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Two problems or one? Climate engineering and conceptual disaggregation

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ABSTRACT

The term "climate engineering" is an ambiguous label for two categories of technologies for mediating global warming, Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM). Whether CDR and SRM should be grouped together under a common umbrella term, or whether they should be treated as two disparate problems in need of disparate solutions, has long been a matter of debate. This paper first provides an empirical analysis of disaggregation. Topic modelling the scientific literature on climate engineering, I highlight a trend towards disaggregation driven by growth in the specialized literature on CDR. Second, I explore inconsistencies in the theoretical rationale for disaggregation and challenges in its practical implications. Third, I elaborate on the theoretical and practical utility of maintaining an integrated concept of climate engineering for highlighting the challenges of governing large-scale, hypothetical technological interventions into the climate system subject to deep uncertainties and mitigation deterrence.

1. Introduction

Climate engineering, or geoengineering, traditionally refers to a suite of techniques for the large-scale intervention into the global climate system to moderate global warming and its effects (National Academies, 1992; Royal Society, 2009; CBD, 2016). Since the 1990s, the academic debate on climate engineering has been characterized by a certain uneasiness and ambiguity due to the scope of the concept, which comprises a range of proposed methods that cut across the categories of Carbon Dioxide Removal (CDR) and Solar Radiation Modification (SRM). Whereas CDR reduces global warming via the large-scale and long-term removal of atmospheric carbon dioxide, SRM would redirect a small fraction of incoming sunlight to reduce or stop global average surface temperature increases regardless of the level of atmospheric greenhouse gas concentrations.

From the beginning of the debate, the integration of CDR and SRM into an umbrella concept of climate engineering has been debated and contested. This paper critically explores what I refer to as conceptual disaggregation in the climate engineering discourse: the analytical differentiation between CDR and SRM as distinct technological fields characterized by different problem structures, collective action problems and governance implications (e.g. Heyward, 2013; Jinnah and Nicholson, 2019a; Jinnah et al., 2021), also manifesting itself as the exclusive use of the term climate engineering for referring to SRM, but not CDR (Long et al., 2015). Disaggregation, based on differences in the ways that CDR and SRM act on the climate system, initially emerged as a historical contingency (see Möller, 2021). More recently, a tendency to frame CDR as a form of mitigation (see Honegger et al., 2021a) lends further support to its separation from SRM and the umbrella term of climate engineering.

This text provides an empirical assessment and critical theoretical reflection on conceptual disaggregation in the climate engineering debate. The starting point is that political problems are contingent outcomes of complex processes of social construction rather than inevitable results of objective, material factors (Allan, 2017). The disaggregation of climate engineering into two distinct political problems has become commonsensical in the contemporary debate. Since the adoption of the Paris Climate Agreement in 2015, CDR and SRM have followed distinct political and economic trajectories, as the former has increasingly become part of the climate policy mainstream (Anderson and Peters, 2016), attracting considerable public and private funding in the process. In contrast, SRM has become the subject of considerable controversy, with some scholars recently calling for an international moratorium (Biermann et al., 2022).

This text contributes empirically and conceptually to this broader debate. *First*, using machine-learning techniques, I show a tendency towards disaggregation in the scientific literature over the past decade, primarily driven by considerable growth in the specialized literature on CDR. *Second*, I argue that disaggregation entails overestimation of homogeneity within the SRM and CDR categories respectively; that it fails to account for the cognitive and political functions of umbrella terms; and that it enables a mischaracterization of CDR as relatively benign

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when compared to SRM. *Third*, I elaborate on the comparative theoretical and political utility of an integrated conceptualization under the umbrella term "climate engineering". This entails a shift from mechanisms of action as a differentiating factor to scale of intervention as a unifying element. It highlights problems of governance and governability for uncertain and large-scale technological responses to climate change prone to deter emission reduction efforts. Understanding climate engineering as one single problem may also facilitate governance integration towards greater fairness and effectiveness in international cooperative outcomes.

Section 2 provides an overview of the debate over integration versus disaggregation. Section 3 presents the empirical findings of the topic model. Section 4 elaborates weaknesses in the theoretical rationale for disaggregation and problems of conceptual implications. Conversely, section 5 makes the case for conceptual integration. Section 6 concludes.

2. The debate over disaggregation versus integration

From its beginnings, the academic debate on climate engineering has struggled with the problem of different technologies that differ in purposes, modes of action, risk profiles and other characteristics being subsumed under a single concept. The concept of climate engineering has itself been defined in various ways: as "large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry" (National Academies, 1992: 433); as "a deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts" (CBD, 2016: 8); as "large-scale efforts to diminish climate change resulting from greenhouse gases that have already been released to the atmosphere" (Caldeira et al., 2013: 232); or as methods for intervening in the climate system "by deliberately modifying the Earth's energy balance to reduce increases of temperature and eventually stabilise temperature at a lower level than would otherwise be attained" (Royal Society, 2009: 1). Despite some actors' attempts to frame certain technique as natural or nature-based (Low et al., 2022), climate engineering is distinctly technological in character, including when leveraging components of the natural environment for potential beneficial climate impacts (see Markusson, 2022).

