precipitation, decreased precipitation, more cloudiness, less cloudiness, whatever. It is viewed as a form of distributed climate engineering. It's weather modification and regional climate engineering.

This stigma of weather modification was framed by R034 as "*the greatest risk*" to SRM since "*concerns about weather modification could stall deployment in its tracks*."

3.4.3. Difficulty in scaling and commercialization

Another concern arising from our expert data is difficulty in scaling up certain solar geoengineering technologies and commercializing them. R035 spoke, regarding approaches located on the Earth's surface, about how:

I don't see how it is possible to scale up solar geoengineering to possibly account for the magnitude of what needs to be done, unless there are huge reductions in CO2 emissions to start with … I mean you would need to put reflective particles on a size of land greater than the Sahara, just to make a dent.

They went on to say, regarding marine cloud brightening, that:

…there are also ideas about ships that float around, creating sea spray, and they produce whitening effects, whitening over the ocean, which reflects more sunshine to space … Those particular technologies have been demonstrated, but to have that sort of thing working all the time and working at sufficient scale just, again, seems implausible to me, so I wouldn't believe that is realistic.

R011 commented, regarding stratospheric aerosol injection, that:

…to put aerosol injection into context, humanity would need four or five Pinatubo eruptions a year every year to control the RCP 8.5 pathway, so five a year, 50 every ten years and the equivalent of 500 eruptions a century to produce the necessary tropospheric aerosols … And then you still need to invent airplanes that can get into the stratosphere and have enough of them.

Depending on how much one's views correspond to those of the above experts, such quotations might be striking or contentious. At the same time, there is evidence in the literature noting that solar geoengineering schemes could involve very large dispersal patterns or require extensive infrastructures. At the most extreme end, Baum et al. (2022) note in reviewing some space-based proposals that these could involve materials covering 1 million square kilometers. Stratospheric aerosol injection is thought to be a more technically feasible approach. Nonetheless, Robock (2014) notes that any effective stratospheric aerosol injection program would need to inject sulfur dioxide particles at an altitude of about 20 km into the atmosphere every year in the Tropics and/or simulate the force of multiple volcanos for several months if the eruptions are at higher latitudes. A recent engineering assessment, from Smith (2020), has calculated the implementation costs of doing so at $18 billion per degree of temperature reduction - which lies only within the capabilities of advanced economies.

3.4.4. Path dependence and the risk of "termination shock"

The fourth-most mentioned concern connects to the longevity problem, path dependence and termination shock (Horton and Reynolds, 2016; Russell et al., 2012), namely, that once you start deploying solar geoengineering, you must keep deploying it forever (or at least, over long periods of time). R023 explained the issue as follows:

With solar radiation management, some of the techniques suffer from the termination problem. If you were doing it and you suddenly stopped doing it and you hadn't been reducing your emissions in the background, you would get the sudden rise in temperature. That is a big concern if you were going to go down that route.

R96 added that:

Yes, definitely SRM has path dependence because you are making a promise that who knows how many generations have to continue fulfilling. Once you start on it, once you rely on it, it cannot stop happening until we have decreased atmospheric concentrations under a certain level. You can phase it out, but it will take generations.

R101 also expressed concern that once you start doing SRM, "*you are stuck with SRM forever*."

3.4.5. Will require government intervention and financing

A final negative co-impact mentioned by experts was the dependence of SRM techniques on government intervention or financing. That is, the viability of any commercial model and the ability to establish a durable competitive advantage (e.g., R057) is much less than for carbon removal, and would instead need up to *trillions* of dollars of support in the case of some of the technologies. R024 here talked about the particular requirements of space-based geoengineering:

It's incredibly expensive. I mean, to paraphrase Lyndon Johnson, "A trillion here, trillion there, pretty soon you're talking real money." We spent $5 trillion on Coronavirus and we're coming out of it stronger than ever. The logic behind space-based action is "what is money from a state perspective?"

What emerges from many experts is the sense that the existence of a prospective '*business model*' is predicated on state security, and presumes that governments will exercise oversight over it as a type of national public good – though not necessarily a global public good, in which international coordination would be necessary (e.g., R032, R047, R053, R081, R088, R091, R106, R117). R048 added that they do not see much of a private sector business model to deliver SRM, leaving it in the domain of governments and state sponsors:

One thing that I find really interesting about something like SAI is the marketisation, the potential for it is quite limited. There're some interesting ideas around how it could link to carbon markets. Those are really, really new. But basically, it's largely got to be a state intervention. There's not really much room for a private market. I think the profitability, direct profitability, is much more on the CDR side than the SRM side.

