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An earth system governance research agenda for carbon removal

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ABSTRACT

Carbon dioxide removal (CDR) – the creation, enhancement, and upscaling of carbon sinks – has become a pillar of national and corporate commitments towards Net Zero emissions, as well as pathways towards realizing the Paris Agreement's ambitious temperature targets. In this perspective, we explore CDR as an emerging issue of Earth System Governance (ESG). We draw on the results of a workshop at the 2022 Earth System Governance conference that mapped a range of actors, activities, and issues relevant to carbon removal, and refined them into research questions spanning four intersecting areas: modeling and systems assessment, societal appraisal, policy, and innovation and industry. We filter these questions through the five lenses of the ESG framework and highlight several key 'cross-cutting' issues that could form the basis of an integrated ESG research agenda on CDR.

1. Introduction

In this perspective, we explore carbon dioxide removal (CDR) – the creation, enhancement, and upscaling of carbon sinks – as an emerging issue of earth system governance, and construct a research agenda grounded in the five lenses of the Earth System Governance (ESG) framework (Burch et al., 2019).

CDR has become a pillar of national and corporate commitments towards Net Zero emissions, as well as key to some pathways towards realizing the Paris Agreement's ambitious temperature targets. Successive Intergovernmental Panel on Climate Change (IPCC) reports (IPCC et al., 2014; 2018, 2022) and a burgeoning literature (Smith et al., 2023; Dooley et al., 2022; Sovacool et al., 2023) capture the wide scale, diversity, and deep uncertainties surrounding existing CDR proposals (see Fig. 1). Biogenic approaches describe the management of terrestrial and marine ecosystems as an opportunity to enhance carbon sinks – from afforestation and reforestation, to fixing carbon in soils as part of agricultural practices, to the enhancement of wetlands, mangroves, and seagrasses. There are also yet unscaled but much-discussed engineered approaches – e.g. direct air capture and carbon storage (DACCS) – that

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would rely on large-scale infrastructures for carbon capture, transport, and storage. Many CDR approaches defy easy categorization. Bioenergy with carbon capture and storage (BECCS) combines biomass energy production with point source carbon capture technology to try and create net-negative emissions. Enhanced weathering accelerates natural carbon drawdown from the breakdown of rocks and minerals – and, depending on the kind of rock and the location of deployment, could leverage mining industries, create fertilizer substitutes, or combat ocean acidification (ocean alkalinity enhancement) (National Research Council, 2015).

The envisioned purposes of CDR are similarly diverse. CDR could complement emissions reductions, balance 'hard-to-abate' emissions (loosely defined as emissions whose reduction is economically or technologically prohibitive), and clean up past or 'legacy' emissions in the atmosphere (Schenuit et al., 2023). However, CDR-reliant climate action could also backfire and delay necessary emissions reductions, if the availability or reliability of novel carbon sinks in the future are relied on too heavily as a rationale to continue emitting now. CDR approaches also have synergies and trade-offs. Both biogenic (i.e., forestry and agricultural management) and more technological approaches (i.e., direct air carbon capture and storage) may offer novel co-benefits for eco-systems restoration, socio-economic development, and sustainability transitions (see Fig. 1). But they may also pose socio-ecological risks, as many have profound energy, materials, and spatial demands – and antecedents in food-or-fuel conflicts and extractive industries warn of the risk of land-grabs and pollution dumping (Honegger et al., 2021a).

In this sense, carbon removal is hardly new. From carbon markets, to nuclear, shale gas and biofuels as bridging fuels, to carbon capture, to carbon removal today, the history of global climate governance is one of imperfectly scaled or repurposed socio-technical systems that were initially assessed and described as promising – and later more critically, with expectations scaled down as they were captured by incumbent policy and industry interests (Carton et al., 2020; Low and Boettcher, 2020; McLaren and Markusson, 2020). CDR as a category of climate action appears driven by ecological modernization or neoliberal environmentalist perspectives (Bäckstrand and Lövbrand, 2016; Bernstein, 2001), where assessment of carbon removal has been predominantly seen as techno-economic and innovation driven (Smith et al., 2023)

In this vein, we ask: How can carbon removal be developed and scaled differently – and what could the role of the earth system governance community be? In section 2, we draw on the results of a workshop at the 2022 Earth System Governance conference (in Toronto) that mapped a range of *actors, activities, and issues* relevant to carbon removal, and refined them into *research questions* spanning four intersecting areas: *modeling and systems assessment*, *societal appraisal*, *policy*, and *innovation and industry*. In section 3, we distil a research agenda by refining and filtering these questions through the five lenses of the ESG framework (Burch et al., 2019). We conclude by highlighting several key 'cross-cutting' issues that could form the basis of an integrated ESG research agenda on CDR.