While these and other definitions vary in their nuances, climate engineering is widely understood as defined by two key elements: scale and intentionality (e.g. Keith, 2000: 247; Bellamy et al., 2012). Methods for climate engineering would operate at the level of the Earth system, setting them apart from sectoral solutions for addressing climate change such as carbon capture and storage-based solutions for residual industrial greenhouse gas emissions. Large-scale interference with the Earth system would, moreover, be an intentional act aimed at climate stabilization, thus being different from *unintentional* large-scale interventions, notably anthropogenic greenhouse gas emissions themselves that produce global warming as a side-effect of fossil-fueled development. While useful for conceptual orientation, both scale and intent can run into problems. Sub-global SRM schemes have been proposed for protecting regional marine biodiversity from global warming (McDonald et al., 2019) or for re-freezing the Arctic (Field et al., 2018), with neither scheme being akin to a global intervention with the climate system. Similarly, CDR can be implemented by hooking up existing biomass flows with technology for carbon capture and storage, at much lower scales than proposed global deployment of bioenergy with carbon capture and storage (BECCS) for implementing negative emissions at the Gigaton-scale. Judging by the criteria of scale and intentionality, neither regional SRM deployment nor limited retrofits of biomass installations with carbon capture and storage would qualify as "climate engineering". Even for field trials exploring the impacts and viability of different techniques, the label of climate engineering is problematic due to the limited scale and the lack of intent to interfere in the climate system (see Low et al., 2022) Whether the scale and intentionality behind the global deployment of climate engineering methods is of a categorically different nature than the scale and intentionality behind a global phase-down of greenhouse gas emissions is a further issue where perspectives can diverge (see Reynolds, 2021: 133).

The definition of climate engineering via scale and intent is thus not without flaws. The parallels (or imperfect analogies) that undoubtedly exist between CDR and SRM in terms of their scale and intent informed the emergence and broad diffusion of an integrated concept of climate engineering starting in the late 1990s. The uneasy relationship between the two categories came to the forefront in the context of the 2009 Royal Society report on science, governance and uncertainty. This report prominently distinguished between CDR and SRM as different classes of climate engineering but emphasized "major differences in their modes of action, the timescales over which they are effective, temperature effects and other consequences, so that they are generally best considered separately" (Royal Society, 2009: ix) - a choice that appears to have been a matter of some dispute in the scientific deliberations preceding publication (Möller, 2021: 25–26). Others subsequently echoed the Royal Society's sentiment, with one observer noting that, in light of their differences, "it is puzzling why CDR and SRM are brought together and discussed under the name of 'geoengineering'" (Heyward, 2013: 23; see also Bellamy et al., 2012).

While the inclusion of CDR and SRM under the umbrella concept of climate engineering has been a matter of debate from the outset, the past decade has seen an intensifying tendency towards their disconnection, as I will substantiate in section 3 below. Increasingly, scholars emphasize the distinctness of the two technological fields as well as the differences in their risk profiles, political problem structures and governance challenges. Jinnah and Nicholson (2019a: 385), for instance, argue in favor of categorical demarcation "largely because the governance and other challenges associated with SRM tend to be markedly different from those associated with CDR" (ibid.). A similar argument for conceptual splitting has been proposed based on differences in the problem structures that characterize CDR and SRM, translating into differences in associated collective action problems and governance challenges (Jinnah et al., 2021). Others are conceiving of CDR as a form of mitigation (Honegger et al., 2021a; Heyward, 2013: 23), bringing it conceptually closer to greenhouse gas emissions reduction than to SRM. Still others are reserving the term climate engineering for SRM, similarly accentuating the conceptual disconnect from CDR (Long et al., 2015).

One major driver of the emerging conceptual split is the normalization of CDR as integral part of emissions pathways that are consistent with the long-term temperature targets of the 2015 Paris Agreement and would "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Paris Agreement, Article 4.1). Whereas the need for future SRM deployment is not entirely obvious at present, large-scale CDR is baked into the long-term climate strategies of virtually all major political actors (Anderson and Peters, 2016; Hale et al., 2022). Similar to how the life sciences industry separated pharmaceutical-from agricultural biotechnology to avoid contamination with the genetically-modified food controversies of the late 1990s (Falkner, 2009: 245–246), the separation of CDR and SRM would thus prevent negative spillovers from a group of technologies framed as risky, uncontrollable and dangerous to a group of technologies framed as comparatively benign (see Möller, 2021: 25). In addition, there appears to be a tendency among developers of field experiments with various types of CDR and SRM techniques to reject the climate engineering/geoengineering label altogether to preempt controversy and contestation (Low et al., 2022).

3. Topic modeling the climate engineering debate

Although conceptual disaggregation has been widely debated for more than two decades, there are no empirical attempts so far to measure its extent and to gauge its historical trajectory. This section provides such an empirical analysis for assessing the practical relevance of the conceptual argument for the academic literature. Specifically, I estimate a keyword-assisted topic model (keyATM) to substantiate the empirical scope of conceptual disaggregation and its changes over time. Topic models are a class of statistical methods for identifying latent semantic structures across large bodies of text (see Churchill and Singh, 2022). At their core, they assume that such semantic structures can be represented as terms that cluster into specific topics; and that documents vary in the extent to which they express various such topics. Topic models thus have two primary components: a topic-term matrix capturing the strength with which each term in the corpus is associated with each topic; and a document-topic matrix that represents the way in which topics are distributed across all documents in the corpus. KeyATMs allow for the specification of keywords associated with different topics prior to model estimation (Eshima et al., 2023). Where the latent semantic structure of a given corpus is partially already known, this in principle allows better performance than with other types of topic models.

