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# Coupling for climate intervention: Sectoral and sustainability couplings for carbon removal and solar geoengineering pathways

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A R T I C L E   I N F O

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A B S T R A C T

Solar geoengineering and negative-emissions technologies are attracting greater attention as prospective ways to tackle and mitigate the worst impacts of climate change. Until now, such options have rarely been examined in a comprehensive manner. Rather, insofar as this has been done, research focused on one or the other, rather than considering a portfolio contribution and, more often, has taken a sectoral approach that looks at the options germane to the agriculture or energy sectors, but not in relation to climate change. Arguing for the need for a wider lens, the current article aims to understand the kinds of couplings and linkages most germane for the effectiveness of a particular option. In specific, we employed a novel dataset garnered from a large expert-interview exercise ($N = 125$) to conceptualize and consider crucial couplings to solar radiation management and carbon dioxide removal at many levels (across different sectors, differing dimensions of sustainability, productive or destructive impacts, and direct and indirect relationships). Our analysis thereby provides insights into the understanding of climate transitions by explicitly considering the most salient couplings in general as well as how, and to what extent, the various options relate to each other, as a portfolio for climate intervention, and together to climate mitigation and adaptation.

## 1. Introduction

Solar geoengineering and negative-emissions technologies are attracting greater attention as prospective ways to tackle and mitigate the worst impacts of climate change (IPCC, 2022a). Stratospheric aerosol injection, an example of the former where aerosols such as sulfur dioxide would be dispersed into the upper atmosphere, has been portrayed as a relatively cheap and fast, if imprecise, emergency mechanism to reduce how much sunlight reaches the Earth's surface and thereby slow the rate of global warming – or, less optimistically, grant countries more time to adapt to the new normal (Barrett et al., 2014; Keith and Irvine, 2016). Deployment of negative-emissions technologies (NETs), meanwhile, would aim to remove sufficient levels of $CO_2$ from the atmosphere to keep warming below 1.5 °C, in line with the Paris Accord (Minx et al., 2018; Fuss et al., 2020). In particular, NETs have been discussed as a way to compensate for the residual “hard to abate” emissions from industrial sectors like steel and cement (Fennell et al., 2022; IEA, 2021).

Such options, especially if deployed at scale, would however be attended by a host of risks and challenges (see Biermann et al., 2022 on solar geoengineering; see Grant et al., 2021 and Vaughan and Gough, 2016 on NETs). Looking at stratospheric aerosol injection, such risks may include potentially adverse impacts on monsoons and precipitation patterns (Da-Allada et al., 2020; Krishnamohan and Bala, 2022; Tracy et al., 2022); ecosystems disruption and threats to biodiversity (Trisos et al., 2018; Tracy et al., 2022), the inability, at best, to counteract climate-related damages for agricultural production (Proctor et al., 2018; Fan et al., 2021; Kravitz, 2021); and shifting incidence and range of diseases such as malaria (Carlson et al., 2022). In the case of NETs, the challenges vary depending on the technology considered, notably, nature-based approaches such as afforestation or more engineered approaches like direct air capture (Dooley et al., 2021; Low et al., 2022a). While the former is subject to conflicts around land use and food security (Kreuter and Lederer, 2021; Heck et al., 2016), engineered CDR will have to face issues ranging from high energy use and how well such approaches can be scaled up quickly (Creutzig et al., 2019; Madhu et al., 2021) and questions related to public acceptance (Wolske et al., 2019), including whether such efforts might undercut motivation to reduce

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emissions (Hart et al., 2022; Carton et al., 2023). More generally, risks and challenges may also stem from the emergence of new actor networks, which will likely entail, inter alia, the need to manage conflicts among an uncomfortable mix of progressive new-entrants and more conservative incumbents (van Sluisveld et al., 2020; Sovacool et al., 2022).

Nonetheless, confronted with escalating emissions levels and climate impacts (Steffen et al., 2015; Persson et al., 2022), a diverse portfolio of climate-intervention options is now under discussion (Morrow et al., 2020; Sovacool, 2021; Bertram et al., 2015; MacMartin et al., 2018), with such options looked at as potential complements to climate mitigation and adaptation. At the same time, there is at best a very limited understanding of the kinds of couplings which will need to be successfully managed for any portfolio to serve as an effective pathway for dealing with climate change. For instance, in spite of the tendency to examine the various options from an exclusively technical perspective, the extent to which these novel technological systems may be deployed to establish a more viable pathway towards limiting global warming, including one which includes overshoot and temperature and/or emissions debts (Asayama and Hulme, 2019), is contingent on how they are coupled to diverse physical and societal infrastructures. Indeed, there is greater appreciation that, ultimately, the viability of such options, on their own but especially as a portfolio, will depend on the “socio-technical” contours of their deployment (Sovacool et al., 2023a), i.e., the extent to which their potential is facilitated or impeded through a variety of societal, political, economic, and resource-related factors.

Understanding the couplings and linkages most germane for the effectiveness of different types of options (i.e., solar radiation modification (SRM), nature-based CDR, and engineered CDR) is thus a core prerequisite of further policy consideration. Indeed, couplings are critical in a multi-faceted sense and must therefore take into account different dimensions: that is, to assess how such options might be grouped with other (ongoing) developments, notably, around renewable energy; to other SRM and CDR techniques, in portfolio, to deliver co-benefits for farmers, a variety of industrial sectors, and those communities striving to undertake transitions out of fossil fuels over the coming decades; and to possibly function in tandem with traditional mitigation and adaptation activities to avoid the worst impacts of climate change. Accordingly, in this paper, we draw on data from 125 expert interviews to map the ways in which negative emissions and solar geoengineering technologies could be coupled, as immature or prospective systems of innovation, to existing or potential socio-economic and socio-technical systems. In particular, our analysis offers insights into the understanding of climate transitions by explicitly considering the most salient couplings on a general level vis-à-vis key sectors and dimensions of sustainability as well as how, and to what extent, the various options relate to one another, to serve as a portfolio for climate intervention, and jointly to climate mitigation and adaptation.

We conceptualize and thereby consider crucial couplings to solar radiation management and carbon dioxide removal on four fundamental levels, cutting across sectors, dimensions of sustainability, productive or destructive attributes, and direct and indirect relationships.

## 2. Research design and conceptual approach

### 2.1. Interview data

Our research design is grounded in the use of original data collected from a large-N set of semi-structured expert interviews. We conducted 125 interviews from May to August 2021 in order to explore and gain insights into, and develop a comprehensive understanding of, the opportunities and challenges around research, development, deployment, and (prospectively) commercialization of CDR and SRM technologies (Table 1). For instance, we asked, “What energy systems or other sociotechnical systems could or should be coupled with solar geoengineering and negative-emissions technologies?”. Though the current article focuses on responses to this question, due to the semi-structured nature of the interviews, answers and discussions relating to some of the other questions could also be employed, where relevant, to derive insights on relevant couplings. Indeed, the need to consider responses to other questions is underscored by the initial unfamiliarity of some experts with exploring this topic through the lens of coupling, and the fact that, often, their thinking evolved during the interview, thus resulting in their referring back later to this topic.

**Table 1**
Breakdown of interview structure.

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

Source: Authors.

Our recruitment and sampling of experts aimed to reflect and be representative of diverse viewpoints regarding the different climate-intervention options being considered. Accordingly, we employed a number of criteria, including to ensure a diverse, often antagonistic spread of stances and positionings, i.e., that critical voices (potentially from civil society) were engaged along with those of proponents, and to include experts from a range of disciplines (technical or engineering sciences, social sciences and humanities, economics, environmental and climate science). We also strove for broad representation across a range of sectors (academic research, technology development, industry and start-ups, government and policy, civil society along with nongovernmental organizations (NGOs)). Alongside experts from academia, the sample thus includes thought-entrepreneurs for carbon removal and/or solar geoengineering or those involved in policy and/or technological development (Table 2). In addition, given the animated historic debate on what constitutes ‘climate geoengineering’, we took care that individuals with diverse expertise and topic focus related to the technologies in question were included (‘climate geoengineering’ as an umbrella category, solar geoengineering or negative emissions suites, or individual approaches). Crucially, we refrained from imposing any limitations on experts with respect to what the might discuss, instead

**Table 2**
Summary of the demographics of participating experts.

| Summary information | No. |
|---|---|
| No. of experts | 125 |
| No. of organizations represented | 104 |
| No. of countries where experts are based | 21 |
| No. of experts whose current position falls into the following areas | |
| Civil society and nongovernmental organizations | 12 |
| Government and intergovernmental organizations | 8 |
| Private sector and industrial associations | 12 |
| Universities and research institutes | 94 |
| No. of experts from the Global South[a] | 12 |

Note: The sum equals 126 due to the dual affiliation of one expert.

[a] Respondents from the Global South were categorized according to the classification provided by the World Population Review (2022). Many of these participants were identified through the assistance of the DEGREES Initiative (formerly the Solar Radiation Management Governance Initiative), which collaborates with Global South countries and experts.

allowing them to comment on any topic they wished, rather than dictating ourselves where their expertise did or did not reside.

As a further step to improve rigor and validity, participants were screened to identify those who have published academic peer-reviewed research papers on solar geoengineering and negative-emissions technologies within the past ten years (2011–2020), along with considering those possessing patents and intellectual property. This was intended as an (imperfect) proxy for expertise, although also to ascertain if someone continued to be involved and have understanding of the subject matter. We deemed this to be crucial given both the pace with which the literature and discourse of SRM and CDR technologies is evolving along with, particularly in academia, experts might switch their fields of interest. In any case, this criterion was applied to participants outside of academia, e.g., from civil society or the private sector, to ensure a common baseline of expertise and knowledge – given the tendency for those working in civil society and environmental NGOs to rather publish public-facing reports and other materials, leeway was given where individuals or organizations were broadly recognized as being influential in this space. In total, invitations were sent to 210 experts, along with up to two reminders being sent, making use of email addresses and social-media channels such as LinkedIn. With interviews ultimately conducted with 125 participants, this process yielded a response rate of nearly 60 %.

We acknowledge that, while interviews were conducted with members of civil society and NGOs, governments as well as commercial entities in the private sector, the sample is strongly concentrated towards universities and research institutes (Table 2). In part, this is a reflection of where much of the discussion around climate intervention has tended to occur until now- but certainly should not be understood as any sort of evaluation of the types of groups and actors which should be consulted in the future nor of the kinds of knowledge (i.e., expert versus lay) which matter more. In any case, the sample includes a dozen participants from the Global South, here determined by the country of origin of the participant and/or their current location. We point to this as an initial step regarding the greater need for outreach and engagement with those in the Global South on this topic.

To enable experts to speak more freely about their expertise and own assessments, and given the potential sensitivity of the topic, interview quotes are presented anonymously and by reference to a randomly assigned respondent number (e.g., R010 for respondent 10, or R110 for respondent 110). For further notes on our methodology and data analysis, see Appendix A.

### *2.2. Conceptualizing "coupling"*

To delve down into how solar geoengineering and negative-emissions technologies (and the specific technologies within these categories) could unsettle, influence, and potentially come to provide the foundations of economies and societies undergoing transitions towards greater sustainability – and as they wrestle with the challenge and growing impacts of climate change – it is crucial to engage with the character and depth of couplings that might eventuate. As a first step, looking at couplings offers a useful way to sketch out those nascent linkages that could serve as bridges to other sectors, thereby mapping out the extent to which elements of an emerging, more sustainable regime – either centered around the various climate-intervention technologies or in which such technologies might play a crucial role – is already in place. Alternatively formulated, the mapping of such couplings, as an exercise, can also reveal if the development of certain technologies, as seen by their affirmative linkages to other sectors and aims, remains little more than a promissory note for climate intervention. In sum, assessing the scope and strength of couplings enables us to identify the likelihood that a particular technique could offer a solution to climate change in the increasingly short horizons established by recent IPCC reports (IPCC, 2021, 2022a, 2022b) and what would be required for its development, deployment, and (potentially) commercialization, including how it might be perceived by society at large, in view of the salient couplings which are materializing.