R047 similarly expressed that:

If you go to SRM, the ideal business model is an open-facing, public-benefits model. You don't have to create a B Corp for it, or make everybody eat Ben and Jerry's ice cream, or make Bernie Sanders the CEO – well, I guess he wouldn't be called CEO for that kind of company, but Grand Poobah, equal among equals, or whatever corporate bullshit speak there is around that – but it's a public-facing institution that is providing a public benefit, and is, in *effect, working an option that then can scale as needed. So that's a warm chestnut over a roasting fire, and we have warm wine and spiced wine to drink with it, and so on, and it's all beautiful.*

R121 concurs:

…the bottom line you always have to remember for SRM is it only happens if the government incentivises you to do it, because there's no value for it … Otherwise, why would you do it? There's just no reason. You have no product.

4. Discussion: relationality, coupling, intent and consensus in deployment pathways

Section 3 presented a copious collection of prospective positive and negative co-impacts, but it did not discuss how these co-impacts necessarily relate to each other. Nor did it analyze possible couplings of technology (and co-impacts) to be co-deployed together, whether the described co-impacts were intended or accidental in nature, and which ones had the most (or least) expert consensus. We elaborate further on these four themes in this Discussion section.

4.1. Relationality and risk-risk trade-offs

As can be gleaned from Tables 1-4, both carbon removal and solar geoengineering options have arrays of prospective positive and negative co-impacts, and vice versa. Across our entire expert interview data, we see 52 positive co-impacts (38 for carbon removal, 14 for solar geoengineering) and 55 negative co-impacts (31 for carbon removal, 24 for solar geoengineering). As Fig. 3 depicts, with regards to the positive co-impacts, most of these (25) are financial and economic, followed by 18 socioenvironmental co-impacts, 17 technical ones and 9 political and institutional ones. Negative co-impacts have a different pattern, with most (12) being socioenvironmental followed by 10 financial and economic, 8 political and institutional, and 8 technical.

One finding from Fig. 3 is that carbon removal as a whole has a broader range of perceived positive co-impacts, along with greater consensus across experts, in terms of how frequently these are mentioned: notably, with 15 such co-impacts mentioned by (at least) around 10% of experts. Solar geoengineering, however, has only a total of 14 positive co-impacts noted, only three of which by more than 10% of experts.

Nonetheless, the extent to which experts were generally in agreement about the most salient positive co-impacts is dwarfed by that for the negative co-impacts, both for carbon removal and solar geoengineering. For carbon removal even if the overall number of negative co-impacts (31 versus 38) is slightly smaller, the frequency counts of the most highlighted negative co-impacts were on a different level. While the most referenced positive co-impact had a relative frequency count of 32% ("Nature-based carbon removal can enhance protection of life above land"), there were seven negative co-impacts mentioned at least as much: six of which by at least 40% of experts and two by more than half ("May interfere with water security and scarcity"; "Creates moral hazard and mitigation deterrence"). For SRM, the story is clearer still, with the total number of negative co-impacts exceeding that of positive co-impacts (24 versus 14) and twice as many negative co-impacts mentioned by (at least) 10% of experts (7 versus 3).

In addition, Fig. 3 illustrates that, when it comes to the types of benefits, those for CDR tend to more strongly centered on finance and the economy, whereas the risks emerge more from the socio-environmental domain. SRM is different – the perceived risks outweigh the benefits, both in number and in strength and frequency of analysis, thereby signaling either the greater unfamiliarity or undesirability of these technologies, or perhaps both. At the same time, it is notable that some risks characterize both suites of technology (e.g., difficulty in scaling, limited social acceptance and legitimacy, doing little to address ocean acidification), whereas others are unique to a particular technology (e.g., air pollution from stratospheric aerosol injection, or land