The data for the analysis below consists of 1760 abstracts of articles published in scientific journals between 1992 and July 2023. These articles were identified using a search for the expressions “climate engineering”, “geoengineering”, “solar radiation management”, “solar radiation modification”, “albedo modification”, “carbon dioxide removal” or “negative emissions technolog*" in the Web of Science core collection, manually removing irrelevant entries such as on carbon dioxide removal in respiratory medicine or geoengineering in the mining industry. Prior to modelling, I apply a standard pre-processing pipeline consisting of corrections, concatenation of common expressions, removal of stopwords and punctuation, lemmatization and removal of sparse terms. I estimate the model by seeding three topics with terms respectively associated with CDR (e.g. “negative emissions” or “direct air capture”), SRM (e.g. “stratospheric aerosol injections” or “aerosol geoengineering”) as well as with climate engineering in a general sense (e.g. synonyms such as “geoengineering” or “climate-related geoengineering” but also the terms “scale”, “intentional” and “deliberate” as central semantic elements of most conventional definitions of climate engineering). Keywords have been chosen both manually and by running an exploratory Latent Dirichlet Allocation model on a random subset of the corpus. I include a fourth, non-keyword topic in the model to capture semantic unrelated to SRM, CDR or climate engineering in general. Table 1 presents high-probability terms associated with each of those three topics as well as the respective keywords used for seeding the model. Inspection of the texts most-strongly associated with SRM, CDR and climate engineering, respectively, shows that semantic content strongly aligns with the topical structure identified by the model.

The upper panel of Fig. 1 below shows changes in topic prevalence across the corpus over time.[1] The “general” climate engineering topic increases in prevalence until about 2015, remains approximately constant until 2020 and then declines slightly. The prevalence of SRM declines continuously throughout the entire period. Conversely, the CDR topic increases strongly in prominence from 2017 onwards. The middle- and bottom panels show the annual density distributions of the CDR- and SRM topics over documents. Where distributions skew to the right, the respective topic is being addressed, at the level of different texts, in conjunction with other topics. Where distributions skew to the left, texts tend to primarily, or predominantly, center on either CDR or SRM, with limited inclusion of other topics. Interestingly, discussions of CDR and SRM appear to evolve into different directions: Whereas the literature on SRM becomes less specific and more accommodating of other topics over time, the debate on CDR has moved towards greater specialization, with academic publications increasingly tending to address CDR without reference to SRM, climate engineering in general or residual, miscellaneous issues.

This analysis shows a) that there is a measurable tendency towards conceptual disaggregation in the academic debate on climate engineering; b) that this tendency is driven exclusively by growth in the specialized academic literature on CDR; and c) that this specialized literature in increasingly dominant in the academic discourse on climate engineering. In the following two sections, I develop several considerations on why the tendency towards disaggregation may warrant deeper conceptual reflections, both in terms of its theoretical rationale as well as its practical consequences.

4. The case against disaggregation

While the umbrella term “climate engineering” has been contested practically from its very origins, the analysis in the previous section shows that recent years have been marked by a gradual shift from an integrated conceptualization to a disaggregated one. The theoretical reason for disaggregation is primarily in the different ways in which CDR and SRM would operate on the climate system. The practical implications of disaggregation are to consider CDR and SRM as distinct governance challenges: whereas CDR is typically considered a collective action problem associated with the supply of global public goods, SRM is associated with the freedriver problem of preventing potential unilateral deployment from a single state or a small number thereof (see Jinnah and Nicholson, 2019a; Jinnah et al., 2021; Maher and Symons, 2022).

The disaggregated conceptualization that draws a categorical distinction between SRM and CDR is not as intuitive as it may appear. It may also encourage a bias towards risks over costs, making the bottom line of CDR appear less problematic than that of SRM. In this section, I highlight the conceptual and political challenges that come with disaggregation. This argument against *disaggregation* is, by itself, not an argument in favor of *integration*. In principle, the problems with conceptual disaggregation could also lead to the conclusion that further downwards disaggregation is required, for instance by introducing marine- and terrestrial CDR as distinct categories. They might also encourage further upwards aggregation, by conceptualizing both CDR and SRM as elements of a broader category of climate response measures that could also include, say, climate adaptation. Such alternative choices of granularity would give rise to challenges, and perhaps advantages, of their own. However, the purpose of this present section is simply to provide some critical reflections on disaggregation as the default manner of structuring the contemporary debate. This will later allow me to demonstrate more clearly the comparative advantages of maintaining “climate engineering” as an integrated umbrella concept.

4.1. Variation within and variation between categories

One chief problem with conceptual disaggregation is the underpinning assumption that the categories of CDR and SRM are more different from each other than the specific techniques subsumed under each of them. In other words: CDR and SRM are different enough to separate them but the techniques within each category are similar enough to group them together. At an abstract, there undoubtedly major differences in the respective problem structures of CDR and SRM, linked to the differences in the way that they would operate on the climate system (see Zürn and Schäfer, 2013; Jinnah et al., 2021). But the same applies to various techniques inside of each category. BECCS, Direct Air Capture or various forms of marine carbon sequestration all operate in the same basic way, by drawing down atmospheric carbon dioxide and storing it in perpetuity. But this is almost where the similarities end. BECCS is poised to cause major impacts on the global land system, food production and biodiversity. Direct Air Capture requires major financial investments yet allows for an extremely high degree of geographical centralization. Marine CDR in the form of ocean fertilization or ocean liming is very likely to cause adverse impacts on marine biodiversity. Carbon storage in subsoil geological formations requires specific forms

[1] Fig. 1 shows data from 2008 onwards. Prior to 2008, the number of annual publications in the dataset hovers in the low single digits so that single publications have considerable influence on aggregate topic prevalence and the distributions of topics over documents.