2. Mapping the carbon removal space

This perspective builds on the inaugural activities of the Carbon Removal Working Group of the ESG network, as members attempted to define the role and value of the Working Group in a burgeoning space of CDR activities. During a meeting of the Working Group at the 2022 ESG conference in Toronto, Canada, participants conducted a mapping activity, which generated key research areas and questions regarding CDR (see Figs. 2 and 3). Subsequently, a number of these participants – the authors of this perspective – refined the mappings as a guidance for future activities of the Working Group, and for CDR assessment in general.

The framework for conducting these mappings was adapted from two previous reviews of carbon removal activity: Boettcher et al. (2021), on marine carbon removal, and Sovacool et al. (2023), a wider

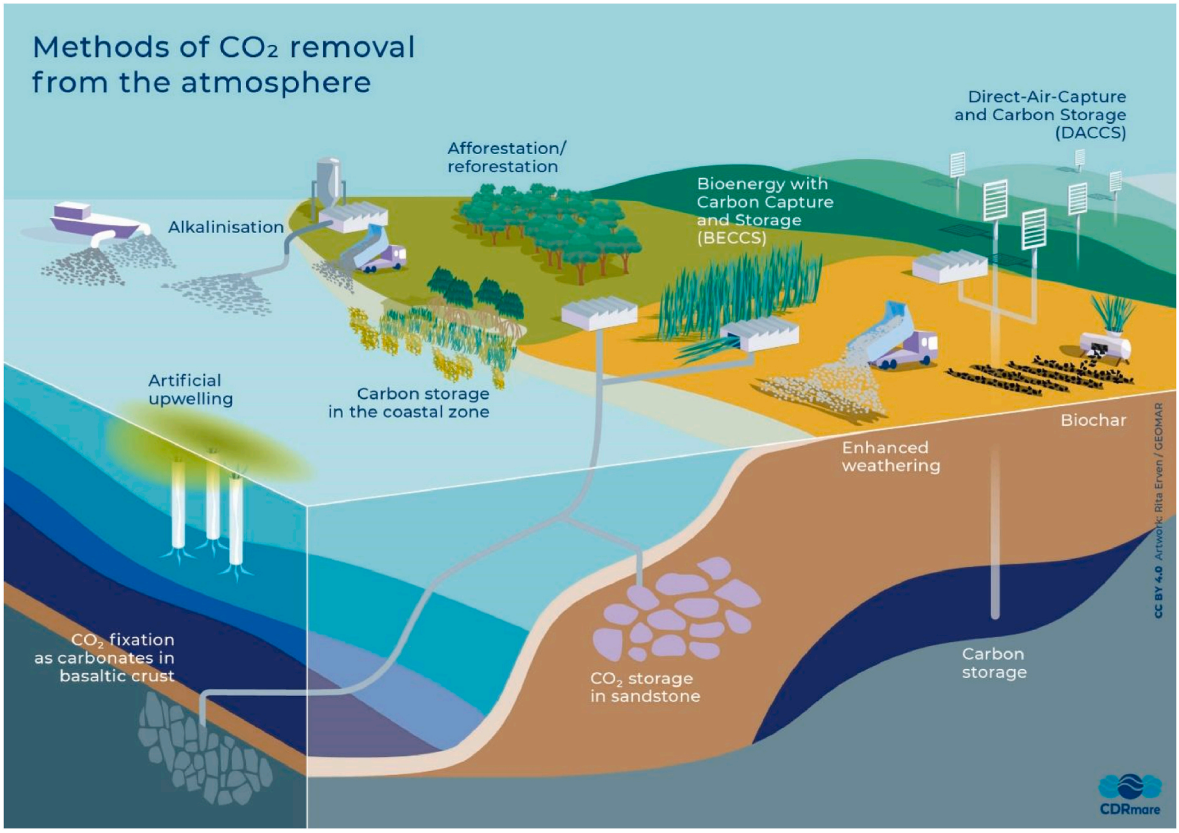

Fig. 1. Methods of carbon dioxide removal, artwork © Rita Erven/GEOMAR.