Broadly stated, the notion of coupling (or integration) has been employed as a way to conceive of the importance of deeper connections and linkages between energy sectors in order to increase the flexibility of supply, demand, and storage, and thereby seek to reduce the overall demand for energy consumption (Fridgen et al., 2020; Hansen et al., 2019a). This is directly undertaken, first, by highlighting the general need for more renewable energy and the core issue of intermittency (Bloess et al., 2018; Hansen et al., 2019b) and, second, to reckon with the types of tradeoffs and competition likely to emerge between contesting uses, like heating, industry, transportation, even communication for the growing (but limited) supply of such energy that exists (Bačeković and Østergaard, 2018; Schiebahn et al., 2015; Dominković et al., 2016). As a result, sectoral coupling represents both an objective to foster the decarbonization of the energy sector and a lens with which to understand the (un)expected consequences that may emerge from pursuing this aim. Alternately, such a lens has been used to identify drivers that increase the extent of such couplings as well as the barriers or bottlenecks that keep such couplings interrupted. As an example, a report for the European Parliament exploring how sector coupling could be used to "foster grid stability and decarbonize" places its focus on identifying barriers of a techno-economic (e.g., technology, resource availability, infrastructure) or policy/regulatory nature (e.g., climate and energy policy, market design) (Van Nuffel et al., 2018: 45). In short, coupling thus provides insights that can be of both a descriptive and proscriptive character.

Regarding the couplings identified, coupling can be at the same time *competitive*, for instance, among different uses or between sectors seeking to secure a limited supply of materials or resources, and *synergistic*, with changes in one domain having an effect elsewhere – or, more optimistically, with the development of technologies driving much wider shifts in an economy and society and thereby delivering more comprehensive benefits. Furthermore, the attention to the growing integration between energy-consuming and energy-producing sectors signals how positive change in one such sector, e.g., greater energy efficiency in the building sector, can free up energy (relative to the pathway to decarbonization) for use in transport and industry or else to alleviate pressure on energy supply. As a result, such changes could facilitate reductions of environmentally harmful or situationally undesirable sources. Then, there is the case of greater energy storage being employed, not to reduce demand or increase supply in the long term, but rather to promote a more desirable balancing of supply and demand – whereby any temporal mismatch between the generation and consumption of renewable energy sources is moderated. Here we have an example of how a specific technology – or set of technologies – affects decision-making and assessment of what is possible (e.g., in terms of decarbonization) and the extent to which sectors either are or might be coupled. Indeed, as such examples reveal, coupling can occur in a sectoral or spatial sense, that is, between where energy is produced and where it is consumed, as well as in a temporal sense. All such multidimensional considerations must be weighed together when determining which policies, approaches and technologies are needed to achieve the coupling and integration central to decarbonization.

In the Section that follows, we explore four fundamental types of coupling, drawn from the literature:

- Sectoral coupling, i.e., between parts of the economy such as industry, aerospace or agriculture;
- Coupling across different sustainability dimensions, i.e., between technical, political, economic, or socio-cultural aspects;
- Productive or destructive coupling, i.e., coupling with net positive or negative social or other impacts;
- Direct or indirect coupling, i.e., whether linkages are strong and primary, or weaker and secondary.

By engaging with the various types and levels of coupling (e.g., sectoral, spatial, temporal), we also gain access to emerging insights about telecoupling. While coupling tends to feature more in the energy context, the concept of telecoupling is used to generally examine environmental interactions and consequences that occur across large distances (Young et al., 2006; Friis et al., 2016). Highlighting those linkages between geographic locations across borders and at multiple scales, there is a shift from looking at causes, effects, and flows limited to one specific location towards how such outcomes are spread across different places, and indeed link places together (Liu et al., 2013; Eakin et al., 2014). As a result, this framework has proven useful to understand trade (e.g., food commodities, forestry products, or natural resources), migration, transnational certification, information flows, technology transfer, transnational land deals, and spread of GHG emissions (Liu et al., 2018; Parish et al., 2018; Xiong et al., 2018; Garrett and Rueda, 2019). There have also been notable applications of telecoupling to identify spillovers at a global scale, including to illustrate causes and effects of smallholder actors at distant locales on one another (Zimmerer et al., 2018) and as a lens to establish the wider sustainability impacts of consumer demand on indigenous populations in the Amazon and rural communities in the southeastern United States (Liu et al., 2019; Zhang et al., 2019). Instead of stressing negative consequences, there are additional attempts to explore positive feedback effects on sustainability, along with the kinds of activities or structures that positively contribute here (e.g., Liu et al., 2018).

## 3. Results: exploring four different types of sociotechnical coupling

This section presents our core results according to differential types of coupling (sectoral, in relation to sustainability, productive/destructive, and direct/indirect).

### 3.1. Sectoral couplings

Insights into sectoral couplings can be gathered from the expert-interview exercise in a few ways. Having iteratively coded the data using *NVIVO* and a tripartite coding scheme (see Appendix A for a more detailed description of methodology and data analysis), we could consider how often a given coupling is described (i.e., through a quantitative frequency analysis), which gestures at its prominence for the set of experts as well as delving into more detailed statements on a specific theme or topic in order to examine how the identified sectors broadly relate to one another and how they correspond to different elements of sustainability.

Looking at the results of the quantitative frequency analysis of specific couplings (Table 3), we identify a total of 15 categories mentioned by at least 5 experts, with 11 highlighted by (at least) nearly 20 % of the sample. The most prominent coupling, mentioned by nearly half of all experts, was to the sector of food and agriculture, also crucially interlinked with the issues of land use and land use change. Also, the energy sector was a common point of discussion, relating to matters of energy consumption (and related infrastructure) and production – the former mentioned much more often. As sub-categories of energy consumption, we observed an emphasis on sources of renewable energy, i.e., solar, wind, hydroelectric, and geothermal, and couplings to fossil fuels, mining and extraction, and nuclear power. Energy production, meanwhile, entailed linkages to biomass energy and biofuels, electricity, hydrogen, and next-generation synthetic fuels. Here we also point to explicit couplings to renewable energy, which ranked among the top four of those most-often cited.

On the one hand, the prominence of these categories in part reflects our use of a focused sub-question (i.e., to Question 2, Table 1) to inquire into synergies and tradeoffs of the climate-intervention options with renewable energy. Thus, there is the potential for responses here to overlap with the other categories, specifically those relating to the energy sector. On the other hand, we still opt to include them in Table 3 (i) to highlight the slightly greater recognition of synergies versus tradeoffs and (ii) to demonstrate the key role of couplings to renewable energy more directly. Although not as frequently mentioned as these other categories, a key function for society and governance was carved out, as reflected by the categories of social arrangements and siting considerations. Both categories underscore the role of societal and political factors alongside ones of a climate/environmental or technical nature.

**Table 3**
Frequency of couplings to sectors.

| Rank | Sector | Frequency | Dimension of sustainability |
|---|---|---|---|
| 1 | Food and agriculture | 59 (47.2 %) | Environmental, Economic |
| 2 | Energy consumption/ infrastructure | 55 (44.0 %) | Economic, Technical |
| 2 | Synergies with renewable energy | 55 (44.0 %) | Technical, Political |
| 4 | Tradeoffs with renewable energy | 43 (34.4 %) | Economic, Social, Political |
| 5 | Social arrangements | 36 (28.8 %) | Social, Political |
| 6 | Energy production | 35 (28.0 %) | Economic, Technical |
| 7 | Transportation and storage | 33 (26.4 %) | Technical |
| 8 | Siting considerations | 32 (25.6 %) | Social, Political |
| 9 | Heavy industry | 31 (24.8 %) | Economic, Technical |
| 10 | Biodiversity and ecosystems | 26 (20.8 %) | Environmental |
| 11 | Local development and economy | 24 (19.2 %) | Economic, Social |
| 12 | Marine economy | 12 (9.6 %) | Economic, Environmental |
| 13 | No coupling | 8 (6.4 %) | N/A |
| 14 | Buildings | 6 (4.8 %) | Technical, Political |
| 15 | Climate adaptation | 6 (4.8 %) | Environmental, technical |
| 16 | Space travel/Moon economy | 5 (4.0 %) | Technical, Economic |

Source: Authors. All categories included were mentioned by at least five experts. The two categories referencing “renewable energy” employ data from a sub-question (to Question 2, Table 1). Dimensions of sustainability were characterized through broad assessment of the nature of the detailed statements belonging to each node or theme.

### 3.2. Dimensions of sustainability

Turning to the dimensions of sustainability (Table 3), of the 15 categories – excluding “No coupling”, which was mentioned in relation to SRM to stress its separateness – the most often cited were of an economic or technical nature, together accounting for more than half of all mentions. Notably, sectoral couplings that entailed both kinds of couplings include energy production and consumption, heavy industry, and space travel – with storage and transportation on the technical side. In part, the prominence of these dimensions replicates the tendency so far in the literature on carbon dioxide removal and/or solar radiation management to focus on exploring and addressing techno-economic concerns (e.g., Minx et al., 2018; Fuss et al., 2018; Nemet et al., 2018). At the other end of the spectrum, the dimension which was referenced least often is environmental – which is surprising in view of the background of climate change and environmental degradation against which discussion of climate-intervention technologies takes place. That said, the environmental dimension is central to couplings for food and agriculture – the sector most cited by experts – as well as for the marine economy and biodiversity and ecosystems, both of which are becoming more prominent in the literature (Proctor et al., 2018; Fan et al., 2021; Kravitz, 2021; Boettcher et al., 2021; Cox et al., 2021; Aspen Institute, 2021). Regarding the social and political dimensions, we observed that these tend to co-occur, i.e., for social arrangements and siting considerations. As these were referenced by a quarter of experts, there is clear recognition of their role for ongoing development of CDR and SRM, although seemingly in a complementary capacity that would likely only have sway (or be allowed to) as soon as focal technologies are sufficiently ready. The (implicit) principal aim thus seems to be to avoid unwanted resistance from innovation leaders (Hietschold et al., 2020; Bellamy et al., 2021) and the public, i.e., by lacking social license to operate (Cox et al., 2022), both of which could greatly constrain deployment options. In any case, it must be noted that the literature on public perceptions, although beginning to take off, remains quite nascent, with a notable focus on a handful of technologies and countries (Sovacool et al., 2023a).

Further, a range of other couplings was identified as being of interest for a handful of experts: bioeconomy (R081, R120), circular economy (R004, R039, R093), and digitalization (R063, R083). Others underlined the relevance of couplings of the climate-intervention options to critical topics like 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 SRM with everything (R105), given its broad (and somewhat uncertain) impacts. A few experts pointed to specific couplings for tourism (R036) and insurance (R091, R113), while other experts highlighted CDR options as possibly performing the core function of waste management, where materials like biochar can tackle the growing issue of landfilling by making productive use of by-products or helping improve water treatment and storm water management (R019, R084, R090).

Lastly, we employ Fig. 1 as a way to outline how various sectors and sustainability dimensions relate to one another, here drawing on and synthesizing data from the statements provided by experts to better understand the kinds of conceptual linkages that exist. The size of the different bubbles is drawn to reflect how frequently they were mentioned. While location on Fig. 1 is not intended to be meaningful, there is a generally left/right split between sectors with more socio-environmental character (left) and those more technical and industrial (right). One of the initial takeaways is the prominence of couplings to food and agriculture, according to experts, and how this dwarfs that of other related sectors – indeed, the greater focus on land rather than oceans here is illustrative of the stronger attention that has been given to the former in (NAS, 2021), broad reluctance by the public to countenance interventions in the ocean (e.g., Boettcher et al., 2021; Cox et al., 2021) and, perhaps, the fraught experience of prior experiments with ocean iron fertilization (Low et al., 2022b). In any case, the implicit presumption of experts is that engaging actors and systems around food and agriculture will represent a key domain of future activity, whether for CDR options like soil carbon sequestration, biochar, afforestation, and enhanced weathering, or for SRM activities entailing albedo modification. From Fig. 1, moreover, the host of "intermediate" couplings relating to societal factors does afford a greater sense, according to experts, that the research, development, and deployment of SRM and CDR cannot take place without the involvement of such actors or addressing their potential concerns.