Table 1
Keywords and topic-term associations. Multiword expressions such as "carbon dioxide" or "climate change" were concatenated during model estimation to treat them as single terms (rather than multi-term expressions). Occurrences of "SRM" and "CDR" were de-acronymized.

	SRM	CDR	Climate engineering (general)
Keywords	Albedo modification, solar radiation management, solar radiation modification, solar geoengineering, stratospheric aerosol injections, marine cloud brightening, aerosol*, aerosol geoengineering, cirrus cloud thinning, ship-wake brightening, space mirrors, reflect, sunlight, cloud	Carbon dioxide removal, negative emissions technologies, negative emissions, beccs, direct air capture, ocean fertilization, ocean iron fertilization, ocean liming, carbon capture and storage, carbon storage, carbon removal, greenhouse gas removal, biochar, direct air carbon capture and storage, enhanced weathering, ocean alkalinity enhancement, energy, gas, biomass, soil, plant, capture, sequestration	Geoengineering, climate engineering, climate geoengineering, climate-related geoengineering, scale, intentional, deliberate
Non-keyword top terms by probability	Climate, temperature, change, geoengineering, global, effect, response, stratospheric, surface, increase, force, reduce, injection	Carbon dioxide, emission, net, system, cost, potential, technology, low, use	Climate, climate change, research, policy, technology, risk, mitigation, future, global, governance, deployment, approach

of risk assessment and risk management to address potential leakage or migration. The political challenges and corresponding governance solutions differ considerably.

The same applies for SRM. Stratospheric Aerosol Injections strongly lend themselves towards unilateral action due to their relative ease of implementation. This can raise concerns from a perspective of international security (e.g. Parker et al., 2018; Young, 2023). Marine Cloud Brightening, in contrast, requires complex and highly visible global shipping operations that are accordingly easy to disrupt. The security implications of Stratospheric Aerosol Injections thus do not exist for Marine Cloud Brightening. The problem of potential unilateral implementation posed by Stratospheric Aerosol Injections is, conversely, much more similar to the case of marine CDR techniques such as ocean fertilization, than it is to other techniques within the category of SRM (see Rabitz, 2016).

Another important differentiating criterion in the category of SRM is the emergence, in recent years, of proposed regional applications. These do not aim to influence global average surface temperatures but rather seek to mitigate regional environmental impacts caused by climate change. Marine Cloud Brightening is being considered for shielding the Australian Great Barrier Reef from increases in regional sea temperature (McDonald et al., 2019). This proposed use would make the technique more of an instrument for biodiversity policy than for climate policy. The use of Marine Cloud Brightening and other SRM techniques is also being explored for the restoration of Arctic ice cover (Field et al., 2018). Such regional SRM schemes are bound to have drastically different problem structures, as well as governance implications, than global SRM schemes aimed at slowing down or halting anthropogenic global warming as such. On one hand, this could justify greater granularity and introduction of further categorical divisions. On the other hand, it shows that some forms of upwards aggregation are already taking place without receiving nearly the level of scrutiny as the upward aggregation of CDR and SRM into an umbrella concept of "climate engineering".

From a governance perspective, the organization of CDR and SRM into neat and distinct categories is thus not a foregone conclusion. In effect, it risks trivializing the considerable differences in the governance implications associated with different techniques inside of the two categories. We may question whether, say, ocean fertilization has governance implications that are considerably more different from Marine Cloud Brightening than they are from Direct Air Capture. In fact, within each category, there is considerable variation in factors shaping the respective governance problem. In both categories, some techniques allow for centralized implementation by a single or a small number of actors (thus raising problems of free-driving); while others would require distributed implementation (with potential global deployment thus hinging on international cooperation). The existence of such fundamental differences in the collective action problems that are associated with different techniques in either category highlights the limited utility of disaggregation from a governance perspective.

4.2. *The function of umbrella terms*

The second inconsistency in the theoretical rationale for conceptual disaggregation is closely related: due to the categorical differences between CDR and SRM, the use of "climate engineering" as an umbrella term is considered inappropriate or inaccurate. Yet this misrepresents the function that umbrella terms play in the political and scientific discourse. One major study on the role of umbrella terms considers them essential for linking "research areas and directions […] with a view to relating them, as a whole, to certain societal concerns and policy issues" (Rip and Voβ, 2013: 40). Umbrella terms do not *need* to capture phenomena with a high degree of similarity to each other. Adaptation and mitigation, for instance, refer to profoundly different types of activities that differ considerably in their problem structures and governance implications. Both, however, are conventionally understood as constitutive elements of the umbrella term "climate policy". Intuitively, the utility of abandoning the term "climate policy" in order to treat mitigation and adaptation as disparate problems with disparate solutions seems to be limited. Similarly, it is mistaken to assume that differences in the way that CDR and SRM would operate on the climate system would preclude their integration into an umbrella term of "climate engineering". Interestingly, Möller (2021: 26) observes that it is the very distinction between CDR and SRM, popularized by the Royal Society (2009) report, due to which "the main defining aspect of geoengineering - scale - became obscured by the microlevel mechanisms of carbon sequestration and reflectivity potential".

