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Towards system-aware governance of marine carbon dioxide
removal: a review of interdependent challenges

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E-mail: lina.roeschel@rifs-potsdam.de**Keywords:** marine carbon dioxide removal (mCDR), ocean governance, socio–ecological–technological systems (SETs), climate policy, interdependent governance challengesSupplementary material for this article is available [online](#)**Abstract**

Marine carbon dioxide removal (mCDR) is increasingly discussed as a potential climate response, yet its governance remains underdeveloped. This study conducts a structured literature review, following the preferred reporting items for systematic reviews and meta-analyses framework, to identify and analyse governance challenges associated with mCDR within the broader context of multilateral ocean governance. Using the socio–ecological–technological systems (SETs) framework, challenges were systematically coded to capture interdependencies across social, ecological, and technological (S/E/T) domains. The analysis of 35 peer-reviewed publications identified 100 distinct governance challenges, revealing that most cannot be categorised within single-system domains. Instead, challenges frequently span intersections between S/E/T systems, highlighting issues such as fragmented governance structures, ecological risks from technological interventions, and legitimacy concerns linked to deployment. These findings underscore the systemic nature of mCDR governance challenges and the limitations of siloed governance approaches. The study demonstrates that applying a SETs perspective enables the identification of cross-domain trade-offs, synergies, and coordination gaps, supporting the development of system-aware governance frameworks for mCDR.

1. Introduction

Marine carbon dioxide removal (mCDR) has emerged as a potential strategy to support global climate mitigation, particularly in scenarios aiming to reach net-zero emissions and sustain long-term net-negative emissions (IPCC 2018). By enhancing the ocean's natural capacity to sequester carbon, mCDR could help offset residual emissions and draw down atmospheric CO₂. A variety of approaches are under consideration, including ocean fertilisation, ocean alkalinity enhancement, artificial upwelling and biomass sinking, each with distinct potentials, uncertainties and ecological interactions (NASEM2022, Oschlies *et al* 2025). However, while these approaches could play a meaningful role in addressing climate change, their potential deployment has far-reaching governance questions that extend beyond environmental risk to encompass institutional readiness, ethical legitimacy, and societal acceptance (Doney *et al* 2025). As a suite of novel and largely untested interventions in a highly dynamic and transboundary

environment, mCDR challenges the capacity of existing governance frameworks to respond in a timely, coordinated, and equitable manner.

Despite growing interest, regulatory and governance frameworks have struggled to keep pace with the potential scale, diversity and complexity of mCDR approaches, reflecting a readiness gap in governance institutions and frameworks (Cooley *et al* 2023, Webb 2024). Existing governance arrangements, particularly those under multilateral ocean regimes, were not designed for interventions that operate at the intersection of marine ecosystems, emerging technologies, and global climate targets. This gap is most evident in the London Convention and Protocol (LC/LP)¹, administered by the International Maritime Organisation, which currently serves as the

¹ The 1972 Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and the 1996 Protocol on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Protocol) are generally referred to as a treaty complex (LC/LP).

principal legal regime for marine geoengineering. Since 2008, the scope of the LC/LP has expanded in response to environmental and health concerns, particularly around ocean fertilisation (Fuentes-George 2017), and some scholars argue that its mandate could be further adapted to regulate a wider range of emerging ocean interventions (Lyons *et al* 2024, Vivian and Del Savio 2024). Yet, the framework's narrow orientation toward environmental risk assessment and binary decision-making makes it difficult to capture the cross-domain interdependencies of mCDR, such as interactions with climate mitigation goals, social legitimacy or reversibility (Röschel and Neumann 2023). Moreover, as Boettcher and Kim (2022) and Möller (2020) emphasise, the governance capacity of LC/LP may be constrained by discursive framings that shape what is considered as governable and by a broader mismatch between geoengineering problem definitions and existing institutional structures, further limiting its ability to engage systemic and cross-domain dimensions of mCDR. While recent developments under the LC/LP indicate movement toward broader inclusion of mCDR approaches (LC 44/17, Annex 2), its existing regulatory logic risks being overwhelmed by the scope and complexity of interventions that span social, ecological and technological (E/T) systems.

Addressing these governance challenges requires moving beyond fragmented, issue-specific regulatory approaches toward a systems perspective capable of capturing the interdependencies inherent in mCDR governance. This paper argues that the governance of mCDR should not be understood as a discrete regulatory task but as a multi-dimensional systems challenge embedded within the intersections of social, E/T domains.

To advance this perspective, the study conducts a structured literature review to systematically map governance challenges associated with mCDR using the socio-ecological-technological systems (SETs) (McPhearson *et al* 2022). SETs enables the examination of how governance challenges span and interact across social systems (institutions, values, equity), ecological systems (marine biogeochemistry, ecosystem services), and technological systems (infrastructure, monitoring, innovation). By aligning governance challenges with the SETs framework, the study demonstrates that many of the barriers to effective mCDR governance arise not from isolated issues but from dynamic interactions across domains.

This systems perspective reveals the limitations of current siloed governance approaches and highlights the need for integrated, adaptive, and reflexive governance models capable of addressing the systemic complexities of mCDR. Ultimately, the study contributes to a more comprehensive understanding of what it means to responsibly govern mCDR within the broader context of ocean sustainability and climate mitigation.

2. Methodology

This study applies a structured literature review to identify and analyse governance challenges associated with mCDR, following the preferred reporting items for systematic reviews and meta-analyses framework (Page *et al* 2021) to ensure transparency and reproducibility. The review synthesises insights from academic literature concerning barriers, risks, and enabling conditions for mCDR within the broader landscape of multilateral ocean governance.

A review protocol was developed to determine inclusion and exclusion criteria, target databases, and procedures for data extraction and synthesis. Literature searches were conducted in Scopus and Google Scholar using a Boolean string combining terms related to marine CDR and governance ([‘carbon dioxide removal’, ‘negative emissions technologies’, ‘marine geoengineering’] AND governance). Snowball sampling, a method where additional sources are identified through the reference lists of initially included papers (Greenhalgh and Peacock 2005), was used to capture relevant literature not identified through database searches. Publications were included if they were peer-reviewed, in English, and addressed governance aspects of mCDR. Studies with an exclusive focus on technical or biophysical aspects without governance relevance, or those centred on terrestrial CDR or solar radiation management, were excluded.

After title and abstract screening, eligible publications underwent full-text review. A total of 35 references were included for in-depth analysis. From these, 100 distinct governance challenges were extracted and entered into a structured database, including metadata (author, year, DOI) and relevant contextual notes.