Switching to the right side of Fig. 1, it is the couplings to the energy sector that stand out, reflecting discussions around CDR (notably direct air carbon capture and sequestration, or DACCS) about the availability and use of sources of renewable energy vis-à-vis fossil fuels (e.g., Beutler et al., 2019; Breyer et al., 2020; Sodiq et al., 2023) and, with regards to SRM, about the potential that such options pose a moral hazard by undercutting the motivation for climate mitigation in the energy sector (e.g., Andrews et al., 2022; Corner and Pidgeon, 2014; Burns et al., 2016). In contrast, explaining its slightly smaller size, energy production centers on the potential for options like DACCS, bioenergy with carbon capture and storage (BECCS), and even afforestation to serve as energy sources or be coupled with nascent technologies such as hydrogen and synthetic fuels (e.g., Fuhrman et al., 2021; Kreuter and Lederer, 2021). Yet, the need to link such developments with transportation and storage infrastructure or with developments in heavy industry, whether through the search for new partners, establishment of new supply chains, and/or innovation in business models, underscores the changes in the wider systems that would be required for couplings between the energy sector and SRM and CDR to ultimately take hold. As a result, this reinforces and offers nuance for some of the discussions now emerging of what would be needed for, e.g., the carbon-sequestration potential of DACCS or BECCS to not only materialize at scale but also to do so with the speed required (Fuhrman et al., 2021; Nemet, 2019; Sovacool et al., 2022).

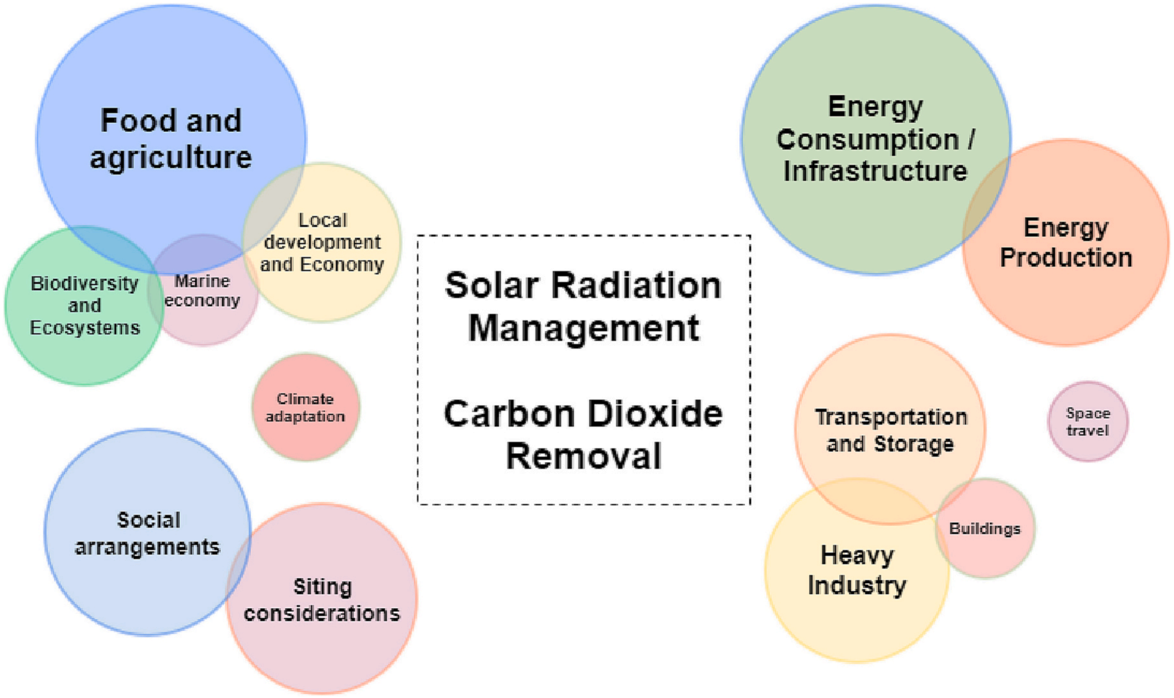

**Fig. 1.** Diffuse sectoral couplings to solar radiation management and carbon dioxide removal.
Note: Bubbles are sized to reflect their prominence across the set of experts, regarding how frequently they were mentioned. Placement is undertaken to highlight conceptual similarities between categories, but without indicating any assessment of importance, or linking potential couplings to a specific class of technologies.

Smaller, currently abstract links to buildings, as possible sites of urban albedo modification (R001, R042, R073), or even as a long-term sink of carbon (R125), and to space travel and the so-called Moon economy (R024, R033, R088, R092) were also indicated.

### 3.3. Productive or destructive coupling

Having discussed couplings between different sectors or dimensions of sustainability, we next examine the *directionality* of coupling, and whether it has a net positive or negative impact on society or ecosystems. Continuing to draw on the expert interviews, we reclassify couplings in this section by drawing on particular statements, which had been coded according to theme and topic, in order to explore whether specified couplings are productive (that is, they enhance sustainability goals and objectives) or destructive in nature. As such, we continue to reference the randomly assigned respondent number to which such a statement is attached to give a sense of the number of experts supporting such a view – and thus the extent to which there is broadly agreement or disagreement among the experts interviewed. We begin by describing destructive couplings for SRM and CDR, respectively, before detailing the productive couplings for each.

#### 3.3.1. Destructive couplings with SRM

One destructive coupling element supported by our data is that SRM deployment could negatively impact the deployment of renewable energy. Expressed in terms of moral hazard or mitigation deterrence, potential tradeoffs with renewable energy were by far the most frequent point of discussion (e.g., R004, R011, R025, R035, R039, R048, R099, R100, R116). For R004, among others, this could be put down to features of SRM: "*At the end of the day we can't lose sight of the fact that SRM has moral-hazard potential because it's quite fast acting*" (also, R103). Moreover, SRM was charged with a failure to address the root causes of climate change:

> "*Okay, so we're going to screw up nature more to solve the screw up that we've already done." It's like a tourniquet… it's not a solution. The solution is to leave the fossil fuels in the ground, and we can do it.*
>
> (R011; also, R080)

Indeed, multiple experts (e.g., R075, R091, R099, R100) explicitly highlighted the potential of SRM being co-opted by fossil-fuel companies or countries reliant on fossil fuels, in line with long-standing efforts at climate denial. Moreover, by not addressing causes of climate change directly, several experts acknowledged that SRM was unlikely to provide a solution for critical issues in marine ecosystems, such as ocean acidification (e.g., R081, R091) or impacts of rising sea levels on vulnerable populations and coastline communities (R025, R078). R081 was direct in their criticism here, on the failure of SRM to consider other climate impacts:

> What do you do about CO2? Let the oceans turn into vinegar and say we have solved the problem? I mean, it's even more one-sided as a technology… It's super partial and it's like radiation management in general. I mean, it doesn't solve the CO2 problem, so what are we going to do about the CO2 problem then?

Overall, the prevalence of such concerns echoes the frequent criticism, including from studies considering the perceptions of the public, that SRM represents, at best, a mixed solution to the climate crisis (Carr and Yung, 2018; Merk et al., 2019) – notably given its potential to undercut the much-needed reduction of emissions (Corner and Pidgeon, 2014; Wibeck et al., 2015; Burns et al., 2016).

Still, while most experts noted the negative indirect couplings of SRM with renewable energy, by way of moral-hazard issues, others were dismissive of such concerns (e.g., R022, R069, R084, R087). In the first place, some experts (e.g., R084) perceived less risk of such issues for SRM than CDR, as most people ultimately did not see it as feasible and thus not as something that could reasonably be counted upon. In their words:

> People who want to be convinced that you don't need to do anything about climate change will be convinced by anything. I think it's a bit harsh to label SRM as a moral hazard, just because an idiot thinks it's justification for not doing anything about climate change.

Others like R022 and R069, meanwhile, contended that little evidence had materialized in the last decade(s) that research into SRM had distracted from mitigation. Instead, many experts (R022, R066, R069, R084) offered that growing consideration of SRM may, counterintuitively, focus minds on the "scale of the climate threat" (R022) or strengthen deployment of renewable energy. This could occur by highlighting the scope of what we face – "*Seeing as this ridiculous idea is now being taken seriously, people might realize, "Okay, climate change is, perhaps, more of a problem than we thought.*" (R022) – or by clearly posing the available options – "*…it pushes for going towards using renewable energy more, because otherwise geoengineering is the other option if we don't*" (R066). In sum, notions of how SRM can be coupled with the aim of climate mitigation, rather than undermine it, are also evident – something also evident in the literature to an extent (Reynolds, 2015; Bodansky and Parker, 2021).

Similar indications emerged for how SRM, specifically stratospheric aerosol injection (SAI), might also negatively couple with climate adaptation, centering on the idea SRM could be used as a "band-aid solution" (R069) or for "shaving the peak" (R022). Seen in this way, SRM might provide time for adaptation (or mitigation) efforts to work. According to R022, the fundamental question is not one of moral hazard but the risks of using versus not using SRM:

> "If we have good reason to believe that using SRM would reduce risk, versus not using SRM, then it should be seriously considered for use. That's the one test that I think is necessary. … Fossil-fuel companies can be saying and doing what they want; and I don't care if SRM would reduce climate risks for vulnerable people."

Pointing to the long timescales of investment decisions for climate adaptation, R022 suggested SRM and adaptation "*could come into direct policy competition*", to the point of SRM being seen as a threat to national efforts on adapt. Offering one real-world example, R078 recognized that Bangladesh, as "a very adaptation-focused country" with strong capabilities in this domain, had little desire to devote funding to "purely technical research" like SRM, which is perceived to be a "western idea" with limited practical relevance for development and poverty alleviation. Pointing to skepticism from both policy and research circles, with some authors (Biermann and Möller, 2019) even dismissing it as a "rich man's solution"), R078 summarize the assessment of SRM of such nations to be: "*We are not an expert of it, and we don't want to be an expert.*"

#### 3.3.2. Destructive couplings with CDR

Destructive couplings also emerged for the various types of CDR. R087 (and R026) questioned the logic of trying to maximize carbon storage (specifically, through afforestation) at the cost of biodiversity and ecosystem health, pointing to studies on the climate impacts of boreal forests:

> …the boreal forest has a net-warming influence. And people were then like, "Oh, should we cut down the boreal forest?" And it's like, "No." One of the reasons you might want to keep the Arctic cold is so the boreal forest can persist. You know, we're not trying to destroy ecosystems to save the climate. We're trying to save the climate to protect ecosystems… basically, just to be blunt, I probably would not manage ecosystems for carbon at all.

To an extent, such perceptions reflect the legacy of the United Nations Programme on Reducing Emissions from Deforestation and Forest Degradation (REDD) and its voluntary counterpart, REDD+ (Carton et al., 2020; Kreuter and Lederer, 2021), specifically the failure to engage with local communities on the ground (R012, R036, R040, R047, R048, R053, R085, R096, R103), or to recognize the consequences that eventuate:

> *It forces you to think about communities and livelihoods on the other side of who would actually be delivering it… again all of the learning you have from REDD and REDD+ on having solutions that work at a feet-on-the-ground perspective rather than your top down… You need both. You need the top down to make sure it adds up, and you need the bottom up to make sure that it's meeting more than just a carbon metric, carbon and cost.*
>
> (R012)

> *Especially if it's Global North money pouring into it to get the climate benefits, but we don't see the social or environmental negative impacts on the ground. It's going to be very easy for us to continue doing this because that is, to be honest, what humanity has been doing for the last thousands of years, is looking for other areas to screw over.*
>
> (R096)

Ocean-based CDR was also criticized for its negative couplings. The ocean was broadly viewed as something different though regarding how it would interact with such technologies (R072, R080, R087), with R072 explaining that:

> the land can act as like a filter for materials, so what's coming out of rivers could end up just being alkalinity, the ultimate end-impact of enhanced weathering on the land surface could just be the addition of alkalinity to the ocean, whereas the application of minerals to the ocean could be the increase in ocean alkalinity. But it could also be the dissolution of other materials, potentially other bioactive materials from the rock.

As a result, impacts of enhanced weathering (and biochar) in particular, whether in terrestrial or marine ecosystems, ultimately occur in the ocean. Noting the potential for "*biomagnification through the food web where you have increasing concentrations of a toxin, or a metal, or what have you*", R080 stressed the need for ecotoxicology assessments on a large scale as a necessary part of future research. In the end, the matter of whether benefits or risks would be greater was left unclear, motivating and underscoring the need for future research (Gattuso et al., 2021), not to mention how the overall balance would likely depend on the specific context and situation.