Hirsch and Levin (1999) propose a life-cycle model of umbrella terms which is driven by conflicts between, on one hand, proponents of broad and inclusive conceptualizations and, on the other, "more methodologically oriented researchers who call for narrower perspectives that conform to more rigorous standards of validity and reliability", also termed the "validity police" (ibid.: 200). In this model, umbrella terms can provide cognitive structure to fields that consist of multitudes of complex and fast-moving processes. Politically, umbrella terms can facilitate the building of bridges between research communities while also facilitating the creation of linkages with real-world policy priorities. Hirsch and Levin (ibid.) propose that the stability of umbrella terms is shaped by their academic-as well as non-academic constituencies. A possible corollary is that the trend towards conceptual disaggregation in the climate engineering debate is driven by the emergence of (commercial and other) constituencies with vested interests in CDR seeking to insulate themselves from the controversies surrounding SRM. I return to this latter point in the conclusions to this text. What the above considerations show, though, is that the use of umbrella terms is not constrained by apparent dissimilarities among their constituent elements.

4.3. *Risks and costs*

While the previous two subsections addressed inconsistencies in the

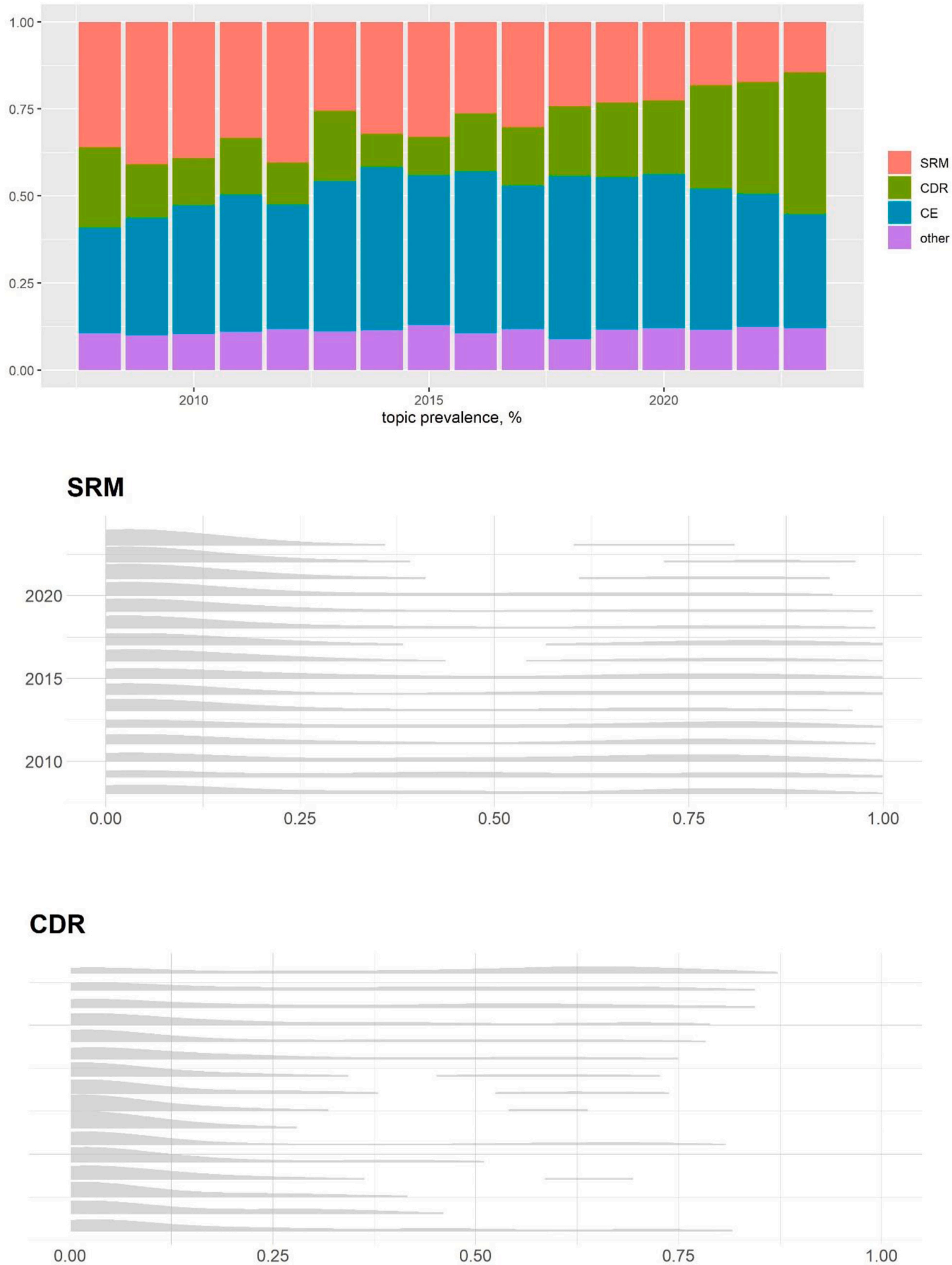

Fig. 1. Changes in topic prevalence over time (top), ridgeline plots of topic density distributions per year (middle and bottom).

theoretical rationale for conceptual disaggregation, there is also a crucial practical consequence: a bias towards risks over costs. The framing that emerges from disaggregation is that, despite its various social, economic and environmental challenges, CDR is relatively benign when compared to SRM (Möller, 2021: 25). Through disaggregation, the problem of large-scale technological intervention into the Earth system which is at the core of the climate engineering concept is replaced by the separate problems of carbon drawdown and albedo modification. It also enables the whitewashing of CDR by overemphasizing differences to the aggregate adverse impacts of SRM: stressing the different characteristics of CDR and SRM facilitates stressing differences in the nature and magnitude of their respective effects, a phenomenon that has similarly been observed in the biotechnology debates of the 1990s (Falkner, 2009).