To align the analysis with the systemic nature of mCDR governance, challenges were systematically coded using the SETs framework (see table 1). SETs, originally developed in urban systems research (McPhearson *et al* 2022), conceptualises governance contexts as composed of interacting social systems (e.g. institutions, legitimacy, power dynamics), ecological systems (e.g. biodiversity, ocean biogeochemistry), and technological systems (e.g. deployment infrastructures, MRV processes). This framework was selected because it explicitly captures the role of technological systems alongside social and ecological (S/E) systems, a critical feature for analysing mCDR governance where technological interventions are inseparable from social legitimacy and ecological risk considerations.

Alternative frameworks, such as the social-ecological systems (SESs) framework (Ostrom 2009) and the socio-technical systems approach (Geels 2004), have been widely used to analyse governance challenges in environmental contexts. However, SES frameworks typically underrepresent technological

Table 1. SETS-informed mapping of governance challenge domains across references included in the literature review.

Reference [Author (Year)]	S	S/E	S/T	E/T	S/E/T
Galaz (2012)	X		X	X	X
Fajardy <i>et al</i> (2019)	X				
Boettcher <i>et al</i> (2023b)	X				
Sovacool <i>et al</i> (2023)	X		X		X
Nawaz <i>et al</i> (2023)	X				
Günther and Ekardt (2022)			X		
Cox <i>et al</i> (2021)	X	X	X		X
Cox <i>et al</i> (2022)			X		
Ricart <i>et al</i> (2022)					X
Loomis <i>et al</i> (2022)	X	X	X		
Biermann <i>et al</i> (2022)	X		X		
Rabitz <i>et al</i> (2022)			X		
Battersby <i>et al</i> (2022)	X				
Parson and Reynolds (2021a)			X		
Parson and Reynolds (2021b)	X		X	X	
Hall and Davis (2021)			X		
Reynolds (2021)	X		X	X	X
Boettcher <i>et al</i> (2021)	X		X		X
Nolan <i>et al</i> (2021)			X		
Healey <i>et al</i> (2021)			X		X
Sovacool (2021)			X	X	X
Mace <i>et al</i> (2021)					X
Jinnah <i>et al</i> (2021)			X		
Dooley <i>et al</i> (2021)				X	
Cox <i>et al</i> (2021)	X	X	X		X
McGee <i>et al</i> (2018)	X		X		X
Delina (2020)			X		
Vaughan and Gough (2016)			X		
Williamson <i>et al</i> (2012)				X	
Mengis <i>et al</i> (2023)	X	X	X	X	X
Low <i>et al</i> (2024a)			X		X
Röschel and Neumann (2023)	X				X
Chuffart <i>et al</i> (2023)			X		
Preston (2013)			X		

systems as a distinct domain, while socio-technical frameworks often focus on technology adoption and transition processes without systematically incorporating ecological system dynamics. The SETS framework was therefore chosen for its suitability in examining interdependencies, trade-offs and cross-domain coordination needs in mCDR governance, supporting a systems-aware analysis that conventional governance categories may obscure.

Each governance challenge was reviewed and categorised under the SETS framework as social (S), ecological–technological (E/T), social–technological (S/T), social–ecological (S/E), or systemic interdependencies spanning all three domains (S/E/T). Challenges were assigned to intersections (e.g. S/T) when they substantively engaged with both domains beyond peripheral mentions, ensuring alignment with the core focus of each excerpt. Purely technological or ecological challenges were rare, reflecting the inherent interdependencies of mCDR governance challenges. Coding was conducted by the author and cross-checked through AI-assisted analysis using

OpenAI’s ChatGPT GPT-4 to enhance consistency and methodological transparency, functioning as a reflective dialogue to verify coding decisions in the absence of a second coder. This structured approach provides a robust, system-aware mapping of governance challenges across SETS dimensions and their intersections, supporting the subsequent analysis of governance design for mCDR.

3. Results

This structured review applied the SETS framework to code governance challenges related to mCDR across the peer-reviewed literature, enabling a structured analysis of the interdependencies between social (S), ecological (E), and technological (T) domains.

Across the 100 systematically analysed excerpts, the coding revealed a predominance of intersectional challenges that underscore the systemic complexity of mCDR governance. Challenges intersecting S/T domains were most frequently identified ($n = 43$), followed by challenges engaging all three domains

(S/E/T, $n = 20$) and challenges framed primarily within the social domain (S, $n = 18$). E/T challenges appeared in 14 instances, while S/E challenges were identified in 3 instances, and purely technological challenges (T) were rare ($n = 2$). This distribution illustrates the specific modalities through which governance challenges intersect with technological implementation and ecological system considerations.

3.1. Social domain (S)

Within the social (S) system domain, the review identified several governance challenges critical to the development of mCDR frameworks. These include justice and equity concerns, particularly regarding potential sacrifices by the Global South and the limitations of single-issue justice framings in achieving climate justice (Reynolds 2021, Biermann *et al* 2022). For example, Sovacool *et al* (2023) describe concerns that mCDR may exacerbate global inequities if wealthy nations deploy these technologies in ways that displace environmental risks onto vulnerable communities.

Institutional fragmentation and governance gaps were evident, reflecting disconnected policy landscapes and the inadequacy of existing frameworks like the LC/LP to systematically address mCDR (Loomis *et al* 2022, Röschel and Neumann 2023). Boettcher *et al* (2021) highlight how the current ocean governance landscape creates overlaps and contradictions, hindering coherent regulation of emerging ocean-based interventions.

Tensions between corporate governance priorities and climate objectives were noted, alongside the role of economic development drivers in shaping mCDR governance (Fajardy *et al* 2019, Reynolds 2021, Battersby *et al* 2022). Challenges related to stakeholder participation and civil society into governance processes were highlighted (McGee *et al* 2018), with Cox *et al* (2022) noting the importance of community engagement to avoid legitimacy crises during mCDR deployment.

Additionally, the role of knowledge systems and normative framings in structuring mCDR governance debates (Cox *et al* 2022) was evident, with Reynolds (2021) emphasising how dominant techno-economic narratives risk overshadowing ethical and social considerations in governance discussions. Legal and regulatory complexities contribute to fragmented, reactive governance, underscoring the need for system-aware, forward-looking frameworks for mCDR governance.

3.2. Intersection between S/E domain

Within the S/E intersection, the analysis identified challenges related to the ocean's ecological connectivity and its implications for governance. The ocean's scale, fluidity, and ecological connectivity require

governance approaches that transcend national jurisdictions, highlighting the need for safeguarding the ocean as a shared and interconnected space within ocean and mCDR governance (Loomis *et al* 2022). For example, Mengis *et al* (2023) illustrate how interventions like ocean alkalinity enhancement require transboundary cooperation due to the movement of water masses across jurisdictions.