Destructive couplings were also mentioned in terms of land use. A need for more mines to be opened would lead to questions about siting, not to mention the potential environmental impact (R026, R027). To an extent, two experts (R019, R099) noted potential acceptability issues for biochar as well, mostly centered on siting and, especially, if it were to infringe on environmental justice. Where risks of societal backlash were most evident, however, related to any activities in the ocean. While noting a potential for leakage of "alkaline waters" from one location to another, R036 considered how people would react if this was perceived to infringe on their "nice beach vacation". To this point, such aesthetic concerns have played a limited role in the literature at large – although Kolbert (2021) has evocatively described potential outcomes of "white skies", from use of SAI, and "green beaches", from enhanced weathering. Predicting that this "*would become a GM* [with] *all the NGOs lining up against*", R026 explained that:

> The moment [the public] hear this stuff is going into the ocean or there's any coupling with ocean pollution, that's a very touchy subject for people because people believe the ocean should not be polluted. There's a strong cultural belief that the ocean is the last pristine environment and, therefore, it's very bad to be putting pollutants into the ocean.

Indeed, given the tendency (as noted by R072) for materials to ultimately end up in the ocean, R027 sketched out a few initial parameters for public acceptance. Notably, they signaled that, while there is surprisingly little concern over mining or energy consumption, interventions in the open ocean were deemed a no go. Even if presented as a way of addressing acidification or correcting past mistakes, i.e., through what Buck (2019a) has described as "climate repair" or "climate restoration", people preferred: "*…the idea of protected spaces where there is no intervention whatsoever than the idea of intervening to try and do something about the mess that we've created*" (R027). For this reason, they concluded by casting doubt on whether ocean activities were "*the best place to spend our time and attention and money*" (ibid.).

Also, if BECCS is ultimately employed as an energy source – rather than as a means for carbon sequestration – its use was highlighted as necessarily being at the cost of land use, thus trading one resource for another. Indeed, R103 stated that, by their rough calculations, having BECCS to the extent imagined by, e.g., IPCC (2021) would require "*one, two, even three times the land area of India*". As a result, adverse impacts of BECCS on the biosphere were one of the most prominent couplings mentioned. Notably, BECCS scaling up to such an extent would entail unavoidable impacts on agriculture and land use (R002, R005, R013, R018, R027, R032, R042, R043, R049, R057, R058, R059, R067, R081, R085, R090, R093, R102, R103), the shift towards monoculture in agriculture and forestry (R041, R042, R094, R103, R119) and worsened demand for water, fertilizers, chemicals, etc. (R002, R036, R058), and adverse impacts on food security as crops are displaced for energy production (R010, R030, R032, R036, R053, R058, R064, R071, R081, R082, R113, R122). To add to the list, BECCS was pinpointed as a possible driver of species loss and mass extinctions (R042, R049, R053, R058), with R042 emphasizing that, if we were to assume that "*the issues of ecosystem service loss and mass extinction are as serious as climate change, any option that aggressively demands further land is a problem and a high-risk strategy*." Furthermore, R041 called out the idea that bioenergy could substitute for fossil fuels as "*not even science fiction; it's only fiction without science*", while R043 pointed to these issues as the reason that "*people have moved a little bit away from imagining that you could have BECCS making sense*". In total, for R119, the focus on BECCS as a solution thus was itself symptomatic of a fundamental shortcoming of broader modelling efforts:

> Many of us who are involved in coming up with global scenarios and advising policymakers, and many policymakers, tend to think in the big picture and miss the interconnectedness.

Furthermore, given historic couplings of monocultures and large-scale agriculture with land grabbing and infringements on indigenous and traditional property rights, a few experts (R010, R042, R064) highlighted these as further negative couplings of BECCS. Indeed, even were BECCS to avoid many of this long list of problems, R010 and R081 highlighted how the reliance on biomass at any large scale could produce a "resource curse" for local and national economies, not unlike that of fossil fuels. In fact, R109 pointed to an essential illogicality of BECCS, since "*most biomass facilities would need to be quite small, whereas CCS is better in large-scale facilities, as in the economies of scale make more sense in large-scale facilities*." While generally in agreement with such criticisms, R043 positively evoked the case of Sweden as one where BECCS could make sense, because of the role that bioenergy played in the energy system and thus not needing "*one additional hectare of land*". Aside from such narrow cases, the preponderance of destructive couplings for BECCS underscores a general pessimism across the experts over its potential role for climate protection.

Trade-offs between DACCS and land use were however seen to be much less of an issue, with experts pointing to its minimal land requirements, namely relative to BECCS (e.g., R006, R085). Regarding biodiversity, R085 did signal a need for caution given the extensive usage of chemicals in DACCS processes. Another provocative concern was a potential tradeoff in the vicinity of agricultural production since, as expressed by R067, you may not want to conduct DACCS "*too close to agricultural fields because you want to take CO2 out of the air, but you also want to keep high agricultural yields*". Other experts were keen to highlight trade-offs among the CDR options themselves, such as between BECCS and afforestation/reforestation (R094, R107) and/or albedo management, in view of the large-scale effects of land use change (R094, R124).

### 3.3.3. Productive couplings with SRM

However, other statements from our interviewees highlighted many positive couplings. Though rather tenuous, there were even a few researchers who speculated that SRM could even help to bolster renewable energy, with R100 highlighting the potential for increased river flows (and thus hydroelectric power) in South America and other experts (R024, R031, R088, R092) wishing to consider the (admittedly far-off) prospect of solar energy being captured by space-based mirrors and then beamed back to Earth (see Baum et al., 2022 for further discussion about space-based geoengineering). In fact, envisioned couplings to space travel and a future Moon economy (though speculative at present) represent the one unambiguously positive coupling for SRM. Accordingly, involvement of the space industry would likely be crucial for this option to be on the table (e.g., R010, R057, R070, R090, R097, R116), given the capabilities required and technical challenges intrinsic to their development and deployment.

### 3.3.4. Productive couplings with CDR

For CDR, though enhanced weathering and biochar could prove to be beneficial for soil health and the bottom line of farmers, their significant couplings to (and indeed reliance upon) the mining sector pose potential challenges to biodiversity and the environment (R026, R060, R064, R067, R072, R084, R087). On this point, R072 noted there are potential environmental risks and environmental benefits, although with negative impacts tending to be more localized (R067). Crucially, there is still a lot of uncertainty – something put down to a lack of field trials as well as questions over how the production side is managed, where the rock comes from, and how it is being spread. Notably, the crux is whether necessary minerals could be taken as the by-products of mining activities – thus, with rock grinding already having been done – or if an intensification of mining, with its related impacts, would be needed (R041, R064, R072, R084, R087, R099, R103). If enhanced weathering were coupled with intensified mining, there would emerge significant questions of if enhanced weathering, over its entire life cycle, provides net removal of carbon dioxide – given the use of diesel to power activities in modern quarries – not to mention the amount of energy required for mineral extraction and transportation (R041, R060, R072, R103). Indeed, R060 suggested that, if we wished to do enhanced weathering on a global scale: "*We'd need a mining industry that's probably as big as the rest of the mining industry, almost, as exists today.*" If however enhanced weathering could rely on existing rock sources, R103 concluded: "*it's probably both energy efficient… and carbon efficient*". Looking at the latest research, however, there is some doubt to what extent this would be feasible (Larkin et al., 2022), at least not without situating such activities in highly specific geographic regions (Dupla et al., 2023) or concentrating activities around mining operations (Stillings et al., 2023) – which would dramatically reduce the sequestration potential of enhanced weathering, along with excluding potential couplings and co-benefits for farming and agriculture. As such, once we probe what would be needed for such an option to work at scale, difficult trade-offs present themselves between the productive couplings which might be envisioned.

## 3.4. Direct and indirect coupling

A final way to examine potential couplings is according to strength: i.e., strong, primary and direct forms of coupling versus weaker, secondary, and indirect forms of coupling. Given the specificities and dissimilarities between SRM and CDR, not to mention among the various CDR options, it is necessary to consider the strength of couplings for each separately.

### 3.4.1. Direct and indirect couplings with SRM

Fig. 2 presents the strength of the direct and indirect couplings for SRM. In specific, more direct couplings were evident between SRM and renewable energy, e.g., as stratospheric aerosol injection (SAI), by its nature, would affect incoming sunlight and reduce the efficiency of solar panels (R001, R011, R028, R074, R087, R103, R106). Drawing on evidence from past volcanic eruptions, R011 noted that:

> "…after the Pinatubo eruption there were eight [solar panels] already in operation in California and the next summer, 1992, there was a 34 % reduction in electricity that they generated… direct radiation after the El Chichón eruption went down by 34 %."

When it comes to SRM options like SAI or marine cloud brightening (MCB), the lack of a clear business model resulted in frequent reference by experts to the need for such activities to be led by governments, notably, the military and defense contractors – given the use of high-altitude-capable aircraft to deploy SAI and for their ability to operate in extreme environments (R090, R098, R103, R105, R117). According to R117, what would be required are "*big aerial tankers that can operate at the altitudes at which the highest spy planes operate today and that plane just doesn't exist* [as] *there is no customer who has ever needed that mission.*" Coupling with such sectors – and to aviation (R020, R028, R050) – thus serves a principally facilitating role and as a provider of necessary equipment – in other words, as something of a last-resort actor funded by governments for undertaking activities others would not. Some experts (R033, R067, R097, R103, R110) noted that the shipping sector could undertake a similar role for the deployment of MCB, including through use of "unmanned, automatic vessels" to ensure that operational safety and limit disruptions to marine transport (R067). Laying out the specifics, R110 illustrates the potential here:

> If you're looking to do significant cooling, let's say 25 % of global carbon dioxide forcing, to stop the temperature rise being too high. You might want to do 1 W/m$^2$ globally. Then that would be a deployment that would probably need, I would say, 10,000 sprayers, maybe between 5000 and 10,000 sprayers, could be more. That's a lot, right? But it's not a lot compared to the global number of ships over the ocean, which is like 60,000 or something like that.

At the same time, R033 and R110 caution that the locations (and timing) of maritime transport may not overlap with what would be required for optimal deployment of MCB. As a result, it may be necessary to deploy a new fleet of (autonomous) vessels, rather than simply outfitting existing ships with sprayers, thus undercutting any potential couplings. However, this would increase the costs of this activity into the tens of billions of dollars (Anthony, 2022), especially given that, to this point, the ongoing field trials have instead opted to rent out the boats required.

Some of our experts even believed that couplings with SRM to other sectors were weak to the point of being nonexistent. On a final note, of the eight experts who claimed there were no couplings (R001, R002, R033, R039, R073, R105, R113, R114), this framing was employed to stress the broad uncertainties of the technologies at the moment: in terms of how they work, the lack of economic rationale, and even consequences that may eventuate. For instance, R002 underscored that SRM does not "*couple to anything* [as] *it is effectively an independent effort*", with R039 similarly noting how it is "*fairly detached from energy systems*".