Risks, including those of a fat-tailed nature, are arguably at the center of the academic discussion on SRM. Relevant risks include catastrophic impacts from the sudden discontinuation of a global deployment scheme (so-called termination shock); disruption of global precipitation patterns; and political risks in global decision-making on SRM (Biermann et al., 2022). The likely scope of such risks is a matter of some debate (Reynolds et al., 2016). Yet they are frequently drawn upon to justify caution, or even opposition, to the very idea of deploying SRM for the mitigation of global warming. This is not the case for the diverse and considerable social-, environmental- and economic costs that large-scale CDR would entail. There is, to be sure, broad discussion and even skepticism about specific CDR techniques. BECCS would likely entail significantly adverse impacts on the global land-system, including on food production and biodiversity (see Low and Schäfer, 2020). Marine CDR would likely cause substantial harm for marine biodiversity. Direct Air Capture, finally, could indirectly lead to widespread harm due to the scale of the required industrial infrastructure and due to changes in global material flows (Madhu et al., 2021; Qiu et al., 2022). While the risks of SRM frequently disqualify it from serious consideration, CDR is a centerpiece of global climate policy despite the magnitude of its various associated costs (Anderson and Peters, 2016).

No meaningful efforts have so far been undertaken to systematically compare SRM-associated risks with CDR-associated costs. Conceptual disaggregation based on mechanisms-of-action, rather than an integrated concept based on scale-of-intervention (see below), could well obfuscate that differences in the aggregate adverse impacts of CDR and SRM are considerably smaller than commonly assumed. Splitting climate engineering into two separate problems does not help in answering questions such as why, for instance, shifts in global precipitation patterns should preclude deployment of some SRM techniques whereas the large-scale adverse land-system impacts associated with BECCS should *not* automatically disqualify it from being considered for inclusion in the global climate technology portfolio. Integration, in other words, may be a necessary condition for the robust assessment of the comparative advantages and drawbacks of technological options across the SRM-CDR divide.

5. The case for integration

While the previous section highlighted challenges with disaggregation as the default contemporary approach, this section elaborates on the utility of maintaining climate engineering as an integrated concept. The advantage of such a conceptualization is to highlight governance and governability challenges of speculative, large-scale technological interventions into the climate system subject to a variety of uncertainties and prone to generate mitigation deterrence. Politically, it highlights the need for a comprehensive governance approach to climate engineering linked to the international climate regime and in accordance with overarching considerations on precaution and anticipation.

5.1. Scale of intervention

An integrated concept of climate engineering shifts the analytical focus from mechanisms of action (interfering with the carbon cycle versus manipulating planetary albedo) as *differentiating* factors to scale of intervention as a *unifying* factor (see Möller, 2021). The constitutive role of scale has been acknowledged throughout the debate (e.g. Keith, 2000; Bellamy et al., 2012; Caldeira et al., 2013). Placing scale center stage highlights the unprecedented degree of intentional interference in the Earth system which climate engineering technologies, whether CDR or SRM, would present. Scale is not just a numerical question of how many BECCS plants are in operation or how many vessels are spraying nanometer-sized water droplets for marine cloud brightening. Climate engineering at a "large" scale would mean the existence of a global *system* composed of material and non-material infrastructure geared towards targeted interference with the climate system. This is why scale is not fully independent from intentionality.

This situates the political problem of climate engineering in the context of wider (and older) discussions on the capacity limits of human organizations when dealing with complex socio-technical systems (e.g. Luhmann, 1997; Perrow, 1999). It also connects to limitations situated at the individual level, such as hubris in a moral sense (Hamilton, 2013; Preston, 2013: 26; Owen, 2014) or illusions-of-control in a social-psychological one (e.g. Langer, 1975). Some authors argue that contemporary debates on climate engineering link to broader historical and cultural ideas, aspirations and collective imaginations about human mastery of nature (Oomen and Meiske, 2021). Conceptualizing climate engineering in terms of scale of intervention thus situates the political problem in the limitations that humans and human organizations face when attempting to direct complex socio-technical arrangements towards collectively desirable ends. The problem is then less about how different categories of technology would operate on the global climate system; and more about how these limitations to political steering capacities might be overcome.

Some authors have expressed skepticism towards the alleged singular role that scale plays for climate engineering, emphasizing how climate mitigation and adaptation may cause impacts at comparable scales (Heyward, 2013: 24). Against this, Reynolds cautions that efforts seeking "to end ongoing unintentional interventions in Earth systems" may not necessarily amount to interventions themselves (Reynolds, 2021: 133). The key difference, in other words, is that climate engineering constitutes a large-scale intervention into the climate system whereas global mitigation amounts to large-scale efforts at reducing the climate impacts of anthropogenic greenhouse gas emissions. One interferes in nature whereas the other seeks to halt interference and there is limited analytical value in their conflation.