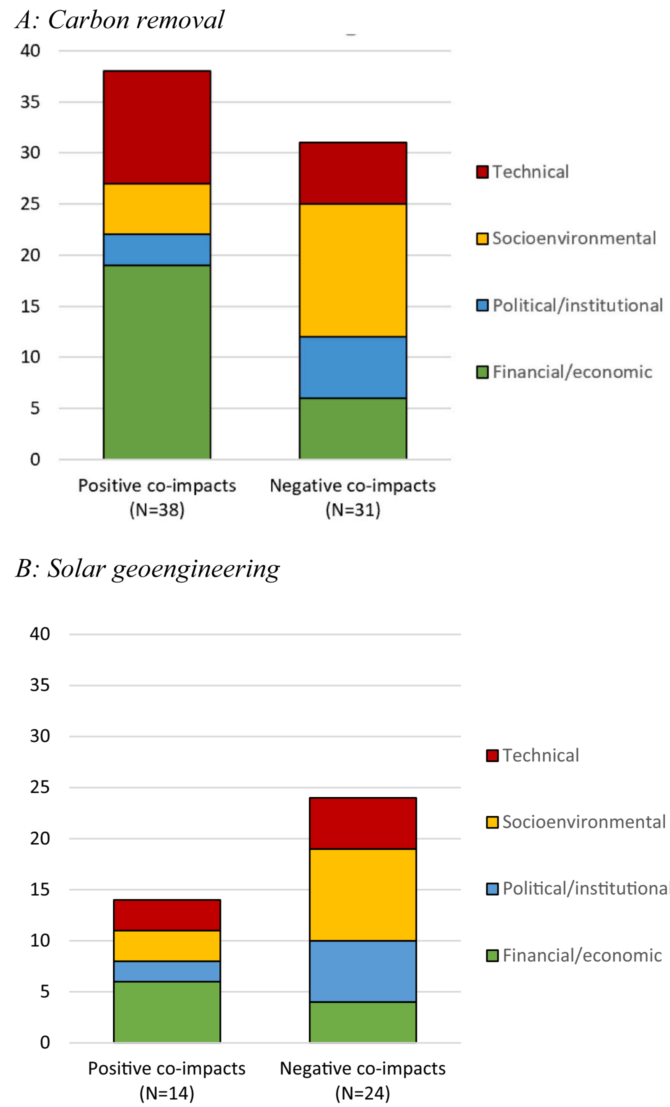

Fig. 3. Cumulative assessment of the prospective positive and negative co-impacts of carbon removal (top panel A) and solar geoengineering (bottom panel B).

use requirements for BECCS, or the coupling of solar energy to DACCS). The extent to which a technological option is intended to be used together or in isolation is thereby also determinative of the kinds of co-impacts which are most relevant and, similarly, of whether uncertainty or unease of the use of multiple technologies might be addressed by focusing on a relatively small subset of the overall (negative) co-impacts which the experts have identified.

Finally, we stress that the positive and negative co-impacts of carbon removal and solar geoengineering are highly relational insofar as they interconnect, as well as potentially normative insofar as experts do not always agree on whether a particular dimension is positive or negative. For instance, one identified benefit of solar geoengineering (mentioned by 7 experts) is that it can protect and prolong fossil fuel assets and thus jobs and a just transition. But this same point is viewed by another 19 experts as "passing on climate risks to future generations." Similarly, the most frequently cited positive co-impact of solar geoengineering ("Provides a boost to the aerospace, defense, and technology industries") is conversely conceived as increasing the risk of "geopolitical conflict and military instability" or, should this cause a re-allocation of scarce resources towards these industries, then as distracting from mitigation or adaptation (i.e., "Could trade-off with climate adaptation" or "Creates moral hazard and mitigation deterrence"). Whether the co-impact itself is perceived as positive or negative thus depends on the positionality of each expert, their own assumptions and perceptions about which normative criteria they are using to evaluate a particular option, and potentially where they are located, that is, in the Global South or not.

4.2. Co-deployment, context, and coupling

It is not only the co-impacts themselves which have the potential to appear together in clusters; different carbon removal and solar geoengineering options can also be co-deployed or coupled together in a portfolio approach. Indeed, across the entire set of 107 co-impacts (positive and negative) identified in Tables 1-4, we observe that almost one-fifth of the co-impacts corresponded to specific constellations or clusters of technologies (or 19 instances) – which does not even consider those co-impacts that broadly pertained to CDR or SRM "as a whole". These include particular constellations or couplings among:

- Enhanced weathering, biochar, BECCS, and DAC, all coupled via land-use management practices and the reliance on biomass or biological storage;
- Ecosystem restoration, soil management, and afforestation, also all coupled via patterns of land-use change as well as management;
- CCUS, DACCS, and BECCS, all coupled due to a collective reliance on carbon capture, transportation, and storage technologies;
- Enhanced weathering, DACCS, and ocean alkalization, coupled via their collective dependence on chemicals and engineering platforms for deployment;
- SAI, MCB, and CCT, which would all rely on similar aerospace delivery mechanisms such as aircraft or balloons.