Additionally, the cultural significance and relational values attached to the ocean underscore the need for mCDR governance frameworks to preserve social and cultural dimensions alongside ecological protection. Cox *et al* (2022) argue that ignoring cultural and relational ocean values may undermine public acceptance of mCDR initiatives. These findings illustrate how S/E considerations are deeply intertwined in mCDR governance, necessitating governance approaches that acknowledge the ocean's unique properties and cultural significance.

3.3. Intersection between S/T domain

At the S/T intersection, governance challenges identified include public perception and risk acceptance concerns (Debnath *et al* 2023, Mengis *et al* 2023), risks of technological lock-in and mitigation deterrence (Sovacool *et al* 2023, Low *et al* 2024b), governance fragmentation and the need for institutional capacity (Galaz 2012, Delina 2020), and justice and equity concerns (Günther and Ekardt 2022, Chuffart *et al* 2023).

For example, Debnath *et al* (2023) report that public sentiment often fluctuates negatively in response to announcements about experimentation, indicating societal unease with technological interventions in the climate system. Risks of technological lock-in were highlighted by Sovacool *et al* (2023), who discuss how the pursuit of mCDR could reduce incentives for emissions cuts, leading to mitigation deterrence.

Additionally, challenges relating to MRV, technological feasibility, and costs (Nolan *et al* 2021, Sovacool 2021) and the role of non-state actors and venture capital (Boettcher *et al* 2021, Reynolds 2021) were highlighted. Geopolitical and security concerns associated with the accessibility and potential unilateral deployment of mCDR technologies also emerged (Parson and Reynolds 2021b, Sovacool *et al* 2023, Young 2023). These findings underscore the deeply interwoven nature of technological readiness, governance structures, and societal legitimacy in mCDR governance.

3.4. Intersection between E/T domain

At the E/T intersection, the structured literature review identified several key governance challenges associated with mCDR deployment. Large-scale implementation of ocean-based climate interventions may result in unintended environmental consequences on e.g. marine biodiversity. For instance,

Williamson *et al* (2012) detail how ocean fertilisation could cause deoxygenation and acidification, impacting marine ecosystems and fisheries.

Monitoring, reporting, and verification of carbon removal effectiveness are complicated by high ecosystem connectivity and the decoupling of sequestration processes in marine environments. Mengis *et al* (2023) highlight the difficulty of distinguishing human-induced carbon sequestration from natural variability in the ocean, complicating accountability.

Governance challenges also emerge from managing systemic risks and interactions in integrated carbon-use systems (Parson and Reynolds 2021b) and addressing trade-offs due to resource competition (Reynolds 2021). Despite these concerns, some interventions may offer ecological co-benefits, such as ecosystem restoration and reduced local heat stress, indicating possible positive synergies (Dooley *et al* 2021). The uncertainties still surrounding mCDR approaches further highlight the need for precautionary yet adaptive governance frameworks. Collectively, these findings illustrate the deep entanglement of ecological impacts with technological deployment decisions in mCDR governance.

3.5. Intersection of all domains (S/E/T)

At the intersection of S/E/T systems, the review identified deeply interlinked governance challenges for mCDR. Systemic trade-offs and potential conflicts with Sustainable Development Goals (SDGs) are evident, as large-scale deployment may threaten food and water security while offering opportunities for ecosystem restoration and sustainability transitions (Mace *et al* 2021, Ricart *et al* 2022). For example, Healey *et al* (2021) note that land-use changes for bioenergy-based CDR could undermine local food security, while also creating opportunities for ecosystem co-benefits if managed carefully.

The governance of mCDR faces challenges of managing systemic risks and uncertainties across scales while maintaining institutional capacity for innovation and precaution (McGee *et al* 2018, Röschel and Neumann 2023). Ethical and justice considerations, including equity in benefits and risks, technological dependence, and termination shock, are central to mCDR governance debates (Galaz 2012). Reynolds (2021) points out that termination of technological interventions could lead to abrupt climate impacts, illustrating the long-term risk entanglements of mCDR.

Protecting marine ecosystems and biodiversity while addressing transboundary ecological risks remains a priority (Cox *et al* 2021). Ongoing debates around precautionary governance approaches underscore the tension between climate urgency and environmental protection (McGee *et al* 2018, Röschel and Neumann 2023). These findings demonstrate the need for system-aware, integrated governance

approaches capable of navigating the complex, cross-domain trade-offs inherent in mCDR.