### 3.4.2. Direct and indirect couplings with nature-based CDR

Nature-based CDR options such as afforestation, soil carbon sequestration and ecosystem restoration similarly exhibited both direct and less direct couplings (Fig. 3). In general, many experts (R002, R007, R018, R026, R027, R059, R067, R101, R107, R124) stressed close and fundamental linkages between nature-based CDR approaches and the health and functioning of land, coastal, and ocean ecosystems. Speaking to the scope of these couplings, R002 stressed that CDR approaches are *"very weighed down by their connections with other things"*, owing to the

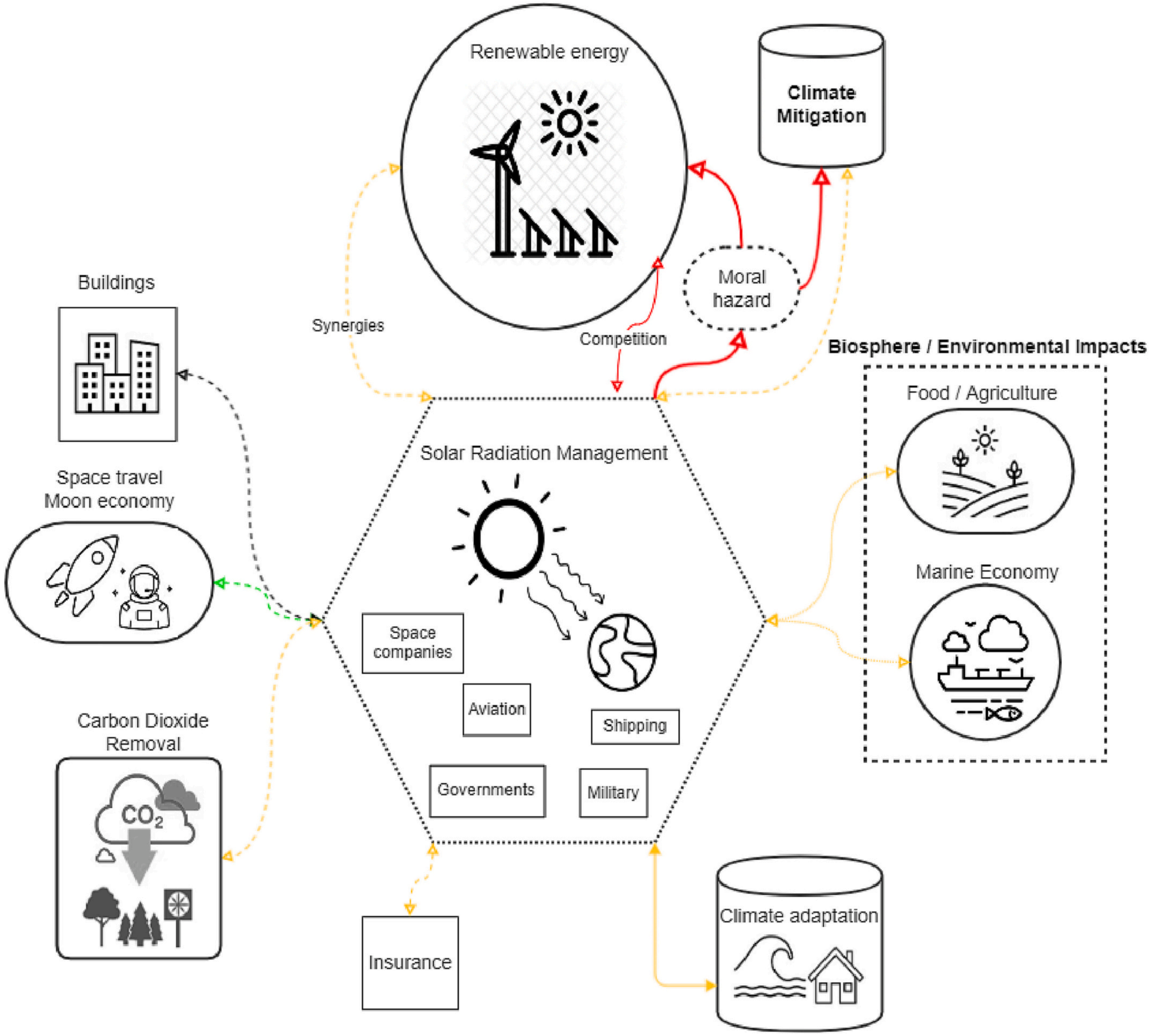

**Fig. 2.** Detailed couplings to solar radiation management.
Source: Authors. Note: Strength of couplings is reflected by thickness of arrows, with dashed lines signaling a presently tenuous coupling. Color of arrows indicates whether the nature of the coupling is positive (green), negative (red), or ambiguous (yellow). Directionality is noted by whether the coupling runs only from SRM to another sector, or in both directions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

large quantities of mass, energy, land, water, and natural resources needed. Furthermore, there is a strong likelihood for large projects, whether in the ocean (R083) or on land (R012, R059, R113), to have wider climate impacts in terms of algae blooms, wildfires, drought, pest disease, and potential changes to the water cycle, precipitation, and weather. As described by R124, there is a significant need for nature-based CDR to deeply think about:

> how the ecosystem is set up, and whether you can improve the value or health of the ecosystem at large by using these technologies which can deliver negative emissions credits… but also improving biodiversity, food production, etc.

Accordingly, one of the crucial requirements, according to experts (R018, R059, R124), for the success of this CDR meta-cluster is to set the terms of engaging with biodiversity and ecosystems, including by agreeing on what constitutes a "nature-based solution". For instance, R018 contended that such a solution can only be one that has "net biodiversity gain" instead of "just planting some trees". Such criticism reflects an appreciation of how afforestation is on its own not a guarantee for the "*long-lived removal and storage of carbon*" (R059), whether due to risks of wildfire (R012, R019) or issues of poor governance and local implementation (R047, R087, R096). More fundamentally, such criticisms signaled the inevitability of trade-offs when land is used for one purpose versus another, notably, how the objective of carbon sequestration tended to be given priority over food security and the needs of local communities (R012, R021 R036, R037, R040, R064, R081, R094, R103, R113). Indeed, mirroring above discussions of BECCS, which is similarly land-based, the prominence of such couplings was taken as a matter of fact, especially for large-scale afforestation projects:

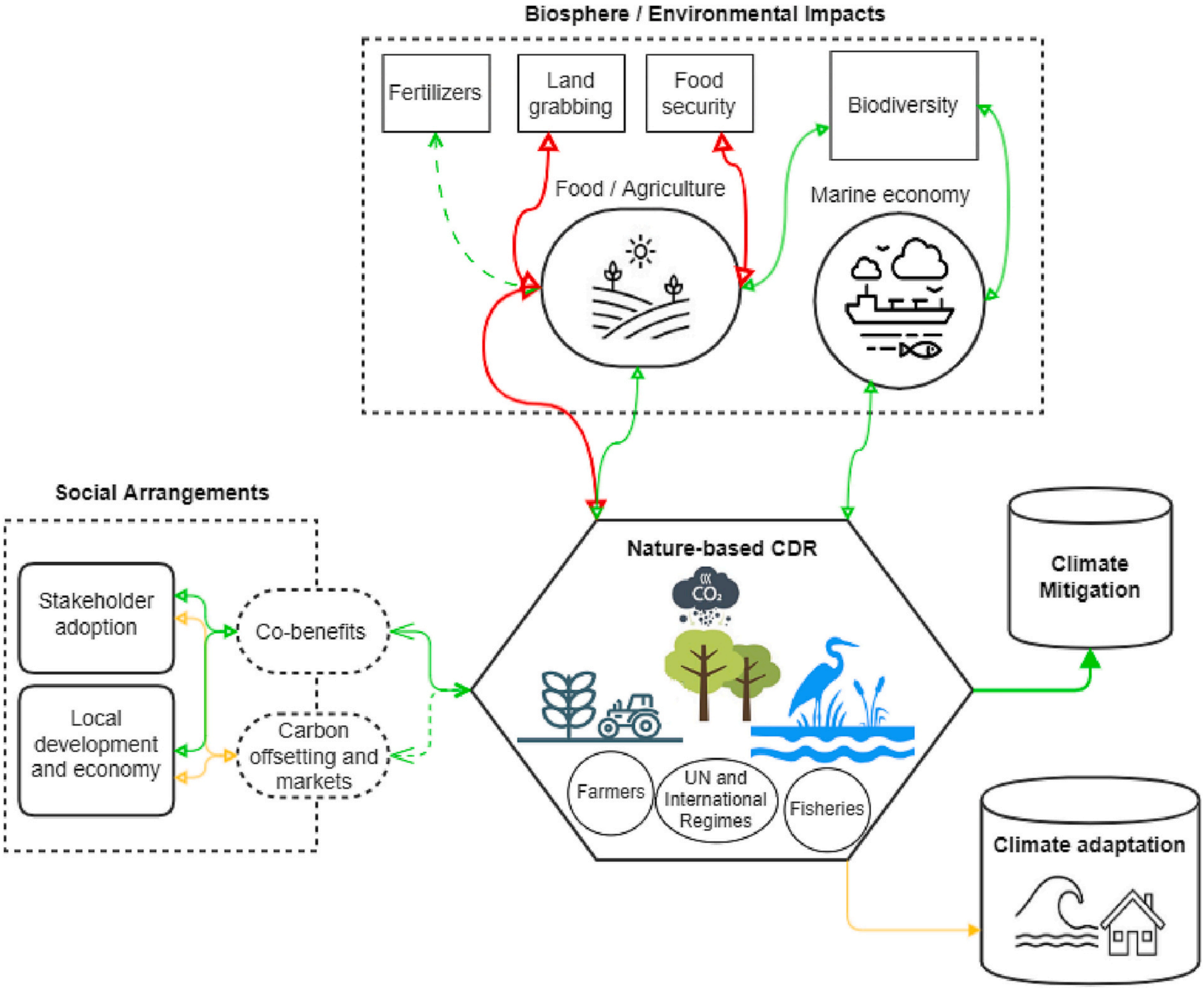

**Fig. 3.** Detailed couplings to nature-based carbon dioxide removal.
Source: Authors. Note: Strength of couplings is reflected by thickness of arrows, with dashed lines signaling a presently tenuous coupling. Color of arrows indicates whether nature of the coupling is positive (green), negative (red), or ambiguous (yellow). Directionality is noted by whether the coupling runs only from SRM to another sector, or in both directions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

> *If you're afforesting large regions, of course, then you also have land-use competition issues. Once you grow a forest for carbon storage, you probably don't want to cut the whole thing down and build a city there or anything like that, or you turn it back into farmland. You want that carbon to stay locked up, so there are certainly trade-offs.*
>
> (R036)

> *You can't unpack the natural climate solutions from land use for food, fiber, and fuel. You are sitting all of that on an underneath landscape of biodiversity, and habitat loss, and climate-change impacts that are already baked in or still coming.*
>
> (R012)

Beyond biodiversity, it is thus crucial to also consider couplings to “livelihoods of people especially in traditional societies, of smallholder farmers that are still there at the scale of one billion people who make their livelihood from land” (R085). If such aspects are neglected, this could lead, as a worst case, to the potential for land seizures or “land grabbing” from vulnerable populations, perhaps in the name of the global good (R012, R021, R064, R081, R085, R099, R102, R104). Indeed, R021 likened an approach “where people are expelled from the land by the military, under the banner of, “We are modernizing them.”” to the plight of the Uighurs in China. Echoing the situation on land, R036 and R113 also noted opportunity costs in the ocean, whereby blue carbon could result in communities “losing access to the coastline and resources on the coastline for other purposes” (R113) or having to forego, e.g., its use for fishing or as a site for wind farms.

### *3.4.3. Direct and indirect couplings with enhanced weathering and biochar*

Similar to nature-based CDR, the most prominent and fleshed-out couplings for biochar and enhanced weathering – the second of the CDR meta-clusters examined – were to biosphere and environmental impacts (see Fig. 4). Looking first at terrestrial couplings related to food and agriculture, many experts highlighted how these might work as soil amendments, thereby delivering co-benefits for enhanced crop production, soil health, and substituting for fertilizers – in addition to potential carbon sequestration (R026, R036, R037, R067, R072, R080, R094, R098, R101, R125). Regarding implementation, while noting the need for further testing and experiments, R098 suggested that: “*if farmers have the material, it's not that complicated to pull your tractor out and have some rounds on your field with that powder*.” Recent trials have, in fact, outfitted existing machinery to do just this, by adding a simple dump attachment to tractors (Copman, 2021; Carbon Drawdown Initiative, 2022). Furthermore, a few experts (R015, R019, R033, R125) focused on how biochar and enhanced weathering could be combined to enhance soil fertility, boost yields, and supplement costly industrial fertilizers – something that R125 designated as a “triple win”, if undertaken with reforestation or ecosystem restoration. According to R015, however, at least in the case of enhanced weathering, the use of so-called “slow-