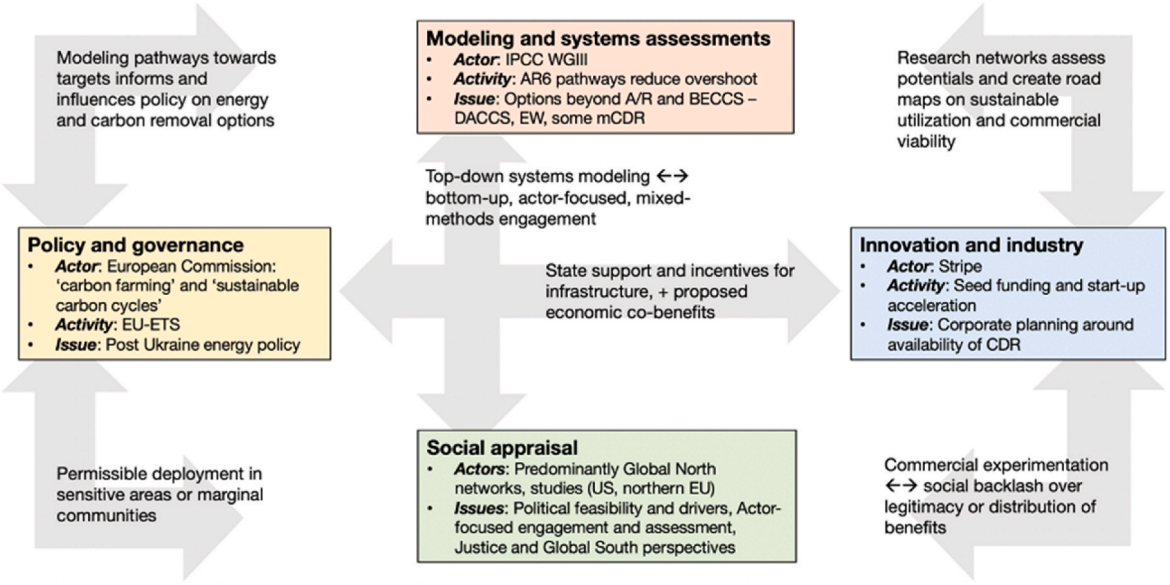

Fig. 2. A mapping framework for carbon removal.
Source: Authors, and ESG Carbon Removal Working Group. The mapping framework is adapted from Boettcher et al. (2021) and Sovacool et al. (2023). It spans four intersecting areas: *Modeling and systems assessment*, *Societal appraisal*, *Policy*, and *Innovation and Industry*. The intersections between each major area (the six grey arrows) posit how activities in each area might reinforce or contest activities in the other three. The actors, activities and issues in boxes are intended as non-exhaustive, illustrative examples as a basis for mapping the wider range of actors, activities and issues relevant in each of quadrants.

Fig. 3. Research questions.
Source: Authors, and ESG Carbon Removal Working Group. High resolution version available here: https://miro.com/app/board/uXjVPMvX2Cc=/?share_link_id=835499307599

'socio-technical' review of a range of carbon removal approaches. The Working Group's coordinators (Boettcher and Low) hoped that this framework would help the participants to organize what they saw as the most significant areas of activity in the emerging carbon removal space.

The framework itself spans four intersecting areas (Fig. 2). The first two describe modes of assessment and engagement – the first top-down, the second bottom-up. *Modeling and systems assessment* describes IPCC pathways in landmark assessment and special reports, and the systems

modeling activities (e.g. integrated assessment models) that underpin them. *Societal appraisal* describes 'situated' (locale, actor, context-dependent) engagements with the constituencies who would put carbon removal into practice, or be affected by them (e.g. publics, local communities, innovators, policy-makers, organizations). *Policy* covers the range of market-driven and regulatory mechanisms emerging at national and regional contexts, as well as at the UNFCCC. *Innovation* covers three emerging trends: corporate planning around the (future) availability of carbon removal; governmental and national industry policy planning; and the proliferation of early-stage, first-mover entrepreneurial innovation in novel forms of carbon removal. The framework also represents the intersections between the major areas, positing how activities in each area might reinforce or contest activities in the other three.