Among other reasons, the broader applicability of specific co-impacts to multiple technologies offers useful information for planning and decision-making purposes. For instance, if the same technologies run the risk of the same negative co-impact, this might signal the need for caution at co-deploying them together; conversely, if many technologies might have a similar positive co-impact, then this potential may be enriched by deploying them jointly. Here, it is interesting to note that some of the constellations, such as enhanced weathering and biochar or ecosystem restoration and soil management, already feature in early-stage climate-intervention trials (Low et al., 2022).

Similarly, multiple experts were keen to highlight the importance of taking into account the context in which a technology would be deployed, given that co-impacts, whether positive or negative, are often less a consequence of the technologies than their fit to a given situation (e.g., R060, R065, R107, R108). On this point, R065 even went as far as to re-conceive carbon removal and solar geoengineering as "*not one single technology; it's a menagerie of different technology chains*." They offered up BECCS as an "arch example":

There are different ways of doing BECCS based on forestry residues, on wastes, on dedicated bioenergy crops, on food crops that get used for fuel as well. And there are a variety of conversion processes and then you can stick that CO2 in several different places afterwards. So even BECCS is not one technology, and it's actually a concatenation of growing stuff for biomass, creating a product from that, deriving some kind of energy product and sequestering the CO2. So, I would say, a lot of the concerns that are raised about removal technologies are often not purely about carbon dioxide removal. They are concerns around elements of the chains.

As a result, the need to employ a portfolio approach was another crucial consideration, which was noted explicitly for CDR by R026:

CDR could consist of co-deployed options. For example, with enhanced weathering and genetically modified crops, enhanced weathering with BECCS, or enhanced weathering with clean coal, there are neat land-based couplings and interactions that can arise.

Indeed, R060 identified the co-deployment of various technologies as necessary given not only the desire to avoid or mitigate certain negative co-impacts that would attend to scaling things up on a grand scale (also noted by R025, R043, R081, R083, R085) but also the scale of the problem itself:

The thing I always come back to is that there is no silver bullet. In practice… it's going to be a portfolio of things because some things will probably never scale to a global scale. … I think, practically, it's going to be more of a local to regional operation if it can get to that scale, and not a global solution, for all sorts of reasons.

According to experts such as R043 and R083, the desire to find and implement global solutions that can correspond to the global scale of climate change neglects what works "*on the ground*" (R043). According to R083, it would be better to find things that "*fit to the local context, only then can you actually implement them.*" They then elaborated as follows:

If you just think, "Okay, globally, we need to do that. Where do we do that?" Then you just impose things, that never works. You really need to work on the national and local scale to be able to implement things and be specific enough and context-specific enough and also identify measures that might be kind of a modular approach in a way. You identify measures in a local context that could be transferred to another local context and then those which are, maybe, specific. I think that's important.

Additionally, the understanding of couplings can be extended to encompass and take into account the different dimensions of a sociotechnical system (see Fig. 4). Some of these, such as connections to agriculture or climate adaptation, were more commonly connected to CDR, and some such as space travel and a prospective aerospace economy, were unique to forms of SRM that are (extra)planetary in scope. Others such as siting considerations, social arrangements, and local development and economy were of relevance across both sets of technologies. This fact that such couplings are held in common illustrates the potential for CDR and SRM options to even become coupled to each other in certain configurations, for instance, through the development and application of diverse portfolios of climate intervention technologies (Caldeira et al., 2013; Sovacool, 2021).

Our data evidences the importance of environmental couplings for food and agriculture – the sector most cited by experts – as well as for the marine economy and biodiversity and ecosystems. Concerning the social and political dimensions, we remark on how these tend to co-occur, i.e., in relation to social arrangements and siting considerations. A range of other couplings were identified as being of interest for a handful of researchers, namely, bioeconomy (R081, R120), circular economy (R004, R039, R093), and digitalization (R063, R083). Others stressed the role of couplings of the climate-intervention options to critical topics such as climate adaptation (R075, R078, R091), including a need for reparations to the Global South (R091), the existence of insuperable biophysical system limits (R093), and indeed the coupling of solar geoengineering with everything (R105) to highlight its broad impacts. A few experts pointed to specific couplings for tourism (R036) and insurance (R091, R113), while other experts noted the relevance of CDR options for the core function of waste management, where materials like biochar could address the growing issue of landfilling by making productive use of by-products or helping improve water treatment and storm water management (R019, R084, R090).