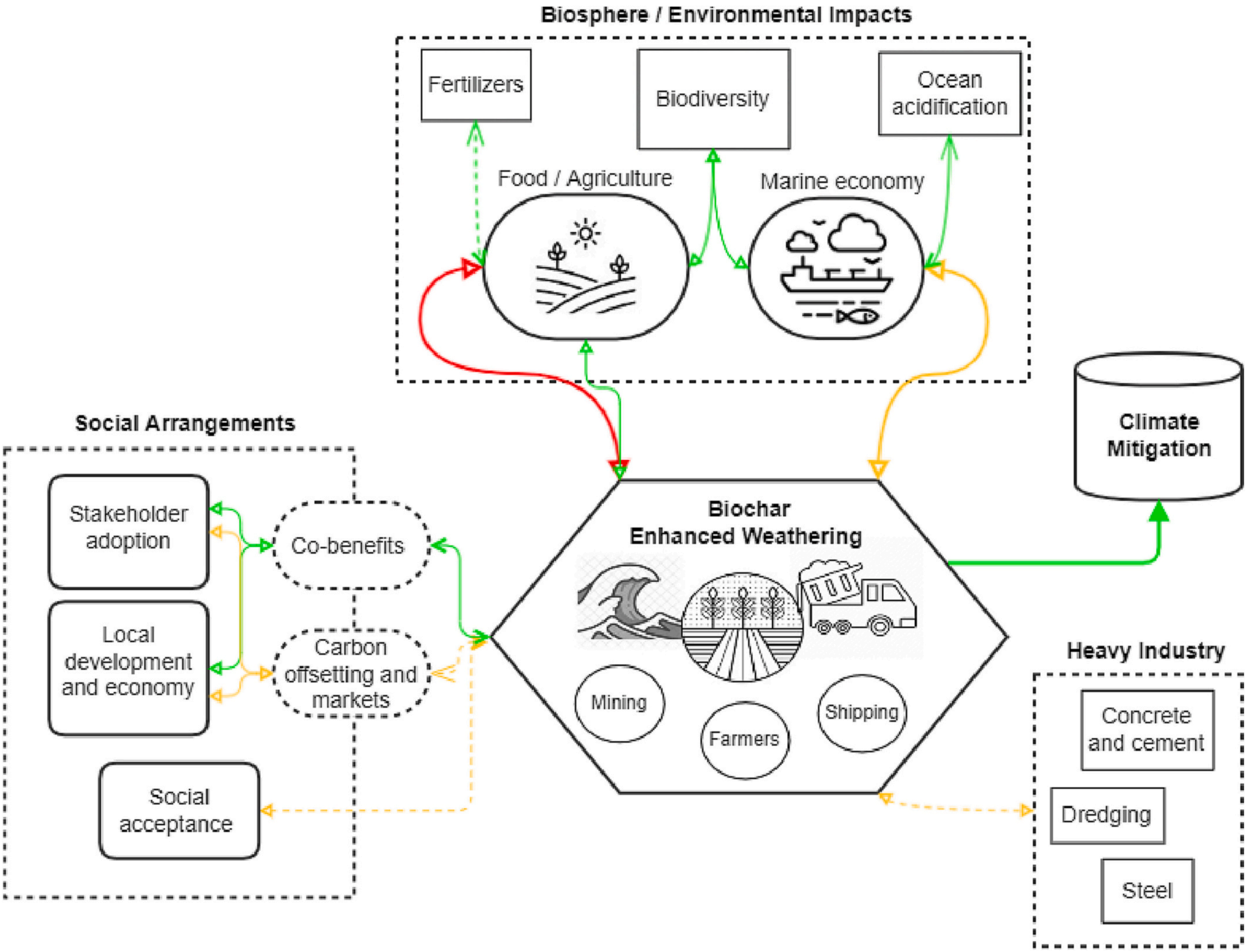

**Fig. 4.** Detailed couplings to enhanced weathering (terrestrial and marine) and biochar.
Source: Authors. Note: Strength of couplings is reflected by thickness of arrows, with dashed lines signaling a presently tenuous coupling. Color of arrows indicates whether the nature of the coupling is positive (green), negative (red), or ambiguous (yellow). Directionality is noted by whether the coupling runs only from SRM to another sector, or in both directions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

release fertilizers" may prove more suitable to climates, such as the humid tropics, which have "*poor soils because of the high rainfall and temperature* […and] *are totally depleted*." With farmers in these regions often lacking money for expensive fossil-based fertilizers, this could prove to be a boon – while mitigating harmful climate impacts of their production and application. While the evidence remains limited, there are early signals enhanced weathering can be effective in real-world contexts – that is, if the coupled practicalities and implementation difficulties can be addressed (Larkin et al., 2022).

In the context of marine ecosystems, since such activities can take place further out to sea, enhanced weathering might be potentially coupled with shipping as well. Mirroring marine cloud brightening in the SRM space, it was specifically understood that shipping fleets could offer a means to deliver the materials necessary for enhanced weathering (R060, R080), or to even use the operations of the ships to generate materials (e.g., lime) required (R015). Indeed, both R015 and R080 underscored that the shipping industry could represent a desirable partner given their search for solutions to become compliant with stronger emissions regulations. Still, R064 underlined that "…*if we were to try and raise the alkalinity of a global ocean, we'd need the entire world shipping fleet to ship the stuff around*", while R060 was concerned about how OAE might affect shipping activities if undertaken at large scale.

Intriguingly, R080 pinpointed emerging connections with the dredging sector as well. In fact, rather than a side coupling, the potential overlap here was deemed to be quite fundamental:

> Basically, enhancement of weathering is large-scale sediment management, or soil management. So, those companies that are very well-positioned to do that, those companies that are specialized in that will be very well-positioned to actually become a seller as well as a developer of these carbon-negative projects.
>
> … Dredging companies are starting to look into this. I mean, these companies have assets that are enormous, literally large ships that can move enormous quantities of sediment. So, they have the whole upscaling thing already, because they work inherently at scale, otherwise it's not feasible, otherwise their business model is not feasible.

Other industrial couplings for enhanced weathering and biochar centered on steel (R072, R084) as well as concrete and cement, and thus the buildings sector (R002, R007, R019, R084, R108). In the first place, this may include changes in types of building materials utilized from greater use of novel construction aggregates including biochar for filtration and remediation, concrete, asphalt, and so on (R007, R019, R108). As stressed by R108, such an approach could dovetail with a stronger push towards the bioeconomy.

Furthermore, R019 and R067 illustrated the coupling of biochar with industry and energy production more broadly, where it could be employed to decarbonize steel production or as a sustainable energy source – with R084 advocating a similar role for a decarbonized approach to lime production. Indirectly but intriguingly, R072 also pondered the potential for enhanced weathering, if gradually adopted at scale, to aggravate competition for rock materials, thereby increasing costs for construction:

> If you put a value of, like, $100 per tonne of CO2, you start to look at a value of rock that could be an order of magnitude greater than what currently it's being supplied at.
>
> So, if you start putting some sort of driver within the industry to use rock, or another demand for that rock that's an order of magnitude greater in value, how does that affect that existing industry and then the knock-on impacts for construction?

Once again, the sourcing and availability of rock materials emerges as a fundamental constraint for enhanced weathering, as well as a potential source of conflict with other uses and sectors.

### 3.4.4. Direct and indirect couplings with engineered CDR (BECCS, DACCS)

Fig. 5 highlights couplings for engineered CDR, showing that linkages of BECCS with energy production tend to be more established and direct; couplings of this type to DACCS are also stressed, mostly related to electricity and, in specific, hydrogen and other synthetic fuels (R017, R051, R055, R068, R064, R076, R086, R125). Use of DACCS for energy production was understood to have many positive couplings, whether directly, by transforming captured carbon into synthetic fuels, or indirectly, by accounting for removed emissions (R051, R055, R056, R086), or otherwise offering a solution to the intermittency of renewable energy (R040). In lieu of vibrant markets for carbon removal in the near term, or given limited storage capacity, such “carbon recycling”, as it was called by R064, was repeatedly labelled as a huge business opportunity (R036, R055, R064, R086).

Despite differences between BECCS and DACCS in terms of their resource demands, we come to a key point of cohesion for engineered CDR approaches: their couplings to heavy industry. Indeed, this is probably the distinguishing element of this meta-cluster – whereas SRM is also couplable to sectors such as aviation and shipping, this is mostly to access specific capabilities lodged in these sectors, rather than any kind of deeper coupling.

Crucially, engineered CDR was thus pointed to as an option to decarbonize “hard to treat” (R056) emissions in sectors such as long-haul aviation (R017, R051, R056), steel, cement and concrete (R008, R014, R016, R017, R038, R039, R052, R057, R061, R068, R079, R084, R115, R120), and chemicals and plastics (R016, R039, R073, R086,

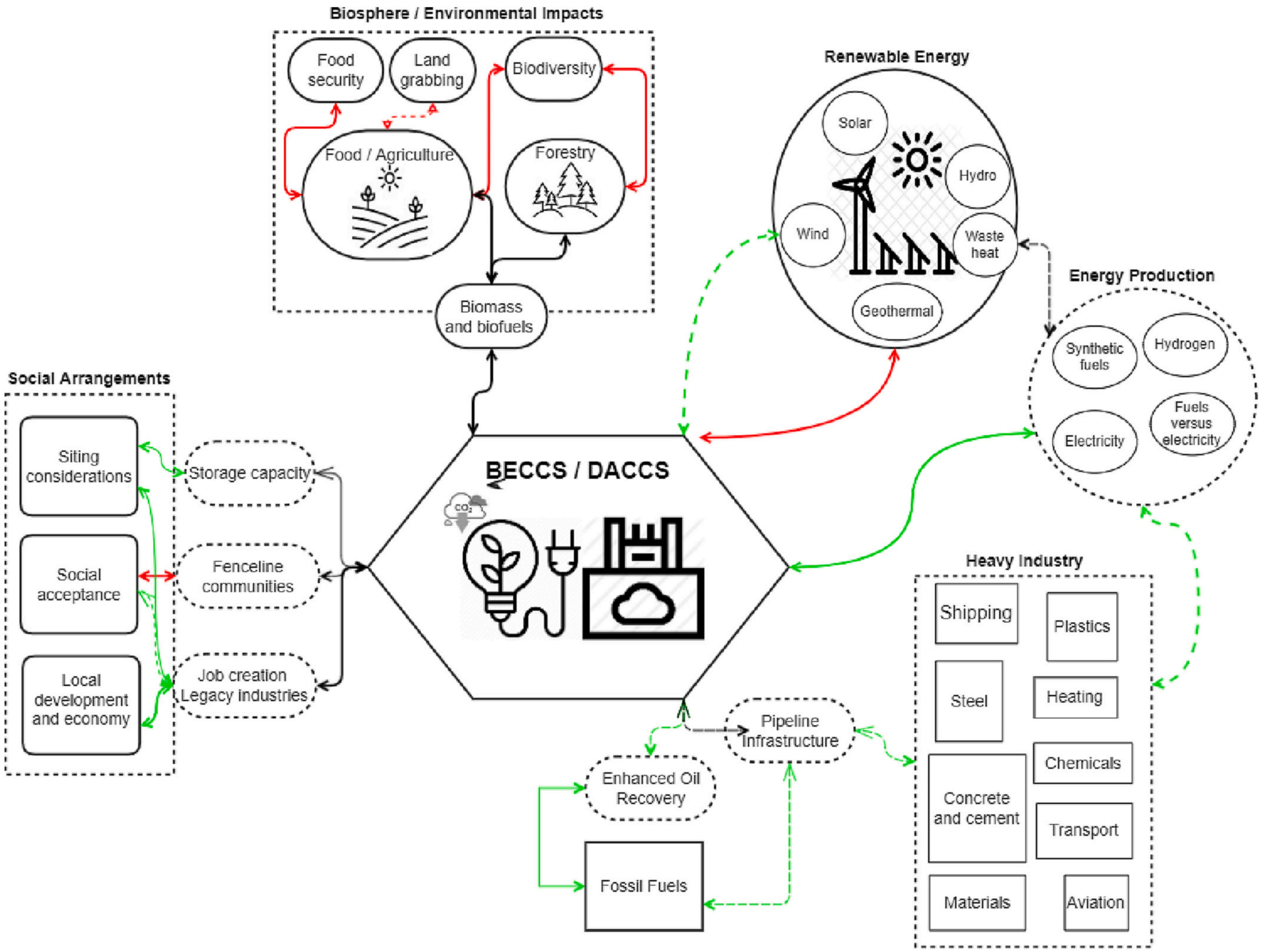

**Fig. 5.** Detailed couplings to engineered carbon removal (BECCS, DACCS).

Source: Authors. Note: Strength of couplings is reflected by thickness of arrows, with dashed lines signaling a presently tenuous coupling. Color of arrows indicates whether the nature of the coupling is positive (green), negative (red), or ambiguous (yellow). Directionality is noted by whether the coupling runs only from SRM to another sector, or in both directions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

R093, R120, R124, R125). For instance, R056 suggested businesses can offer "*carbon-neutral kerosene*" if they were to "*make it carbon neutral*… [and] *remove carbon dioxide from the air to compensate for the emissions that you have put out.*" Here, R051 introduced the possibility of smaller installations of DACCS next to airports, especially in remote, rural areas, thus saving on transport costs. Indeed, since renewable energy is not readily available in such settings, this would signal a potential positive coupling between DACCS and renewable energy, although a more nascent one, and one which could free up other resources (R055). In the case of plastics and chemicals, R086 moreover underlined that this coupling is bidirectional, given heavy reliance of DACCS on "*potassium hydroxide and a lot of PVC*". On specific applications of a more modular, small-scale DACCS approach, R016 and R052 evoked possible couplings to breweries, indoor cannabis production, and the beverages industry – all of which can be understood as niche markets which could be served as DACCS start-ups seek to scale-up (Nemet, 2019, Ch. 10). Citing many of the positive synergies, several experts (e.g., R014, R017) expressed a clear preference for the coupling of engineered CDR to heavy industry over power generation. R055, however, was concerned that attempts to use sequestered carbon as a feedstock for materials and commodities was "*partly a distraction*". R125 offered a suggestion, though, for how it could be paired with utilization:

> Everybody is obsessed about a circular model, but I am asking whether a linear model from atmosphere to landfill might not be a useful one to think about where on the way through you capture the CO2, you produce a polymer chain, you use that and then you landfill it and then you have effectively done CDR.