Participants at the 2022 workshop used this framework to guide a two-part mapping. First, they mapped a range of *actors*, *activities*, and *issues* relevant to carbon removal on a virtual whiteboard which contained the empty quadrants of this framework. In a second step (Fig. 3), participants then refined these initial variables into *research questions* within the four quadrants.

3. Research questions through the 5 ESG lenses

As the final part of the mapping process started in Toronto, here we refine and filter the research questions through the five lenses of the ESG framework to identify how the lenses could be applied to help address these questions. From the mapping exercise we selected 2–3 research questions per lens that best fitted key concepts primarily addressed in the five research lenses. In doing so, we suggest a number of key avenues for a research agenda on carbon removal according to each ESG lens.

3.1. Architecture and agency

The architecture and agency lens focuses on understanding the institutional frameworks and actors implicated in earth system governance and how these institutions and actors resist or respond to change and evolve over time. Key issues that are addressed through this lens include: the causes and effects of the fragmentation of earth system governance, and how to address the increasing complexity of earth system governance issues, including local to global linkages and polycentricity, and investigating the complementary roles of existing architectures and the agency of a variety of actors – states, international and intergovernmental bodies, the private sector, NGOs, scientists, indigenous peoples and citizens, transnational networks – in institutional stability and change (Burch et al., 2019).

3.1.1. How may governance coordinated 'horizontally' across sectors and regimes, or 'vertically' across scales, help address the globally-networked challenges of CDR?

Our mapping exercise (Figs. 2 and 3) reflects how CDR is emerging across modeling and society-engaging assessment, innovation and industry, and policy, highlighting that carbon removal poses a systemic, globally-networked range of governance challenges. Different processes for capturing carbon (e.g. biogenic and ecosystems-based, or chemistry and technology-based) or storage (e.g. in vegetation, soils, geological formations) span different geographies (e.g. farmlands, forests, coasts, and oceans) and economic sectors (e.g. the energy, industry, transport, building, Agriculture, Forestry and Other Land Use (AFOLU) sectors), as evidenced by the fact that the 6th Assessment Report of IPCC Working Group 3 (WG3 AR6) treated carbon removal methods as "cross-sectoral approaches" (IPCC et al., 2022). While multiple land-based CDR methods (e.g. afforestation/reforestation, biochar, enhanced weathering, BECCS) can be integrated into the activities of the AFOLU sector, others (e.g. BECCS and DACCS) could be deployed across multiple sectors of energy supply, industry and transport. The versatility of bioenergy puts BECCS in a unique position, as it can build on the bioenergy sector, and can be deployed both as electricity generation (in the energy supply sector) and liquid fuel production (in the transport sector). Storage in geological formations – for DACCS and BECCS – would implicate both terrestrial and offshore sites, often envisioned to be repurposed reservoirs from fossil fuel extraction.

All these dimensions implicate different governance architectures – from climate change to biodiversity and ecosystems services, food and energy access and security, and marine pollution. At the UN level, assessment of certain CDR approaches is taking place as part of activities organized by the Intergovernmental Panel on Climate Change (Special Report on Land, see IPCC et al., 2019) and the London Convention and Protocol on marine pollution (on 'marine geoengineering', see GESAMP, 2019). 'Synthesis' or 'nexus' assessments could serve as a template and starting point for cross-regime governance of novel issues (see ***3.5 Anticipation and Imagination***).

Moreover, CDR policy is starting to emerge at multiple levels, from the global to the local. IPCC scenarios during the 4th Assessment Report cycle drew attention to the need of stabilizing GHG concentrations over the long-term, creating the concept of 'net-zero GHG (or CO2) emissions'. Most relevant for CDR policy, this led to the inclusion of wording about the need to 'balance greenhouse gas sources and sinks' in the Paris Agreement, stipulating that parties should aim to achieve a balance between 'anthropogenic emissions by sources and removals by sinks of greenhouse gasses (GHGs) in the second half of the century'. This wording reinforced net-zero near 2050 as a guidepost for industrial nations and led to legally binding net-zero targets on European and national levels. In December 2021, the EU Commission presented its CDR policy plans in a communication called 'Sustainable Carbon Cycles', and attempts to establish CDR policy on the EU level are trickling down to national level policy making in member states. Contestations are also emerging at the national level, as policy continues to devolve. The IPCC 6th Assessment Report characterizes CDR as 'unavoidable' to counterbalance emissions that can be described as 'hard-to-abate' or 'residual' (meaning: technologically or economically prohibitive). In turn, sector-representatives in Germany are already declaring their respective emissions as 'hard-to-abate' or 'residual' and, therefore, to be necessarily counterbalanced by CDR (Boettcher et al., 2023; Schenuit et al., 2023).