4.3. Intentional and unintentional implications

Co-impacts can moreover have intended, planned, or first-order consequences but also adverse, unplanned, uncertain or highly second-order effects. Fig. 5 presents our results according to a typology involving four quadrants.

For carbon removal, the positive and intentional co-impacts (in the upper-right quadrant) involve those consequences that were more expected and known, like integration into land conservation and ecosystem restoration that protects life on land, or expansion of innovation, or the provision of decent work. Positive and unintentional (or not well-known or expected) co-impacts (in the upper-left quadrant) included connections with bioprospecting or unexpected synergies with

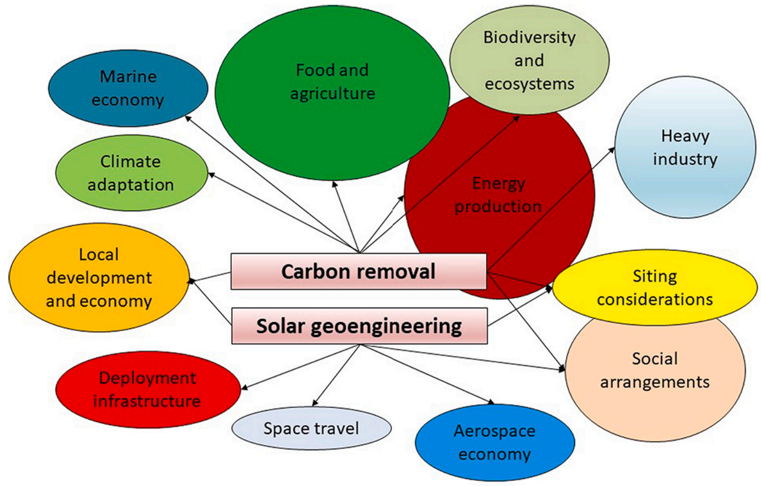

Fig. 4. Diffuse Sectoral Couplings to Solar Radiation Management and Carbon Dioxide Removal.
Note: Bubbles are roughly sized to reflect their prominence across the set of experts, in terms of frequency counts. Placement highlights conceptual similarities between categories, without any relationship to importance.