Nonetheless, while holding out hope for synthetic fuels in the future, a handful of experts were pessimistic about potential couplings with heavy industry. In specific, R093 noted that green versions of chemicals were unlikely to reach cost parity with fossil-based counterparts any time soon. R086 thus clarified that near-term focus is likely to remain on carbon removal: "*it's going to be more expensive to make synthetic fuels than to do DAC plus continue to use the fuels*".

## 4. Discussion and conclusion: towards emerging ecosystems of CDR and SRM

The couplings examined for emerging carbon removal and solar geoengineering options are as dynamic as they are potentially unstable and destructive. Differences among the various types and meta-clusters of carbon dioxide removal have received growing attention, with such categorization frequently broken down into groups based on their core inputs, nature of storage, site of operation, and potential for threats to biodiversity (Minx et al., 2018; Dooley et al., 2021; Morrow et al., 2020). We note here, however, that a focus on particular resources or risks as the basis for characterization can struggle to capture all the diverse elements – in terms of sectors, actors, and resources – which will ultimately be combined to form an emergent sociotechnical system. In this vein, the coupling diagrams presented in Section 3 for engineered CDR, nature-based CDR, and enhanced weathering and biochar can each be utilized to identify components that will be crucial for these emerging systems. In other words, by linking together the different options identified by the strong and productive couplings (i.e., the solid green arrows), one can begin to sketch a "positive" vision of how systems around these technologies may materialize. Notably, while the importance of social acceptance and stakeholder adoption for the emergence of such ecosystems is not always emphasized, or rather is seen to be less pressing than the more technical considerations (Table 3), strong couplings to these actors were identified by experts for each of the CDR options – most of all, for the engineered CDR approaches of DACCS and BECCS. Stakeholder engagement, particularly with local economies, rural communities, and legacy industries, must be central to any prospective vision involving these technologies (Buck, 2018, 2019b; Bellamy et al., 2021).

Importantly, the multiplicity of couplings that might occur thus broadly coincides with the multiplicity of actors that could be involved in SRM and CDR. Such activities face the similar challenge of having to engage with distributed and heterogeneous actors, not least at the scale envisioned for such solutions to have global impact. Of course, it must be acknowledged that both the extent and nature of such engagement differs between SRM and CDR – and to a lesser degree, between the different types of CDR. In fact, this is one reason that certain technologies have tended to receive more consideration in the literature: notably, with stratospheric aerosol injection being viewed as "fast, cheap, and imperfect" (Mahajan et al., 2019) or able to be done, for better or worse, by any individual or small group of actors with the necessary resources (Heyen et al., 2019; Smith, 2022). Nevertheless, the broadly tenuous and ambiguous couplings for SRM (Fig. 2), with the prominent exception of the (adverse) relationships with climate mitigation, is indicative of the rather speculative nature of discussions at present. While some researchers have therefore explored how to gather support for more SRM research (e.g., Keith, 2021; Felgenhauer et al., 2022a), the broad takeaway from the expert interviews is that there is insufficient appreciation of how SRM might, or should, be coupled to not only specific sectors but society at large.

Similarly, DACCS is frequently viewed as more feasible due to the need to examine fewer couplings when establishing operations – despite its sizable energy-use requirements, uncertain pathway to scaling up, and so on. Stating the underlying logic for preferring more "industrial" approaches, R084 for instance stressed that:

> If you're talking about applying stuff over millions of square kilometers, you are talking about engaging with hundreds of millions of people, who all have their own issues. It is hugely complex. That's, personally, why I prefer a more industrial approach, because it is something that can be done in a way that does not require hundreds of millions of people to consent and engagement.

And yet, as the case of DACCS demonstrates, it is not fundamentally the extent of (prospective) couplings that matters, but rather the strength of such couplings and the inevitability of thorny trade-offs. Even though building a positive case for the technologies is important, for instance, for mapping out co-benefits for farmers of enhanced weathering or the utilization purposes of DACCS or BECCS, any tendency to over-emphasize positive aspects might end up presenting such tradeoffs as more tractable than they really are. We discussed them in detail in Section 3 but it is useful to again summarize: for enhanced weathering, these center on the availability and sourcing of rock materials; for engineered CDR, it is the competition for scarce resources, whether renewable energy for DACCS or food and biomass for BECCS; even for nature-based CDR, there are the risks of adversely affecting food security and disregarding the sovereignty of traditional land-owners. The centrality of these couplings to analyses of climate-intervention technologies, both in the literature and in our expert interviews, however indicates that there is a strong appreciation of the kinds of negative impacts which can be expected.

Indeed, a corollary here can be that, when it comes to examination of climate-intervention technologies, it should be the potential destructive impacts of CDR and SRM which frame the discussion – or, at the very least, be given equal standing to any discussion of co-benefits. From this angle, recent calls for an international non-use agreement on SRM (Biermann et al., 2022) might, counterintuitively, be understood as opening up space for discussion, rather than closing it down. Notably, over the pre-conditions and ground rules which could be necessary to, under a strong formulation, make any non-use agreement unnecessary or, in a weaker framing, offer the basis for the political and social legitimacy of such technologies. Although it is not acknowledged enough, attempts to clarify the inherent risks that characterize the relationship of CDR and SRM vis-à-vis climate mitigation are fundamental for engaging stakeholders (Low and Honegger, 2022). Some will likely criticize such an approach as overly restricting, notably of research programs (e.g., Buck, 2022; Wieners et al., 2023). Furthermore, any such risks of climate intervention ultimately must be considered against the damages to be expected from climate change, particularly if the pace of climate mitigation continues to be insufficient (Felgenhauer et al., 2022b; Sovacool et al., 2023b). In any case, it is significant that one response to calls for non-use of SRM has elicited (e.g., Wieners et al., 2023) a more richly elaborated set of ethical principles for research as well as deployment. Given how limited our understanding of the couplings for SRM remains at present (see Fig. 2), the need to establish the basis for more informed decision-making on SRM (as well as CDR) seems reasonable.

In total, our analysis has thus contributed to the development of a more complete lexicon of coupling elements for climate-intervention technologies. Such efforts have encompassed the investigation of sectoral coupling, i.e., between CDR and the food and forestry sectors or (more prospectively) solar radiation management and aviation and shipping, together with coupling across different sustainability dimensions, such as between the political and social domains. Drawing on our expert interviews, we thus revealed many instances, existing and prospective, of productive and/or destructive couplings: coupling with forceful and widespread positive and negative impacts at a social level. We lastly examined the directness of couplings, exposing a host of strong vis-à-vis weak linkages. Ultimately, investigating couplings along each of these dimensions offers a lens and useful tool for gaining insights into any technology whose risks, impacts, and requirements (e.g., in terms of resources, actors, and sectors) are both broad and deep in nature. Given the increasing discussion of CDR and SRM as potentially necessary for the decarbonization of certain sector(s) and to complement climate-mitigation efforts (IPCC, 2021, 2022a, 2022b), these climate-intervention technologies are paradigmatic in this respect.

As a result, one way to support the ongoing discussions and analyses of SRM and CDR would be to potentially consider them as (emerging) systems in their own right, systems which produce spillovers and flows on a wider scale. From this perspective, such technologies, though likely to be deployed in the real world to differing extents, could be conceived of as a kind of action taken to deal with issues of an inherently telecoupled nature. Notably, the couplings for climate-intervention technologies broadly resemble the kind of "action at a distance" that cuts across space and time, and which is typical of telecoupling (Eakin et al., 2014). Indeed, climate intervention is, generally understood, an activity with fundamentally large scope to influence resources, actors, and systems at a range of scales. As such, climate-intervention technologies, and the understanding thereof, are likely to eschew a dichotomy of local versus global in favor of one looking at "diffuse interactions at multiple scales" (Liu et al., 2018; see also Eakin et al., 2017; Friis and Nielsen, 2017). Mapping and assessment of the relevant couplings (even if only existing tenuously at present) therefore represents a useful exercise to gain insights into such interactions and how different sectors may be linked. Or, alternatively, it may be that examining such couplings helps to illustrate what the prerequisites are for such a relationship to exist – or for it to deliver productive versus destructive outcomes. Most of all, this centers on recognition of the inherent tradeoffs at the heart of CDR and SRM. In order for climate-intervention options to make a contribution to viable pathways towards limiting global warming, closer attention to the various dimensions and types of coupling will be required – not least given the likelihood for acceleration and complexity in terms of the multiplicity of actors, their actions at a distance, and their diffuse interactions across planetary and subnational scales.

## 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

### *A.1. Further notes on methodology and data analysis*

Anonymity was mutually agreed at the beginning of each interview to adhere to institutional review board guidelines at the authors' university, together with oral consent to be interview and recorded (strictly for purposes of transcription, and with standards of data protection all being adhered to). We moreover took the decision to have all statements be anonymous in order to encourage candor from participants as well as protect them from any negative consequences. We acknowledge that such an approach, unfortunately, may pose difficulties for triangulation of statements and stances vis-à-vis particular professional characteristics of the experts. At the same time, as individuals were speaking on their own behalf, not that of the relevant institution, we contend that such concerns are somewhat mitigated and, further, must be balanced against the greater richness of responses attained by ascribing anonymity.

In rolling fashion, interviews were sent to a professional transcription service, with transcripts cleaned by authors upon their return before being entered and analyzed in the qualitative data-analysis program *NVIVO*. Making use of a tripartite coding approach, transcripts were coded according to (i) the question to which a statement belonged; (ii) the topic or node mentioned; and (iii) the technology referenced. In this way, transcripts of all 125 interviews were coded in *NVIVO*, with nodes (and sub-nodes) iteratively created as needed – as further distinction in a concept emerged. As coding was undertaken by authors in parallel, there is a possible challenge of coders assigning a statement to a different node or using different language to describe a theme. To avoid such issues, collaborative discussions among authors were repeated during the process: that is, at start of coding, to establish shared expectations and a common terminology, and iteratively over the next four months to mitigate and avoid inconsistencies from emerging.

Ultimately, the final dataset offers a structured coding of interview data, including information on the frequency with which a particular theme or technology was mentioned by participant as well as more qualitatively rich discussion. Both are used to gain insight on relevant couplings for climate intervention in this article, starting with a quantitative frequency analysis before delving into the more detailed statements on a particular theme from the set of experts.