The cross-sectoral, cross-issue, and transboundary nature of CDR therefore raises the politically and ethically difficult question of how to organize responsibility, contribution and accounting. Future research in this vein should include (1) assessing the political economy of CDR across governance sectors; (2) conceptualizing potential cleavages or synergies across assessment, legal, and policy regimes; (3) linking assessment and policies across scales, regarding local risks and (co) benefits to global climate risks and benefits, and not least, (4) defining the goals of CDR – e.g., using CDR to counterbalance survival, residual, or subsistence emissions vs. luxury or hard-to-abate emissions (Lund et al., 2023; Buck et al., 2023).

3.1.2. How can carbon removal governance be expanded beyond the 'ecological modernization' mode of climate governance?

Research and governance of CDR should not be exclusively considered through a cost-benefit maximizing, market-based, techno-economic lens. We should recall long-standing logics for delaying decarbonization through such "time-buying" or "bridging" strategies in assessments and policy (Carton et al., 2020; Low and Boettcher, 2020) - see also ***3.4 Adaptiveness and Reflection***. Emphasis on CDR may lead to less ambition in emissions reductions, as well as dubious expectations of carbon removal that are unlikely to materialise or be reliable if they do (Brown et al., 2019). Research might examine how CDR approaches are built into already-convoluted national commitments and carbon accounting (Dooley and Gupta, 2017). Long-term national strategies already over-rely on land-use CDR approaches (Smith et al., 2022; Jacobs et al., 2023), and countries could define "residual emissions" to over-claim emissions that are subject to balancing through carbon sinks

(Buck et al., 2023a,b) - see also ***3.3 Justice and Allocation***.

There is an especial need to define what kind of CDR activities are included in national net-zero commitments and to what degree these commitments can rely on CDR offsets (Carton et al., 2022), and improve contradicting schemes for carbon certification (Arcusa and Sprenkle-Hypolite, 2022). We might also explore environmental, social, and industry disclosure standards (e.g. GRI, 2023), as well as guidance or regulation on claims of certificates (what can a buyer legitimately claim) and what would constitute false advertising (e.g. carbon-neutral fuels) on the seller side. Confronting carbon removal's technical and funding barriers requires facilitative regulation and incentives for technological niches (e.g. Smith et al., 2023, Chapter 3). However, assessments and policy must be aware of feeding cycles of hype (Boettcher et al., 2021). We can examine perverse incentives and activities from corporate and innovation actors – how they further justify delay (Christiansen et al., 2023), create phantom commodities (Buck, 2016), and shape accounting and offset rules or governmental support to their benefit (Battersby et al., 2022) – and carry our findings into assessment and policy planning processes.

The linkages between CDR and other non-climate issues (energy demand, food security, land use, biodiversity, climate justice, etc.) also need to be taken into account. We see several ways this can be done in future research to guide governance: (1) we can develop holistic assessment frameworks that include a diverse range of technical and societal assessment criteria, indicators, and stakeholder types (see also ***3.2. Power and Democracy*** and ***3.5 Anticipation and Imagination***). We can (2) use the Sustainable Development Goals (SDGs) as a lens to assess the feasibility/desirability of a given CDR proposal in a way that goes beyond cost-benefit analysis, or link the local to the global (Lezaun, 2021) by assessing to what extent a given proposal is locally feasible/desirable (often based on non-carbon-drawdown co-benefits) in combination with evaluating how a given proposal can contribute to achieving global goals (i.e. reducing the effects of climate change, equitably distributing benefits and burdens of dealing with legacy or residual emissions, achieving one or more of the SDGs). We can also (3) undertake comparative policy analysis (e.g. Schenuit et al., 2021) or (4) analyze efforts that seek to link the local and the global on other environmental issues.