5.2. Silver bullets and mitigation deterrence

The shared risk of mitigation deterrence associated with both CDR and SRM provides another important rationale for an integrated concept of climate engineering (e.g. McLaren, 2016; Markusson et al., 2018; Carton et al., 2023): Grouping CDR and SRM together under one single umbrella concept is theoretically justified because both, in addition to their shared scale-of-intervention, constitute flawed temporal substitutes, of unclear social-, environmental- and political feasibility, for deep and comprehensive global decarbonization. They continue, at a larger scale and with considerably greater risks and costs, a series of technological substitute solutions (such as carbon capture and storage or biofuels) that commanded broad attention during the 2000s yet have decidedly failed to live up to their initial hype (Low and Boettcher, 2020). While their respective modes of operation would assign them different roles in complementing global mitigation efforts (e.g. Anderson and Peters, 2016; Asayama and Hulme, 2019), the insufficient pace of emissions abatement is the sole reason why they became objects of consideration in the first place. Conceptual integration highlights this central, shared feature which applies irrespective of the differences in how CDR and SRM act on the climate system.

Accentuating the problem of mitigation deterrence is the speculativeness of both large-scale CDR and SRM, a further major feature that provides a powerful rationale for conceptual integration. Whereas current commercial operators in CDR, particularly Direct Air Capture, stress increasing levels of technological readiness, gigaton-scale removals remain at present as hypothetical as global deployment schemes for stratospheric aerosol injections or other SRM techniques. An integrated concept of climate engineering thus ties into the problematic reliance on supposed technological silver bullets with unclear feasibility at scale, compared to conventional mitigation solutions with proven feasibility (Anderson and Peters, 2016). An important aspect of potential over-reliance on speculative technological solutions from either CDR or SRM is mitigation deterrence, widely understood as a hazard associated with both (e.g. Markusson et al., 2018; McLaren and Corry, 2021; Sovacool, 2021: 8–9; Carton et al., 2023; see also Low and Boettcher, 2020). Both CDR for achieving net zero- or net-negative greenhouse gas emissions, as well as SRM for peak-shaving for avoiding temporary temperature overshoot (Asayama and Hulme, 2019), offer potential future offsets for insufficient mitigation levels in the present. Should they eventually turn out to be infeasible at scale due to their environmental-, political- or socio-economic impacts, the consequence will be greater degrees of global warming than presently anticipated, possibly in excess of contemporary international temperature targets. This is the primary reason why climate engineering is often problematized as a techno-fix, that is, an imperfect band-aid solution to a problem with deep roots in social structure (Hamilton, 2013; Preston, 2013). The distinction between CDR, encompassing techniques framed as relatively benign and increasingly feasible at scale, and SRM, deemed comparatively malign and speculative, obscures this aspect.

5.3. Governance integration

As problem definition is prior to policy action, a major practical implication of an integrated conceptualization of climate engineering is in its facilitation of governance integration. Conceptualizing climate engineering as one single problem, namely of governing intentional and large-scale interventions into the climate system in the context of significant uncertainties as well as environmental- and sociopolitical risks, emphasizes overarching norms and principles related to precaution, risk management and anticipatory governance, and may facilitate broad-based stakeholder engagement. In other words, it places fundamental questions of governance rationales before practical questions of operationalization. An integrated governance approach based on a holistic conceptualization of climate engineering would thus be consistent with the speculative and open-ended contemporary nature of the various contemporary technological proposals.

Governance integration also extends to the role of climate engineering in international climate policy. CDR has gained considerably in relevance due to the Paris Agreement's endorsement of a global net-zero target for the second half of the 21st century. Dedicated governance structures are beginning to emerge in the context of the Paris Agreement's article 6 mechanism (see Honegger et al., 2021b). Conversely, SRM remains disconnected from the climate policy mainstream, although options exist for creating linkages to global emissions control efforts (Reynolds, 2022). In 2019, an initiative for the United Nations Environment Assembly to engage in a more robust fashion with climate engineering faltered due to disagreements on whether CDR and SRM should be treated in an integrated fashion or separately (see Jinnah and Nicholson, 2019b). SRM, but not CDR, has recently been the target of a new campaign for an international non-use agreement (Biermann et al., 2022). The question of whether to conceptualize climate engineering as one problem or two is thus not merely an academic problem but also an eminently political one. Yet the ways in which SRM and CDR are frequently being addressed as distinct problems does not always appear to be justified. An integrated conceptual approach might help overcome some of the internal inconsistencies in the scholarly- and political debate.

The corollary of conceptual disaggregation, including the implied fundamental differences in problem structure and collective action problems between CDR and SRM (Jinnah and Nicholson, 2019a; Maher and Symons, 2022) is that both require separate governance mechanisms. Conversely, while there are strong theoretical reasons for multilateral SRM governance in the context of the Paris agreement and the Framework Convention on Climate Change, its political contentiousness has left it relegated to the sidelines of international mainstream climate policy (see Nicholson et al., 2018). This difference reflects the (likely misinformed) sentiment that the environmental- and socio-political costs as well as the governance challenges of CDR are relatively benign in contrast to SRM.