**Table A1**
List of 125 semi-structured expert interview respondents.

| Name | Actor type | Gender | Country | Institution |
|---|---|---|---|---|
| [Anonymous Aerospace Engineer] | Private Sector + Industrial Associations | Male | Germany | [Aerospace and space systems company focusing on integrated spacecraft] |
| Aganaba, Timiebi | Universities + Research Institutes | Female | USA | Arizona State University |
| Asayama, Shinichiro | Government + Intergovernmental Organizations | Male | Japan | National Institute for Environmental Studies |
| Bauer, Christopher Dean 'Casey' | Private Sector + Industrial Associations | Male | USA | Raytheon Space and Defense |
| Bazilian, Morgan | Universities + Research Institutes | Male | USA | Colorado School of Mines |
| Bellamy, Rob | Universities + Research Institutes | Male | United Kingdom | University of Manchester |
| Beuttler, Christoph | Private Sector + Industrial Associations | Male | Switzerland | Climeworks |
| Biermann, Frank | Universities + Research Institutes | Male | Netherlands | Utrecht University |
| Boettcher, Miranda | Universities + Research Institutes | Female | Germany | Stiftung Wissenschaft und Politik |
| Brauer, Uwe | Private Sector + Industrial Associations | Male | Germany | Planetary Sunshade Foundation |
| Brickett, Lynn | Government + Intergovernmental Organizations | Female | United States | Department of Energy, USA |
| Briggs, Chad | Universities + Research Institutes | Male | USA | University of Alaska, Anchorage |
| Brown, Marilyn | Universities + Research Institutes | Female | USA | Georgia Institute of Technology |
| Bruce, John | Private Sector + Industrial Associations | Male | Canada | Carbon Engineering |
| Buck, Holly Jean | Universities + Research Institutes | Female | USA | University at Buffalo |
| Burns, Wil | Universities + Research Institutes | Male | USA | American University |
| Caldeira, Ken | Universities + Research Institutes | Male | USA | Breakthrough Energy, Carnegie Institution for Sciences, and Stanford University, and Stanford University |
| Camilloni, Ines | Universities + Research Institutes | Female | Argentina | University of Buenos Aires (and Harvard University) |
| Carton, Wim | Universities + Research Institutes | Male | Sweden | Lund University |
| Centers, Ross | Private Sector + Industrial Associations | Male | Germany | Planetary Sunshades |
| Chalecki, Beth | Universities + Research Institutes | Female | USA | University of Nebraska Omaha |
| Chavez, Anthony E. | Universities + Research Institutes | Male | USA | Northern Kentucky University |
| Clarke, Leon | Universities + Research Institutes | Male | USA | University of Maryland |
| Clarke, William S. (Sev) | Private Sector + Industrial Associations | Male | Australia | Winwick Business Solutions |
| Cobo Gutiérrez, Selene | Universities + Research Institutes | Female | Switzerland | ETH Zurich |
| Cox, Emily | Universities + Research Institutes | Female | United Kingdom | Cardiff University |
| Creutzig, Felix | Universities + Research Institutes | Male | Germany | Mercator Research Institute on Global Commons and Climate Change (MCC) |
| Delina, Laurence | Universities + Research Institutes | Male | Hong Kong | Hong Kong University of Science and Technology |
| Di Marco, Leon | Private Sector + Industrial Associations | Male | United Kingdom | FSK Technology Research - Consultant |
| Dooley, Kate | Universities + Research Institutes | Female | Australia | University of Melbourne |
| Draper, Kathleen | Civil Society | Female | USA | International Biochar Initiative |
| Elliott, David | Universities + Research Institutes | Male | UK | The Open University |
| Erbay, Yorukcan | Private Sector + Industrial Associations | Male | United Kingdom | Element Energy |
| Felgenhauer, Tyler | Universities + Research Institutes | Male | USA | Duke University |
| Florin, Marie-Valentine | Universities + Research Institutes | Female | Switzerland | EPFL International Risk Governance Center (IRGC) |
| Forster, Piers | Universities + Research Institutes | Male | United Kingdom | University of Leeds |
| Frumhoff, Peter | Civil Society | Male | USA | Union of Concerned Scientists |
| Fuhrman, Jay | Government + Intergovernmental Organizations | Male | United States | Pacific Northwest National Laboratory (PNNL) |
| Fuss, Sabine | Universities + Research Institutes | Female | Germany | Mercator Research Institute on Global Commons and Climate Change (MCC) |
| Gambhir, Ajay | Universities + Research Institutes | Male | United Kingdom | Imperial College London |
| Geden, Oliver | Government + Intergovernmental Organizations | Male | Germany | German Institute for International and Security Affairs (SWP) |
| Ghosh, Arunabha | Civil Society | Male | India | Council on Energy, Environment and Water (CEEW) |
| Grant, Neil | Universities + Research Institutes | Male | United Kingdom | Imperial College London |
| Gruebler, Arnulf | Universities + Research Institutes | Male | Austria | International Institute for Applied Systems Analysis (IIASA) |
| Guillen Gosalbez, Gonzalo | Universities + Research Institutes | Male | Switzerland | ETH Zurich |
| Haberl, Helmut | Universities + Research Institutes | Male | Germany | BOKU Vienna |
| Haigh, Joanna | Universities + Research Institutes | Female | United Kingdom | Imperial College London/Grantham Institute |
| Hamilton, Clive | Universities + Research Institutes | Male | Australia | Charles Stewart University |
| Hartmann, Jens | Universities + Research Institutes | Male | Germany | University of Hamburg |
| Hawkes, Adam D. | Universities + Research Institutes | Male | United Kingdom | Imperial College London |
| Healey, Peter | Universities + Research Institutes | Male | United Kingdom | Oxford University |
| Heap, Richard | Civil Society | Male | United Kingdom | Carbon Removal Centre, Foresight Transitions |
| Hepburn, Cameron | Universities + Research Institutes | Male | United Kingdom | Oxford University |
| Herzog, Howard | Universities + Research Institutes | Male | United States | MIT |
| Heyen, Daniel | Universities + Research Institutes | Male | Germany | TU Kaiserslautern |
| Heyward, Clare | Universities + Research Institutes | Female | Norway | UiT - the Arctic University of Tromso |
| Honegger, Matthias | Universities + Research Institutes | Male | Germany | Perspectives Climate Group |

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**Table A1** (*continued*)

| Name | Actor type | Gender | Country | Institution |
|---|---|---|---|---|
| Horton, Joshua B. | Universities + Research Institutes | Male | USA | Harvard University |
| Irvine, Pete | Universities + Research Institutes | Male | United Kingdom | University College London |
| Jinnah, Sikina | Universities + Research Institutes | Female | USA | UC Santa Cruz |
| Johnson, Les | Government + Intergovernmental Organizations | Male | USA | NASA Marshall Space Flight Center |
| Kammen, Daniel | Universities + Research Institutes | Male | USA | UC Berkeley |
| Karami, Khalil | Universities + Research Institutes | Male | Slovenia/ Germany | University of Ljubljana/University of Leipzig |
| Karlsberg Schaffer, Madeleine | Civil Society | Female | USA | SilverLining |
| Keller, David | Universities + Research Institutes | Male | Germany | GEOMAR - Helmholtz Centre for Ocean Research Kiel |
| Keller, Klaus | Universities + Research Institutes | Male | USA | Penn State University |
| Kravitz, Ben | Universities + Research Institutes | Male | USA | Indiana University |
| Kruger, Tim | Private Sector + Industrial Associations | Male | UK | Origen Power |
| Kuswanto, Heri | Universities + Research Institutes | Male | Indonesia | Institut Teknologi Sepuluh Nopember |
| Lawrence, Mark | Universities + Research Institutes | Male | Germany | Institute for Advanced Sustainability Studies |
| Lehmann, Johannes | Universities + Research Institutes | Male | USA | Cornell University |
| Lenton, Andrew | Government + Intergovernmental Organizations | Male | Australia | CSIRO |
| Lin, Albert | Universities + Research Institutes | Male | USA | UC Davis |
| MacMartin, Doug | Universities + Research Institutes | Male | USA | Cornell University |
| Mahajan, Aseem | Universities + Research Institutes | Male | United States | Harvard University |
| Malik, Abdul | Universities + Research Institutes | Male | Saudi Arabia | King Abdullah University of Science and Technology (formerly Grantham Institute) |
| McLaren, Duncan | Universities + Research Institutes | Male | United Kingdom | Lancaster University |
| Mengis, Nadine | Universities + Research Institutes | Female | Germany | GEOMAR - Helmholtz Centre for Ocean Research Kiel |
| Merk, Christine | Universities + Research Institutes | Female | Germany | Kiel Institute for the World Economy |
| Michaelowa, Axel | Universities + Research Institutes/Private Sector + Industrial Associations | Male | Switzerland | University of Zurich/Perspectives Climate Group |
| Montserrat, Francesc | Universities + Research Institutes | Male | Netherlands | Project Vesta, Royal Boskalis Westminster N.V. |
| Moore, John | Universities + Research Institutes | Male | Finland | University of Lapland/Arctic Centre |
| Moreno-Cruz, Juan | Universities + Research Institutes | Male | Canada | University of Waterloo |
| Morrow, David | Universities + Research Institutes | Male | USA | American University |
| Muri, Helene | Universities + Research Institutes | Female | Norway | Norwegian University of Science and Technology (NTNU) |
| Obersteiner, Michael | Universities + Research Institutes | Male | United Kingdom | Oxford University |
| Odoulami, Romaric | Universities + Research Institutes | Male | South Africa | University of Cape Town |
| Parker, Andy | Civil Society | Male | UK | SRM Governance initiative |
| Parson, Edward ‘Ted’ A. | Universities + Research Institutes | Male | USA | UCLA |
| Pasztor, Janos | Civil Society | Male | Switzerland | Carnegie Climate Governance Initiative |
| Pidgeon, Nick | Universities + Research Institutes | Male | United Kingdom | Cardiff University |
| Pinto, Izidine | Universities + Research Institutes | Male | South Africa | University of Cape Town |
| Pongratz, Julia | Universities + Research Institutes | Female | Germany | University of Munich |
| Preston Aragonès, Mark | Civil Society | Male | Norway | Bellona Foundation |
| Rahman, Mohammed Mofizur | Universities + Research Institutes | Male | Germany | TH Cologne - University of Applied Sciences |
| Raimi, Kaitlin T. | Universities + Research Institutes | Female | United States | University Michigan |
| Reiner, David | Universities + Research Institutes | Male | United Kingdom | Cambridge University |
| Renforth, Phil | Universities + Research Institutes | Male | United Kingdom | Heriot-Watt University |
| Reynolds, Jesse | Universities + Research Institutes | Male | USA/ Netherlands | UCLA/Independent Consultant |
| Rickels, Wilfried | Universities + Research Institutes | Male | Germany | Kiel Institute |
| Robock, Alan | Universities + Research Institutes | Male | USA | Rutgers University |
| Rothman, Dale | Universities + Research Institutes | Male | USA | University of Denver |
| Rouse, Paul | Universities + Research Institutes | Male | United Kingdom | University of Southampton |
| Schleussner, Carl | Civil Society | Male | USA | Climate Analytics |
| Schmidt, Joern | Universities + Research Institutes | Male | Germany | Kiel Institute |
| Schneider, Linda | Civil Society | Female | Germany | Heinrich Boell Foundation |
| Scott, Vivian | Universities + Research Institutes | Male | United Kingdom | Edinburgh University |
| Simonelli, Lucia | Civil Society | Female | United States | Carbon 180 |
| Smith, Pete | Universities + Research Institutes | Male | United Kingdom | University of Aberdeen |
| Smith, Steve | Universities + Research Institutes | Male | United Kingdom | Oxford University |
| Smith, Wake | Universities + Research Institutes | Male | USA | Harvard University |
| Spangenberg, Joachim | Universities + Research Institutes | Male | Germany | Sustainable Europe Research Institute SERI Germany e.V |
| Stephens, Jennie | Universities + Research Institutes | Female | USA | Northeastern University |
| Stoefs, Wijnand | Civil Society | Male | Belgium | Carbon Market Watch |
| Sugiyama, Masahiro | Universities + Research Institutes | Male | Japan | University Tokyo |
| Sunny, Nixon | Universities + Research Institutes | Male | United Kingdom | Imperial College London |

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**Table A1** (*continued*)

| Name | Actor type | Gender | Country | Institution |
|---|---|---|---|---|
| Surprise, Kevin | Universities + Research Institutes | Male | USA | Mount Holyoke College |
| van Vuuren, Detlef | Government + Intergovernmental Organizations | Male | Netherlands | PBL Netherlands Environmental Assessment Agency |
| Vaughan, Nem | Universities + Research Institutes | Female | United Kingdom | University of East Anglia |
| Victor, David | Universities + Research Institutes | Male | USA | UC San Diego |
| Vivian, Chris | Government + Intergovernmental Organizations | Male | UK | GESAMP |
| Wagner, Gernot | Universities + Research Institutes | Male | USA | NYU |
| Wolske, Kimberly S. | Universities + Research Institutes | Female | United States | University Chicago |
| Wood, Robert | Universities + Research Institutes | Male | USA | University of Washington |
| Workman, Mark | Universities + Research Institutes | Male | UK | Energy Futures Lab, Imperial College London |

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