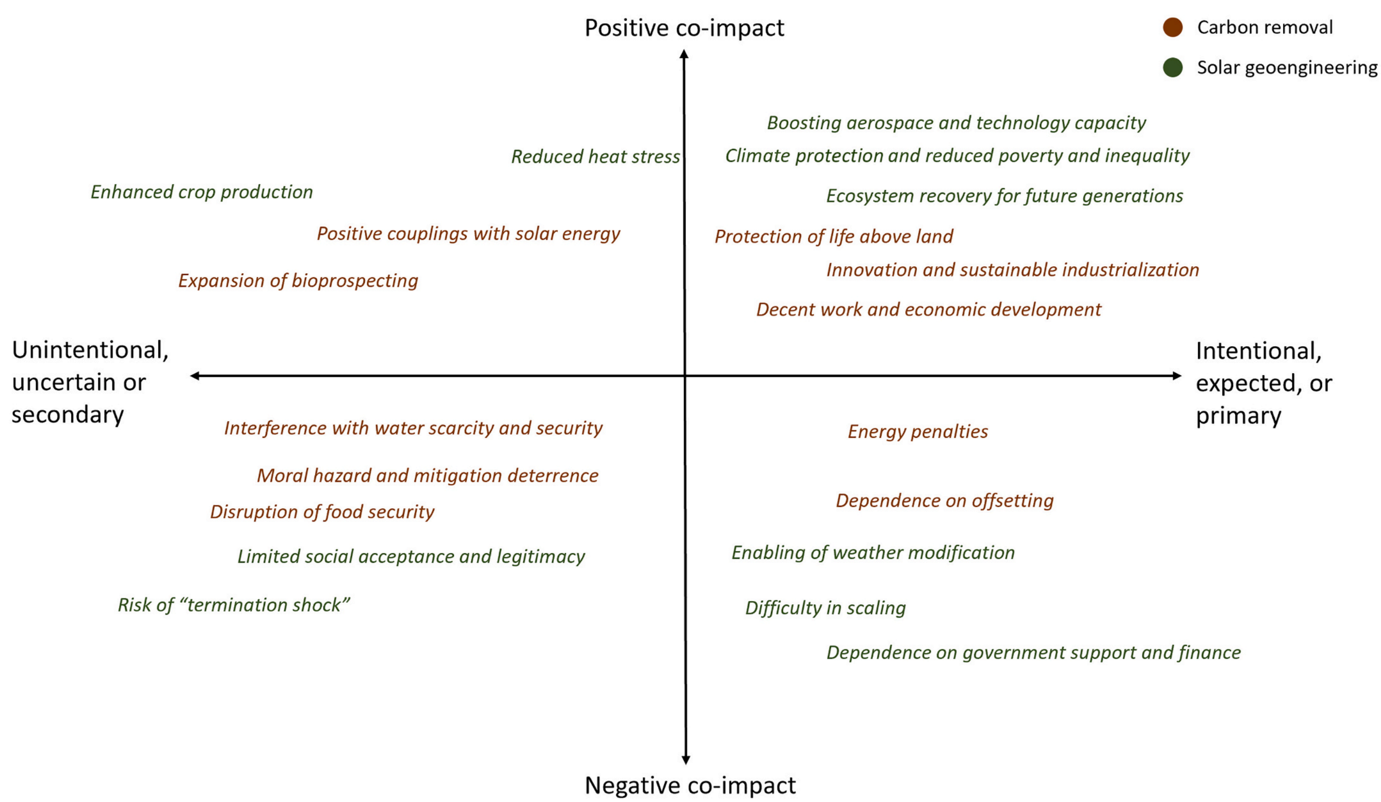

Fig. 5. A typology of positive and negative versus intentional and unintentional co-impacts with carbon removal (brown) and solar geoengineering (green).
Source: Authors, inspired by Ürge-Vorsatz et al. (2014). The diagram presents only the 20 co-impacts discussed in depth in Section 3, rather than all 107 co-impacts identified by the data tables.

solar power. Intentional and negative co-impacts (lower right) include those that are planned for and seen as necessary or justifiable, such as energy penalties and consumption, or use and coupling to carbon-offset markets. The final quadrant (lower left) of unintentional (and not planned for) and negative co-impacts include aspects such as the disruption of food, land, and water, or moral hazard and mitigation deterrence, which depend on the uncertain decisions of future actors.

Fig. 5 also reveals similar dynamics for solar geoengineering, as well as reinforcing the fit and applicability of the typology. Co-impacts that fall into the intended or expected quadrant include the ability for solar geoengineering to boost the aerospace and aviation industry or the technological capabilities of actors, to reduce temperature change and in effect also reduce climate impacts and thus improve well-being, and to protect ecosystems for future generations, that is, if it works. Positive co-impacts of an unexpected or more uncertain character include whether it can truly reduce heat stress or result in improved agricultural productivity at higher latitudes (with targeted temperature changes). Negative co-impacts of a similar type include intended or known

Fig. 6. Degrees of expert consensus and confidence concerning the co-impacts of CDR and SRM.
Source: Authors. Note: high confidence or expert consensus is classified as occurring if a particular benefit or risk was mentioned in more than 10 interviews (i.e., by more than 10 study participants); as being ambivalent if it was mentioned in 5–9 interviews/participants; and as being less confident or having dissensus if mentioned in 4 or fewer interviews/participants. Also, the maximum width in each of the panels is set in relation to the co-impact which was mentioned most frequently for this particular cluster, in order to facilitate comparison among, e.g., the benefits of SRM. Caution must therefore be taken when drawing inferences across the different panels based only on the width of the particular co-impact being displayed.