3.6. Synthesis

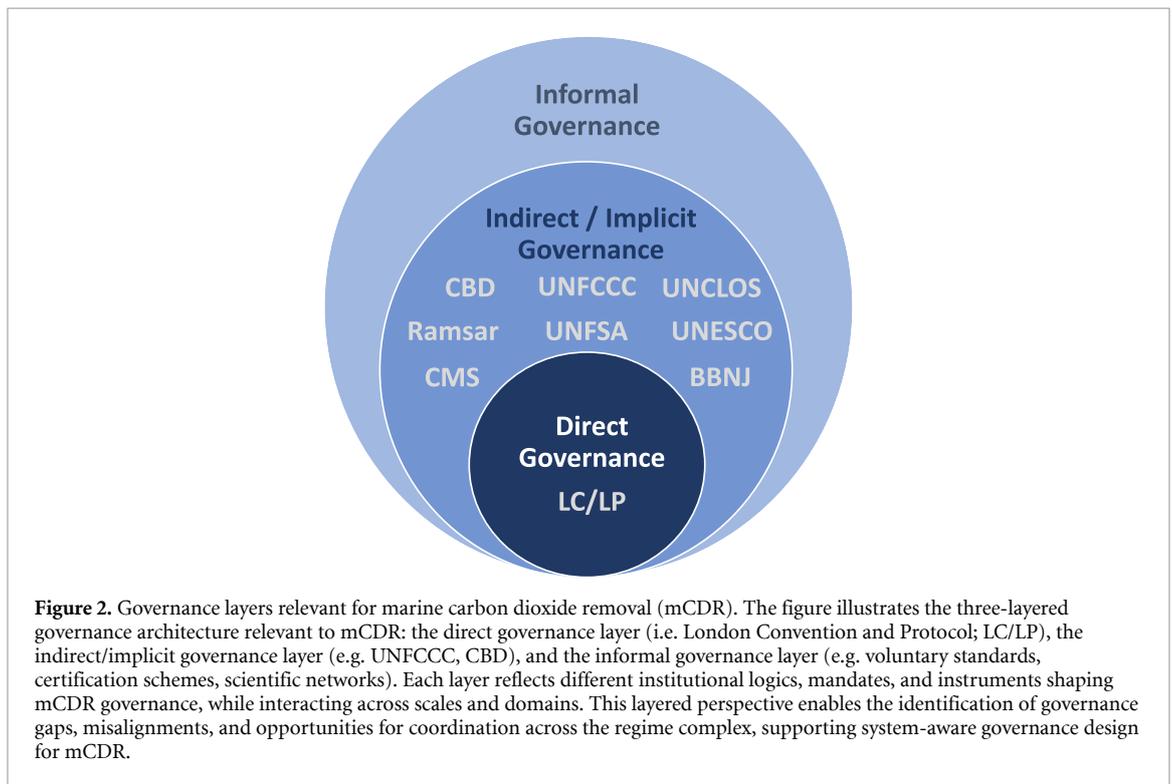
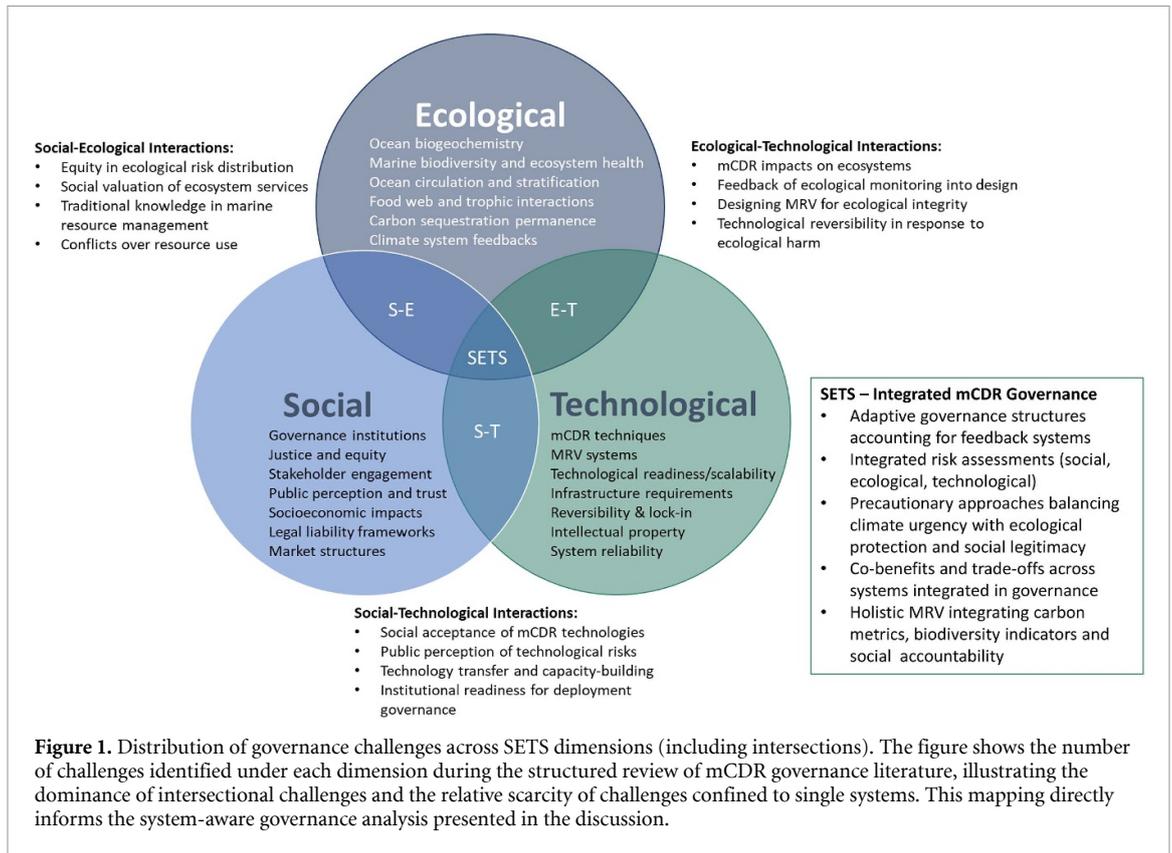
The SETS-informed mapping confirms that mCDR governance challenges are deeply systemic (see figure 1). S/T intersections dominate the discourse, revealing how technological interventions inherently create governance challenges around legitimacy, participation, and justice. Simultaneously, ecological considerations frequently intersect with technological and governance domains, reflecting the difficulties of deploying interventions in complex marine systems.

The low frequency of purely technological or ecological challenges suggests that governance discussions in mCDR cannot be siloed. Instead, they demand polycentric, adaptive approaches capable of addressing interdependencies across systems while maintaining justice, accountability, and ecological integrity.

4. Discussion

Governance of mCDR has largely been approached through a narrow E/T lens, privileging decisions based on environmental risk and technological feasibility (Galaz 2012, Williamson *et al* 2012). This reflects broader patterns in global environmental governance, where precautionary logics dominate, and where institutions often struggle to keep pace with emerging technological innovation and systemic uncertainty (Galaz 2014, Ahern 2025). While this orientation helps contain risk, it often sidelines critical interdependencies with social systems (Baatz *et al* 2025). The literature review reveals that governance challenges emerge most frequently at the intersection of S/T domains, where questions of legitimacy, institutional capacity, political economy and stakeholder participation are central. These concerns are not isolated, but co-evolve with ecological impacts and technological dynamics. These findings suggest that many governance challenges arise from failures to account for how these domains interact, particularly in complex intersections such as S/E/T. To address this, the SETS framework offers a heuristic for exposing governance blind spots, enabling cross-domain integration, and fostering adaptive, reflexive decision-making (McPhearson *et al* 2022).

The following discussion applies the SETS lens to different layers of the mCDR governance landscape to assess how system-aware governance might be operationalised in practice. Building on Röschel and Neumann's (2023) analysis of the mCDR regime complex, this section structures the discussion around three analytical governance layers: (1) the direct (explicit) regime layer, which governs mCDR as 'marine geoengineering' under the LC/LP; (2) the implicit and indirect regime layer, encompassing governance frameworks relevant to the intended and



unintended impacts of mCDR on ocean and climate, as well as coastal and marine ecosystem services; and (3) the informal governance layer, which lacks formal regulatory authority but can influence governance processes through norms, standards and networks

(figure 2). Each of these layers reflects distinct institutional logics, limitations, and intervention opportunities. The SETS framework is applied to each layer to demonstrate how governance can be reoriented toward system-aware, integrated design.