6. Conclusions

The designation of CDR and SRM as elements within the larger category of “climate engineering” has always been contested and ambiguous. Legitimate analytical reasons exist to disaggregate the concept of climate engineering and to treat CDR and SRM as distinct technologies that give rise to different types of political problems and require distinct governance solutions. As this text has shown, there indeed exists a robust trend whereby the scientific literatures on SRM, and especially on CDR, are becoming increasingly specialized over approximately the past decade, with an increasing share of the literature primarily or exclusively addressing either of these technological fields rather than approaching the thematic fields in a more integrated, holistic manner. To some extent, such increasing specialization is to be expected, as the field of CDR is rapidly moving towards implementation on the ground; and as proposed SRM technologies are being placed under increasing scrutiny due to their controversial nature.

While disaggregation has been widely discussed for almost three decades, this is the first time that its extent and historical trajectory has been measured empirically. The empirical results show that disaggregation is present in a large and increasing share of the scientific literature, thus making critical conceptual reflection more urgent. Above, I have suggested disaggregation is not a foregone conclusion. Disaggregation raises challenges of its own, by misrepresenting the function of umbrella terms; by framing CDR as relatively benign compared to SRM, based on a narrow focus on risks rather than broader environmental- and socio-economic costs; and, perhaps crucially, by overestimating the differences between the various proposals within each category relative to the differences used to demarcate those categories from each other. Conversely, an integrated conceptualization of climate engineering loses granularity from giving up on mechanisms of action (carbon drawdown versus albedo modification) as the fundamental dividing line. At the same time, it draws attention to the problem of controllability of large-scale technological interventions (Perrow, 1999); to the design of public policies based on the risk of mitigation deterrence in the context of unproven assumptions about the technical, economic or social feasibility of future technological choices; and to the possibility of an integrated governance approach that could enable strong linkages with the international climate while also providing for greater procedural fairness and participation than fragmented, polycentric governance systems.

A principal value of an integrated concept of climate engineering is thus to highlight the fluidity, open-endedness and speculativeness of intentional, large-scale interventions into the climate system. The normalization which CDR has in recent years been undergoing in the public debate, its considerable technological progress as well as the immense financial resources that are being put towards its operationalization, all cannot mask the fact that the social, environmental, and economic feasibility of gigaton-scale CDR is uncertain and the associated governance challenges immense. While the *act* of atmospheric carbon removal might be conceived of as a form of mitigation by itself and thus possess some similarities to conventional climate response measures (Honegger et al., 2021a), its hypothetical large-scale implementation through technological solutions of uncertain feasibility places it in a different category from contemporary efforts to reduce greenhouse emissions. This applies especially to the extent that reliance on future large-scale CDR weakens present emission reduction commitments (see Carton et al., 2023). The same applies to SRM which, at scale, would present a similar speculative technological intervention of unclear feasibility prone to deter conventional mitigation efforts.

Maintaining both CDR and SRM under a common umbrella term of climate engineering thus highlights problems of governance and governability with complex technological systems (see Coutard, 1999; Perrow, 1999). Such an umbrella term also delineates technological solutions where feasibility at scale is uncertain (i.e. CDR and SRM) from technological solutions where it is not (e.g. terrawatt-scale renewable energy systems). From a policy-making perspective, maintaining an integrative concept of climate engineering could help to prevent overconfidence in governance capacities: If legitimate analytical reasons exist for questioning the capacity to devise fair and effective global solutions for SRM (Biermann et al., 2022), then similar skepticism is warranted regarding the ability to govern vast technological systems for carbon removal at decadal timescales while keeping unintended social, environmental and economic impacts in check. This can aggravate the problem of mitigation deterrence if insufficient governance capacities hamper CDR deployment at scale (Anderson and Peters, 2016). For both CDR and SRM, the immense challenges of finding fair, effective and environmentally safe governance solutions in the future highlight the need to guard against overconfidence in the present.

There is thus a strong case for holding on to an overarching concept of climate engineering insofar as the governance of uncertain and large-scale technological interventions is concerned. However, this does not preclude the existence of contexts in which a CDR-SRM distinction is analytically useful. Differences in the timescale of their deployment, for instance, imply that CDR requires longer (and presumably much greater) resource commitments than SRM for measurable effects on global average temperatures to materialize. CDR can address some aspects of fossil-fueled development, such as ocean acidification, which SRM cannot. The inconsistencies that I have addressed in Section 4 above do not imply a need for abandoning conceptual disaggregation as an analytical approach. When thinking about the governance of large-scale interventions into the Earth system, however, a holistic concept does a better job of emphasizing pertinent aspects related to feasibility and mitigation deterrence that are common to both CDR and SRM.

The way we define, classify and differentiate governance objects has major political ramifications (Allan, 2017; Möller, 2020) and the alleged disconnect between SRM and CDR is not an immutable fact of life but rather a result of the ways in which political- and scientific actors have constructed the wider semantic field. Current developments under the 1996 London Protocol to the 1972 London Dumping Convention show, interestingly, how actors are beginning to transcend the SRM-CDR divide by classifying specific technologies from either category under the larger umbrella term of *marine* climate engineering. Conceptualization and reconceptualization thus remain ongoing processes. The problem constructions which they give rise to have crucial practical implications. At the very least, there is a need for more critical reflection on how and why one type of technology became designated as a fact-of-life and the other as a partial taboo; and on what the precise criteria are for determining that the governance challenges associated with one type of technology, but not another, are too extreme to make its potential deployment the subject of careful consideration (Biermann et al., 2022).

CRediT authorship contribution statement

Florian Rabitz: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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

Data will be made available on request.

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