3.2. Democracy and power

In today's interconnected systems, the exercise of power influencing global environmental governance extends well beyond conventional political institutions, with both civil society actors and private interest groups having the opportunity to play a stronger role. In light of these new dynamics, the Democracy and Power lens helps researchers scope ways of strengthening democratic processes and to investigate the complex relationship between democracy and sustainability within existing power imbalances galvanized during process of project development. Filtering research questions through this lens highlights that a dedicated focus on power is required to illuminate how different forms of unequal power distribution are generated and sustained in governance structures and processes. The lens allows researchers to think about how to secure more accountable state, non-state and hybrid governance arrangements, fundamentally rethink what democracy may mean in the Anthropocene (Burch et al., 2019), and steer society away from the hindrances of ecological modernization (Carvalho and Ferreira, 2022).

3.2.1. How can carbon removal governance expands public participation and strengthens links between global, national, and local democracy?

There is a dearth of knowledge regarding how publics view different kinds of carbon removal in the emerging and developing global South – the vast majority of public engagement exercises have been conducted in the global North, and particularly in the US, UK, and Germany. Moreover, we should be concerned about incentives to site carbon removal infrastructures or storage in marginalized areas – which can lead to misidentification of potential downsides and their realization, as well as public backlash. Carbon removal governance can strengthen democracy only if it prioritizes deliberation and collaborative decision-making across the breadth and depth of communities, institutions, and markets. This will require knowledge exchange processes: analyzing linkages between democratic processes and institutions at different scales (from local to global), while at the same time creating explicit mechanisms for broad inclusion of formal and informal social groups (see also ***3.1 Architecture and Agency***).

With this in mind, research through the democracy and power lens should focus on assessing, improving, and redressing (1) the democratic standards and power dynamics at play in emerging CDR governance practices, including citizen juries, expert working groups, advisory committees, stakeholder forums and mini publics, (2) power imbalances among actors in these governance practices to ensure multiple, diverse perspectives are heard and integrated into decision-making, (3) the role of informed consent, transparency, and trust between various actors involved in CDR decision-making processes, and (4) local and national power-structures and hierarchies to assist in adjudicating conflicting views on knowledge-creation practices, values, and CDR-related desired outcomes (see also ***3.5 Anticipation and Imagination***). Ultimately, research through this lens can help determine whether the promotion of democracy through carbon removal signifies an incremental task of adapting the governance models established and maintained in late modernity, or a task that is transformative of democratic structures.

3.2.2. How can carbon removal governance contribute simultaneously to democracy and sustainability across governance levels?

While the relationship between democracy and sustainability is complex, there is no need for an *a priori* trade-off between them. Instead, the acknowledgement that carbon removal governance and sustainability could or should be mutually reinforcing is an opportunity to investigate how increasing the diversity of voices in decision-making could at the same time potentially improve the sustainability of the resulting CDR governance decisions.

Democracy can be a slow process; thus, urgency should be directed toward research to help create the appropriate institutions to build participation, accountability, and transparency in carbon removal governance. Contributing to local sustainability goals requires both the gathering of local knowledge about ecosystems and communities, and the provision of local access to the emerging knowledge about new removal endeavours (Lezaun, 2021). A major factor in building democratic processes and equity is access to and involvement in the production of knowledge. Future research should therefore focus on assessing who has knowledge, whose knowledge counts (expert, practitioner, local and Indigenous), and who is involved in the production of authoritative knowledge on CDR and its governance.

At this early stage of CDR research and development, academic work through the lens of democracy and power could (1) explore how to develop mechanisms to promote accountability and enable participation in CDR knowledge creation, and to understand how knowledge-power dynamics play out. In addition, (2) frameworks are needed for appraising the feasibility, desirability and sustainability of CDR projects, drawing on lessons learned in relation to other emerging technologies on the ways in which democratic deliberation between diverse stakeholders (and other direct-democratic processes) may build situated/localized consultation and consent (see also ***3.3 Justice and Allocation***, ***3.5 Anticipation and Imagination***).

3.3. Justice and allocation

The Justice and Allocation research lens illuminates how new, countervailing or decolonising discourses and social movements may promote a re-allocation of resources and shift to more just and equitable patterns of use. In addition to addressing questions related to

distributive justice and equitable decision-making on trade-offs in the Anthropocene, this lens also enables the investigation of the role of religious, spiritual, and ethical worldviews as potential drivers of new forms of solidarity and subsidiarity in earth system governance (Burch et al., 2019).