4.1. Direct regime layer

The direct regime layer comprises binding legal instruments, specifically the LC/LP, originally designed to regulate the dumping of waste and other potentially harmful substances into the marine environment. Since 2008, marine geoengineering has formally come under its scope, with ocean fertilisation explicitly addressed under Resolution LC-LP.1 (2008) and further elaborated through the 2013 amendment to the LP, which created a legally binding mechanism (not yet in force) for regulating marine geoengineering activities (LP Amendment, 2013, Article 6bis; Annex 4). The LC/LP operates under a mandate of environmental protection and is anchored in a precautionary regulatory logic, seeking to avoid irreversible ecological harm in the face of scientific uncertainty (Güssow *et al* 2010).

As highlighted in the results, several governance challenges resonate directly with the LC/LP's regulatory approach. At the social domain level, legal and regulatory complexities were found to contribute to fragmented, reactive governance (Loomis *et al* 2022, Röschel and Neumann 2023), reflecting the LC/LP's difficulties in systematically addressing novel interventions. Many challenges coded at the S/T intersection pointed to binary regulatory framings of precaution, which risk sidelining broader questions of legitimacy, reversibility and justice (Reynolds 2021, Sovacool *et al* 2023). At the E/T and cross-domain intersections, the results further highlighted how uncertainties and systemic risks demand precautionary yet adaptive governance frameworks (Williamson *et al* 2012, McGee *et al* 2018). These empirical findings underscore the difficulty of applying a precautionary approach designed for traditional pollutants to novel, cross-domain interventions such as mCDR.

The regulatory logic, anchored in binary decision-making, may struggle to accommodate the multidimensional nature of mCDR. Many of the proposed mCDR approaches, such as ocean alkalinity enhancement or biomass sinking, are neither traditional pollutants nor clearly beneficial climate tools, placing them in a 'regulatory grey zone' as they fall outside established standards and categorical regulation (McKelvey and Saemundsson 2021). Moreover, the LC/LP does not explicitly incorporate key considerations for large-scale mCDR deployment, such as climate mitigation objectives or social legitimacy, into its scope.

Implementation is further complicated by its decentralised nature, as LC/LP provisions are translated through national legal systems, meaning that decisions on permitting, oversight and enforcement occur in domestic contexts. This governance patchwork can lead to inconsistent interpretations of precaution, monitoring standards and public engagement. Notwithstanding these limitations, recent efforts indicate a positive shift toward more integrated governance. The UN GESAMP Working Group

41 is concluding work on a new ocean intervention assessment framework that explicitly calls for incorporating ecological, societal and ethical criteria into marine geoengineering assessments (Boettcher *et al* 2025). If adopted, this framework signals institutional recognition of the importance of inclusive, cross-domain evaluation processes.

Still, the LC/LP remains fundamentally structured as a risk-containment regime, anchored in marine science and state consensus, rather than an agile, integrated governance system capable of managing complexity across domains. As the results of this review show, many mCDR interventions pose cross-system challenges, which cannot be well addressed by a technocratic framework (Machin 2014).

The SETS framework offers a transformative lens for reimagining precaution in the LC/LP's direct regime layer. Rather than functioning as a binary threshold test, precaution can be operationalised as a dynamic, staged and reflexive process that jointly evaluates ecological, technological and social dimensions. In practice, this could mean linking the granting of permits to predefined review milestones that incorporate stakeholder input, embedding reversibility or sunset clauses within project authorisation and establishing multi-stakeholder panels to assess systemic risks and weigh trade-offs across domains. These approaches would not displace the LC/LP's protective function, but rather extend it by enabling precaution to become an iterative practice that reflects uncertainties and interdependencies characteristic of mCDR.

4.2. Implicit and indirect regime layer

The implicit and indirect regime layer includes international agreements and institutions that, while not explicitly regulating mCDR, nevertheless shape its governance landscape. These include, but are not limited to, the United Nations Convention on Climate Change (UNFCCC), the convention on biological diversity (CBD), and regional seas conventions (e.g. OSPAR, Barcelona Convention). Each of these exemplary regimes articulates objectives that intersect with mCDR, ranging from emissions reduction and carbon accounting to marine conservation and biodiversity protection, yet they largely operate in institutional silos with differing mandates, differing Parties to their convention and different levels of binding force for relevant decisions (Röschel and Neumann 2023).

As the results of this review illustrate, such fragmentation is not only institutional but systemic, shaping multiple governance challenges across the SETS domains. For example, a state might seek to include mCDR deployment in its nationally determined contribution under UNFCCC, aiming to generate carbon credits through enhanced ocean-based sequestration. Yet, the same intervention could conflict with marine protected areas or precautionary

provisions under the CBD, or fail to meet regional ecosystem-based management standards. Here, climate policy logics of rapid mitigation intersect with biodiversity commitments to resilience and intergenerational equity (Loomis *et al* 2022, Mengis *et al* 2023). Likewise, the results show how institutional divergence can amplify equity concerns if climate-driven incentives for mCDR shift ecological risks towards vulnerable regions (Sovacool *et al* 2023), or create legitimacy problems when monitoring and reporting requirements are duplicated across overlapping fora.

Without coordination, such divergencies can lead to contradictory governance signals for potential mCDR deployment, creating regulatory loopholes, particularly when international commitments must be translated into national legal frameworks that differ widely in implementation capacity and interpretation. Rather than approaching these frictions as inefficiencies to overcome, the SETS framework makes visible how cross-domain spillovers e.g. between carbon markets and ecosystem integrity, can compound mCDR governance risks if not addressed holistically. For example, carbon removal incentives under climate finance mechanisms may unintentionally undermine ecological goals if biodiversity impacts are poorly understood or insufficiently valued. Similarly, a strict interpretation of environmental precaution could delay or exclude potentially beneficial mCDR options without assessing their broader social or climate value.

SETS-informed governance offers pathways to bridge these divides. For instance, shared monitoring and verification protocols, joint scientific bodies or cross-secretariat working groups could harmonise mCDR governance. The evolving Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction (BBNJ) provides a new institutional framework for integrated environmental assessments and area-based management beyond national jurisdiction, which could serve as testbed for procedural integration, allowing different regimes to retain their normative autonomy while jointly navigating uncertainty, trade-offs and spatial overlaps.