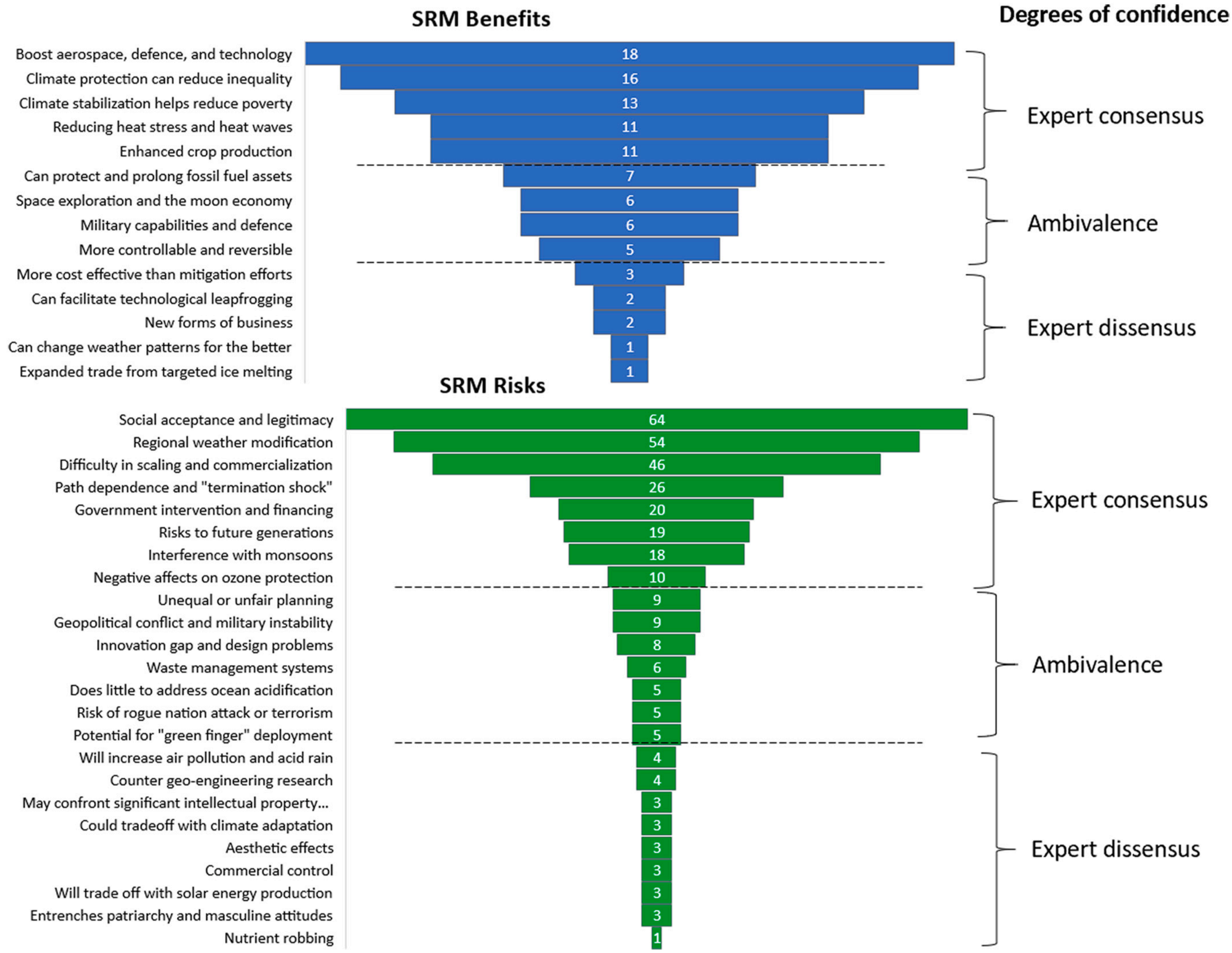

Fig. 6. (*continued*).

consequences such as how it would enable or at least be perceived to enable or be associated with regional weather modification, may face difficulties in commercialization and scaling, and will likely depend on strong state support and finance. Other negative co-impacts were less intentional or more uncertain, such as whether deployment will achieve social legitimacy, or face opposition, and the degree to which termination shocks will occur or be governed adequately by future generations.

4.4. Expert consensus and dissensus

A final theme emerging from our data is the difference with which our experts spoke about particular co-impacts, with some occurring frequently within the interviews (signifying a high degree of confidence or consensus), others falling in the more ambivalent middle, and a final selection occurring infrequently, signifying perhaps a low degree of confidence and dissensus among experts. As Fig. 6 indicates, there was a much higher degree of consensus for the benefits and risks of CDR: sixteen particular benefits were mentioned across more than 10 of the interviews, along with 18 risks. Conversely, experts had less confidence concerning the benefits and risks of SRM, with only five benefits being mentioned by more than 10 experts, and only eight risks being mentioned in more than 10 interviews.

In addition, we note that the discussion of the benefits and risks of CDR was more elaborate and extensive, in terms of both scope and frequency, than that for their SRM counterparts. What also stands out, focusing on SRM, is the greater emphasis on the risks rather than benefits. While the highest frequency count for positive co-impacts of SRM amounted to 1 of every 7 experts, there were seven negative co-impacts matching this criterion, including three mentioned by a third of all experts (“Limited social acceptance, public support, and legitimacy; “(Un) intentional consequences for and associations with regional weather modification”; “Difficulty in scaling and commercialization”). As such, there is a broader and deeper appreciation of the negative co-impacts of solar geoengineering. Accordingly, while certain positive co-impacts of carbon removal did gain traction among a large swath of experts, there is stronger consensus about the potential negative co-impacts of both carbon removal and solar geoengineering.