Additionally, SETS clarifies where integration is appropriate and where maintaining differentiated mandates may act as a safeguard against overconcentration of authority or normative dominance. While institutional coordination can enhance consistency and reduce duplication, it also carries the risk of reinforcing dominant epistemologies or marginalising precautionary perspectives. For instance, if climate mitigation priorities under the UNFCCC were to dictate the design of biodiversity safeguards

under the CBD or BBNJ, there is a risk that carbon-centric logics could override ecological integrity or Indigenous rights concerns. A SETS-informed perspective would argue for integration in areas such as joint impact assessments or monitoring frameworks, but would caution against collapsing institutional distinctions where mandates reflect fundamentally different value commitments or stakeholder constituencies. For example, kelp forest restoration projects may be promoted under climate regimes for their carbon sequestration potential (Duarte *et al* 2017, Gentry *et al* 2020), yet from a biodiversity or local livelihood perspective they may raise concerns about monoculture planting or displacement of small-scale fisheries (Seddon *et al* 2021). SETS helps delineate where shared MRV systems might be appropriate, while retaining distinct approval processes to protect ecological and social values.

4.3. Informal governance layer

The informal governance layer encompasses transnational standard-setting, voluntary guidelines, research codes of conduct, and carbon certification schemes. While these instruments are non-binding, they play a central role in shaping how mCDR is researched, financed, and evaluated. Informal governance in the mCDR context includes voluntary research norms (e.g. Aspen Institute's *Code of Conduct for Responsible mCDR Research* (Boettcher *et al* 2023a)), emerging private certification standards (e.g. Verra's *Verified Carbon Standard*), and non-governmental actors or discourse coalitions (e.g. Ocean Visions) that contribute to agenda-setting, normative framing, and epistemic recognition. These initiatives vary widely in their orientation: while some early efforts have prioritised quantifiable carbon removal and technical feasibility, thereby reflecting a technocratic or carbon-centric logic, others increasingly recognise ethical, social, and ecological dimensions, signalling a move toward more systemic governance approaches.

As highlighted in the results, informal governance mechanisms frequently intersect with challenges at the S/T boundary. For instance, research experiments and early pilot projects often face societal unease, with public sentiment fluctuating negatively in response to announcements of ocean-based interventions (Debnath *et al* 2023). Certification schemes, if designed narrowly around carbon metrics, also risk reinforcing technological lock-in and mitigation deterrence, privileging rapid carbon accounting over long-term ecological or justice concerns (Sovacool *et al* 2023). Moreover, whose knowledge counts in shaping these standards remains contested with dominant techno-economic framings potentially marginalising Indigenous or local knowledge systems and

thereby undermining legitimacy and inclusiveness (Reynolds 2021, Cox *et al* 2022).

From a SETS perspective, informal governance offers both a risk and an opportunity. Without integrated design principles, informal instruments may reinforce siloed decision-making or legitimise mCDR activities with insufficient attention to long-term system feedbacks. Yet, these same instruments could act as laboratories for system-aware governance if certification standards, research protocols and voluntary codes were structured to integrate metrics across domains and intersections while embedding reflexive learning cycles that evolve with emerging evidence.

Informal governance thus has the potential to act not only as a pre-regulatory field, but as a dynamic site of experimentation, norm diffusion, and epistemic pluralism. Integrating principles of epistemic justice, for example, by incorporating knowledge of potentially impacted coastal communities or community-based monitoring, would strengthen the legitimacy, inclusiveness, and responsiveness of mCDR governance. In this way, informal instruments could complement more formal regimes by embedding justice and pluralism at the early stages of governance design, while retaining flexibility to adapt to uncertainties and new insights across social, E/T domains.

4.4. Toward system-aware governance design

The SETS framework does not provide definitive governance solutions but offers a heuristic for navigating governance under conditions of uncertainty, interdependence, and normative contestation. It encourages decision-makers to move beyond siloed approaches by illuminating how governance decisions in one domain across can generate feedbacks and trade-offs in others.

However, applying SETS-informed governance requires institutional capacities that are often underdeveloped. Many governance bodies lack the mandates, procedural tools, or cultures of reflexivity necessary for integrated, adaptive governance. Future research should examine how SETS-informed principles can be institutionalised in practice, including through capacity-building, mandate reform, and the development of transdisciplinary evaluation mechanisms.

Importantly, mCDR governance must not only be system-aware but also justice-oriented. Legitimate governance demands attention to whose voices are included, whose knowledge is recognised, and who bears the risks and benefits of mCDR deployment. These justice dimensions (e.g. epistemic, distributive, procedural) will be central to the development of a normative framework for good governance of mCDR.

Recent work on holistic and systemic governance of (marine) CDR has emphasised the need for integrated, reflexive frameworks capable of addressing the deep interdependencies between technical feasibility, ecological risks, and social legitimacy. For example, Low *et al* (2024a) propose an Earth System Governance research agenda for CDR that spans systems assessment, societal appraisal, policy, and innovation dimensions, calling for cross-cutting approaches that capture interlinked risks and opportunities. Similarly, Healey *et al* (2024) advocate for bottom-up, context-sensitive frameworks in CDR policy design, emphasising responsible innovation within fragmented and polycentric governance systems. Malakar *et al* (2025) highlight the criticality of stakeholder heterogeneity and relational dynamics in shaping CDR governance, aligning with the call for frameworks that can capture socio-technical complexities. Additionally, the High Level Panel for a Sustainable Ocean Economy (2024) has outlined principles for responsible and effective mCDR development and governance, emphasising environmental integrity, social equity, and the alignment of mCDR initiatives with broader ocean sustainability objectives.

Together, these contributions signal a growing consensus that mCDR governance must evolve from narrow techno-economic or environmental framings to systemic, multi-level approaches. The SETS-informed analysis presented in this paper complements and advances this literature by operationalising a system-aware, cross-domain coding of governance challenges in mCDR specifically. It demonstrates empirically how S/E/T domains interlink in the governance landscape of mCDR, illustrating the practical application of systemic governance lenses and identifying where current governance structures (e.g. LC/LP, UNFCCC, or informal standard-setting) may fall short in addressing compound challenges. In doing so, it supports the operationalisation of integrated, adaptive governance architectures suited to the unique challenges of mCDR.

5. Conclusion

This study demonstrates that governance of mCDR is shaped by a range of interdependent challenges that cut across S/E/T domains. Through a structured literature review using the SETS framework, 100 governance challenges were identified and systematically mapped, revealing that most emerge at the intersections of systems rather than within isolated domains. This finding reinforces the systemic nature of CDR governance complexity.

The SETS framework enabled a systems-level interpretation of how governance challenges arise from the interplay of technological interventions, ecological risks and social legitimacy concerns. This perspective highlights that current governance approaches, often narrowly focused on environmental risk mitigation or legal compliance, are ill-equipped to address cross-domain trade-offs, feedback loops and coordination needs posed by mCDR. Governance fragmentation and regulatory inertia risk sidelining these interdependencies, while narrowly technocratic or binary precautionary approaches obscure broader questions of legitimacy, reversibility and justice.

Ultimately, mCDR cannot be governed purely as a technical intervention or as an extension of existing marine protection regimes alone. It is a socially contested, ecologically consequential, and technologically emergent strategy for climate mitigation that raises fundamental questions about planetary stewardship, ethical responsibility and institutional adaptability. Governing such interventions will require new institutional capacities that can operate across epistemic, geographic and institutional boundaries, incorporate diverse forms of knowledge, navigate uncertainty and adapt as the science and politics of mCDR evolve.

This analysis advances the case for system-aware governance approaches that address complexity while also embodying principles of justice, legitimacy and reflexive learning. Building on these insights, future work will develop a framework for good governance of mCDR that integrates normative guidance with systems-based reflexivity, supporting governance architectures capable of managing interdependencies and uncertainties inherent in ocean-based climate interventions.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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Ethical statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The research and activities carried out by the researcher as part of the EU funded OceanNETs project comply with ethical principles and relevant national, EU and international legislation, such as the Charter of Fundamental Rights of the European Union and the European Convention on Human Rights.

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References

- Ahern D 2025 The new anticipatory governance culture for innovation: regulatory foresight, regulatory experimentation and regulatory learning *Eur. Bus. Organ. Law Rev.* **26** 241–83
- Baatz C, Tank L, Bednarz L-K, Böttcher M, Morganti T M, Voget-Kleschin L, Cabus T, van Doorn E, Dorndorf T and Havermann F 2025 A holistic assessment framework for marine carbon dioxide removal options *Environ. Res. Lett.* **20** 054047
- Battersby F, Heap R J, Gray A C, Workman M and Strivens F 2022 The role of corporates in governing carbon dioxide removal: outlining a research agenda *Front. Clim.* **4** 686762
- Biermann F *et al* 2022 Solar geoengineering: the case for an international non-use agreement *WIREs Clim. Change* **13** e754
- Boettcher M *et al* 2025 The UN GESAMP ocean intervention assessment framework (OIAF), One Ocean Science Congress 2025 (Nice, France, 3–6 Jun 2025, OOS2025-1306) (<https://doi.org/10.5194/oos2025-1306>)
- Boettcher M, Brent K, Buck H J, Low S, McLaren D and Mengis N 2021 Navigating potential hype and opportunity in governing marine carbon removal *Front. Clim.* **3** 664456
- Boettcher M, Chai F, Conathan M, Cooley S, Keller D, Klinsky S, Lezaun J, Renforth P, Scobie M and Webb R M 2023a *A Code of Conduct for Marine Carbon Dioxide Removal Research* (A. Institute)
- Boettcher M and Kim R E 2022 Arguments and architectures: discursive and institutional structures shaping global climate engineering governance *Environ. Sci. Policy* **128** 121–31
- Boettcher M, Schenuit F and Geden O 2023b The formative phase of German carbon dioxide removal policy: positioning between precaution, pragmatism and innovation *Energy Res. Soc. Sci.* **98** 103018
- Chuffart R, Cooper A M, Wood-Donnelly C and Seddon L 2023 Old sea, new ice: sea ice geoengineering and indigenous rights in Arctic Ocean governance *Polar J.* **13** 195–215
- Cooley S R, Klinsky S, Morrow D R and Satterfield T 2023 Sociotechnical considerations about ocean carbon dioxide removal *Annu. Rev. Mar. Sci.* **15** 41–66