5. Conclusion

Carbon removal and solar geoengineering options could become instrumental parts of the transition to a net-zero, more carbon-resilient society. Our results indicate that deployment of such options would involve a diffuse collection of co-impacts, almost evenly balanced between positive and negative impacts, as identified by a robust sample ($N = 125$) of original expert interview data. With this in mind, we advance three conclusions.

Firstly, the scope and type of co-impacts delivered by carbon removal and solar geoengineering differ markedly. Carbon removal has more positive co-impacts than negative, as identified by our experts, whereas solar geoengineering is characterized by the opposite pattern, with more negative co-impacts identified. For carbon removal, prospective positive co-impacts are strongly financial and economic in nature, with a more even distribution among other sociotechnical dimensions (socio-environmental, technical, political and institutional). The prospective negative co-impacts are mostly socioenvironmental, however. For solar geoengineering, it is reversed, with more net-negative co-impacts than positive; though again with the positive co-impacts dominated by the financial and economic dimensions, even as the negative co-impacts tended to feature more socioenvironmental themes as well as a larger array of political and institutional risks such as geopolitics, weaponization, and security. Even then, at a higher level, while our experts could point to 52 positive reasons to *do* carbon removal or solar geoengineering (that is, to take advantage of prospective positive co-impacts), they also could point to an equally compelling 55 reasons to *not do it* (to avoid negative prospective co-impacts). If nothing else, this will make discussions and debates about both sets of options highly conflicted and contested, given advocates on each side of the debate have a plethora of potential co-impacts to which they can point in support of their particular stance and in order to advance their preferred claim(s).

Secondly, the complementarity of or potential to couple our options together into clusters or meta-groupings implies that net-zero transitions and climate stabilization may gain momentum when multiple innovations are linked together. The implication here is that many technologies and their potential co-impacts might benefit from complementary forms of governance that attend to how the technologies might be co-deployed. Such potential for coupling suggests the need to move beyond analyzing individual technologies towards the comprehensive assessment of entire systems – and indeed, as we argue above in relation to debates of "lumping versus splitting", to not rule out too hastily the evaluation of the climate-stabilization potential of carbon removal and solar geoengineering options together, rather than strictly in isolation.

Thirdly, and looking across the 20 most frequently mentioned kinds of co-impacts which we have examined in greater detail (due to a greater consensus among experts about their importance), our results pose methodological questions for future research generally. Our findings suggest that while some co-impacts are well-understood and tend to be more intentional rather than unexpected, an entire other assemblage of co-impacts were more hypothetical and could only be proposed, without the ability for current research to either support or refute them. They remain poorly understood, uncertain, or would be unintentional, if they were to exist. The confidence our experts expressed, in terms of frequency with which a co-impact was mentioned across the entire interview sample, turned out to be rather varied; indeed, more than half of the benefits or risks mentioned in our interviews could not be said to have attained any degree of expert consensus.

Furthermore, there is the need to address the uncertainty of how the different co-impacts relate to one another, that is, whether or not they are different in kind and thus in a sense difficult to compare against one another. In other words, can we employ the net-difference between the positive and negative co-impacts as a (rough) gauge of the viability of a given technological option (or cluster thereof), or are some of the co-impacts qualitatively more important? If the latter, then which? Might these perhaps be the ones most frequently mentioned by experts? Or, is this at best partly true, and the frequency of mention best reflects where research has tended to focus so far, for whatever reason? Merely adding up the prospective positive and negative co-impacts into a collective laundry list obscures the difference in scope or magnitude that individual co-impacts may have, and it can distort how co-impacts may be substantially larger or more certain for some options and co-impacts than for others.

Analysts and policymakers should therefore recognize the difficulty in predicting outcomes and in embracing the relationality of co-impacts and the uncertainty in their occurrence, while at the same time maintaining a sharp eye on how any unexpected or unpredicted developments could adversely impact the social acceptance and public support of such technologies. From this perspective, the value of comprehensively entertaining and wrestling with the prospective co-impacts of carbon removal and solar geoengineering technologies, positive and negative, is tied to not only the potential of identifying which options can be co-deployed in pursuit of net-zero emissions and climate stabilization. It can also vouchsafe the legitimacy and trust invested by the public in both the technologies themselves and the decision-makers and politicians who ultimately decide to employ them.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolecon.2022.107648.

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