- Cox E, Boettcher M, Spence E and Bellamy R 2021 Casting a wider net on ocean NETs *Front. Clim.* **3** 576294
- Cox E, Spence E and Pidgeon N 2022 Deliberating enhanced weathering: public frames, iconic ecosystems and the governance of carbon removal at scale *Public Understand. Sci.* **31** 960–77
- Debnath R, Reiner D M, Sovacool B K, Müller-Hansen F, Repke T, Alvarez R M and Fitzgerald S D 2023 Conspiracy spillovers and geoengineering *iScience* **26** 106166
- Delina L L 2020 Potentials and critiques of building a Southeast Asian interdisciplinary knowledge community on critical geoengineering studies *Clim. Change* **163** 973–87
- Doney S C *et al* 2025 *Principles for Responsible and Effective Marine Carbon Dioxide Removal Development and Governance* (World Resources Institute)
- Dooley K, Harrould-Kolieb E and Talberg A 2021 Carbon-dioxide removal and biodiversity: a threat identification framework *Glob. Policy* **12** 34–44
- Duarte C M, Wu J, Xiao X, Bruhn A and Krause-Jensen D 2017 Can seaweed farming play a role in climate change mitigation and adaptation? *Front. Mar. Sci.* **4** 100
- Fajardy M, Patrizio P, Daggash H A and Mac Dowell N 2019 Negative emissions: priorities for research and policy design *Front. Clim.* **1** 6
- Fuentes-George K 2017 Consensus, certainty, and catastrophe: discourse, governance, and ocean iron fertilization *Glob. Environ. Polit.* **17** 125–43
- Galaz V 2012 Geo-engineering, governance, and social-ecological systems critical issues and joint research needs *Ecol. Soc.* **17** 10
- Galaz V 2014 *Global Environmental Governance, Technology and Politics: The Anthropocene Gap* (Edward Elgar Publishing)
- Geels F W 2004 From sectoral systems of innovation to socio-technical systems: insights about dynamics and change from sociology and institutional theory *Res. Policy* **33** 897–920
- Gentry R R, Alleway H K, Bishop M J, Gillies C L, Waters T and Jones R 2020 Exploring the potential for marine aquaculture to contribute to ecosystem services *Rev. Aquacult.* **12** 499–512
- Greenhalgh T and Peacock R 2005 Effectiveness and efficiency of search methods in systematic reviews of complex evidence: audit of primary sources *BMJ* **331** 1064–5
- Günther P and Ekardt F 2022 Human rights and large-scale carbon dioxide removal: potential limits to BECCS and DACCS deployment *Land* **11** 2153
- Güssow K, Proelss A, Oschlies A, Rehdanz K and Rickels W 2010 Ocean iron fertilization: why further research is needed *Mar. Policy* **34** 911–8
- Hall S and Davis M 2021 Permission to say “capitalism”: principles for critical social science engagement with GGR research *Front. Clim.* **3** 708913
- Healey P, Kruger T and Lezaun J 2024 Responsible innovation in CDR: designing sustainable national greenhouse gas removal policies in a fragmented and polycentric governance system *Front. Clim.* **5** 1293650
- Healey P, Scholes R, Lefale P and Yanda P 2021 Governing net zero carbon removals to avoid entrenching inequities *Front. Clim.* **3** 672357
- High Level Panel for a Sustainable Ocean Economy 2024 Marine carbon dioxide removal: pursuing an ocean climate action agenda
- IPCC 2018 *Global warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al* p 630
- Jinnah S, Morrow D and Nicholson S 2021 Splitting climate engineering governance: how problem structure shapes institutional design *Glob. Policy* **12** 8–19
- Loomis R, Cooley S R, Collins J R, Engler S and Suatoni L 2022 A code of conduct is imperative for ocean carbon dioxide removal research *Front. Mar. Sci.* **9** 872800
- Low S *et al* 2024a An earth system governance research agenda for carbon removal *Earth Syst. Governance* **19** 100204
- Low S, Fritz L, Baum C M and Sovacool B K 2024b Public perceptions on carbon removal from focus groups in 22 countries *Nat. Commun.* **15** 3453
- Lyons Y L, Santillo D and Catonini F 2024 Legitimate scientific research: objective scientific assessment of marine geoengineering activities under the london convention and london protocol *Int. J. Mar. Coastal Law* **39** 528–40
- Mace M J, Fyson C L, Schaeffer M and Hare W L 2021 Large-scale carbon dioxide removal to meet the 1.5 °C limit: key governance gaps, challenges and priority responses *Glob. Policy* **12** 67–81
- Machin A 2014 Ends, means, beginnings: environmental technocracy, ecological deliberation or embodied disagreement? *Ethical Perspect.* **21** 47–72
- Malakar Y, Brent K, Bester A, Gardner J, Howard W and Lenton A 2025 Navigating stakeholder heterogeneity in carbon dioxide removal governance *Nat. Rev. Clean Technol.* **1** 95–105
- McGee J, Brent K and Burns W 2018 Geoengineering the oceans: an emerging frontier in international climate change governance *Aust. J. Marit. Ocean Aff.* **10** 67–80
- McKelvey M and Saemundsson R J 2021 The grey zones of technological innovation: negative unintended consequences as a counterbalance to novelty *Ind. Innov.* **28** 79–101
- McPhearson T *et al* 2022 A social-ecological-technological systems framework for urban ecosystem services *One Earth* **5** 505–18
- Mengis N, Paul A, Fernández-Méndez M and Kuhl L 2023 Counting (on) blue carbon—Challenges and ways forward for carbon accounting of ecosystem-based carbon removal in marine environments *PLOS Clim.* **2** e0000148
- Möller I 2020 Political perspectives on geoengineering: navigating problem definition and institutional fit *Glob. Environ. Polit.* **20** 57–82
- National Academies of Sciences, Engineering, and Medicine 2022 *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (The National Academies Press) (<https://doi.org/10.17226/26278>)
- Nawaz S, Peterson St-Laurent G and Satterfield T 2023 Public evaluations of four approaches to ocean-based carbon dioxide removal *Clim. Policy* **23** 379–94
- Nolan C J, Field C B and Mach K J 2021 Constraints and enablers for increasing carbon storage in the terrestrial biosphere *Nat. Rev. Earth Environ.* **2** 436–46
- Oschlies A, Slomp C P, Altieri A H, Gallo N D, Gregoire M, Isensee K, Levin L A and Wu J 2025 Potential impacts of marine carbon dioxide removal on ocean oxygen *Environ. Res. Lett.* **20** 073002
- Ostrom E 2009 A general framework for analyzing sustainability of social-ecological systems *Science* **325** 419–22
- Page M J *et al* 2021 The PRISMA 2020 statement: an updated guideline for reporting systematic reviews *BMJ* **372** n71
- Parson E A and Reynolds J L 2021a Solar geoengineering governance: insights from a scenario exercise *Futures* **132** 102805
- Parson E A and Reynolds J L 2021b Solar geoengineering: scenarios of future governance challenges *Futures* **133** 102806
- Preston C J 2013 Ethics and geoengineering: reviewing the moral issues raised by solar radiation management and carbon dioxide removal *WIREs Clim. Change* **4** 23–37
- Rabitz F, Feist M, Honegger M, Horton J, Jinnah S and Reynolds J 2022 A preliminary framework for understanding the governance of novel environmental technologies: ambiguity,

- indeterminateness and drift *Earth Syst. Governance* **12** 100134
- Reynolds J L 2021 Earth system interventions as technologies of the Anthropocene *Environ. Innov. Societal Transit.* **40** 132–46
- Ricart A M, Krause-Jensen D, Hancke K, Price N N, Masqué P and Duarte C M 2022 Sinking seaweed in the deep ocean for carbon neutrality is ahead of science and beyond the ethics *Environ. Res. Lett.* **17** 081003
- Röschel L and Neumann B 2023 Ocean-based negative emissions technologies: a governance framework review *Front. Mar. Sci.* **10** 995130
- Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, House J, Srivastava S and Turner B 2021 Getting the message right on nature-based solutions to climate change *Glob. Change Biol.* **27** 1518–46
- Sovacool B K 2021 Reckless or righteous? Reviewing the sociotechnical benefits and risks of climate change geoengineering *Energy Strategy Rev.* **35** 100656
- Sovacool B K, Baum C M and Low S 2023 Risk–risk governance in a low-carbon future: exploring institutional, technological, and behavioral tradeoffs in climate geoengineering pathways *Risk Anal.* **43** 838–59
- Vaughan N E and Gough C 2016 Expert assessment concludes negative emissions scenarios may not deliver *Environ. Res. Lett.* **11** 095003
- Vivian C and Del Savio L 2024 The London convention and protocol: adapting to address the ocean-climate crisis *Int. J. Mar. Coastal Law* **39** 519–27
- Webb R M 2024 *International Governance of Ocean-Based Carbon Dioxide Removal: Recent Developments and Future Directions* (Sabin Center for Climate Change Law, Columbia Law School)
- Williamson P, Wallace D W R, Law C S, Boyd P W, Collos Y, Croot P, Denman K, Riebesell U, Takeda S and Vivian C 2012 Ocean fertilization for geoengineering: a review of effectiveness, environmental impacts and emerging governance *Process Saf. Environ. Prot.* **90** 475–88
- Young D N 2023 Considering stratospheric aerosol injections beyond an environmental frame: the intelligible ‘emergency’ techno-fix and preemptive security *Eur. J. Int. Secur.* **8** 262–80