3.3.1. How can we forestall industry capture or policy diversion over carbon removal – via 'carbon colonialism' by rich countries, companies, and even individuals?

While this question recalls the importance of resilient architectures of ecological modernization (see ***3.1 Architecture and Agency***), it is also important to ensure that funding and upscaling of carbon removal does not replicate the injustices of colonialism, industrialization, and globalization. Scaling up through international financing and technology transfers, for instance, could support poverty alleviation and climate stabilization, but, without safeguards, this could also end up harming local communities, Indigenous peoples, and vulnerable groups in general (Lenzi et al., 2021, Dooley et al., 2022). Similarly, forestry projects meant to protect biodiversity and sequester carbon could lead to large-scale, industrial afforestation projects involving land grabs and displacing marginalized populations (Qi and Dauvergne, 2022). Such projects risk turning poor regions into carbon sinks to offset life-as-usual for the rich, while allocating a disproportionate share of the benefits to those with the greatest wealth and power.

Besides the efforts noted in ***3.1 Architecture and Agency***, research through the lens of justice and allocation could further (1) investigate what types of moral and ethical frameworks or principles have previously been (in)effective in steering and governing CDR projects that are considered just and equitable; (2) compare principles and practice of CDR research and governance that are being put forward by academics and practitioners to assess whether established (technocratic, neoliberal, utilitarian) discourses are being perpetuated, or if alternative discourses (care, restorative justice etc.) are emerging (see ***3.5 Anticipation and Imagination***).

3.3.2. How can we navigate unjust trade-offs in the use of space and resources in CDR governance?

Carbon removal will place demands on land, energy, and technology systems. This will inevitably create various trade-offs: the practical and moral implications of which require urgent clarification through the lens of justice and allocation, especially in light of competing demands (Smith, 2018). Trade-offs must be balanced with ethics and justice in mind, using past environmental movements as guideposts and accounting for the interconnections between regions and their social systems (Dooley et al., 2022). For example, environmental justice advocates have long fought against the export of waste products to areas without sufficient power, knowledge, or resources to enact fully-informed consent (Pellow, 2007). Similar issues are envisaged to arise if carbon removal activities are 'outsourced' to developing countries.

Research through the lens of justice and allocation can help consider whether carbon removed from the atmosphere should be deemed a waste-product to be disposed of, or a resource to be leveraged, and what implications this has for designing just CDR policies. Other ways in which research through this lens could help to address these issues include: (1) Investigating how countries or regions which may become CDR 'importers' or 'providers' can be empowered, i.e., provided with knowledge and resources to enact informed consent and (2) thinking through how principles such as 'polluter pays' may help guide the development of governance to ensure the equitable distribution of benefits and burdens of paying for and conducting CDR research and deployment (see also ***3.1 Architecture and Agency***).

3.3.3. Principles of climate justice and 'common but differentiated responsibilities': how does CDR affect country responsibilities to mitigate, or present opportunities to expand the carbon budget for the global south to further develop?

Countries that are parties to the UNFCCC are required to view climate policies in light of the principle of *Common but Differentiated Responsibilities and Respective Capabilities* (Article 3.1; Paris Agreement article 4.1). This principle is considered to encompass both the Polluter Pays Principle (PPP) and the Ability to Pay Principle (APP), which (respectively) focus upon national contributions to climate change and differential wealth and capabilities (Hayward, 2012). Future research through the justice and allocation lens could investigate how these principles could apply to the manner in which particular forms of CDR are implemented, or how they are distributed across different countries, geographies, and demographics. For instance, biomass for BECCS facilities could either be produced within the home country, imported from systems with high forestry and biodiversity standards, or left to a market approach prioritizing least cost, with correspondingly differing justice implications (see also ***3.1 Architecture and Agency***).

Carbon removal can be envisioned as a method to compensate for the emissions of "hard-to-abate" sectors, or a means to put forward ambitious goals by relying on future large-scale deployment of carbon-removal technologies (Sørensen, 2023; Buck et al., 2023). On grounds of justice, it is generally accepted that given the present shortfall in emissions-reductions any improvements in the effectiveness and affordability of carbon removal should not further slow efforts to reduce emissions (Shue, 2022). Research through the lens of justice and allocation can help to build on the risks of 'mitigation deterrence' (McLaren, 2020) by addressing both historical and potential (in)just and (in) equitable allocations of global carbon emissions and consequent climate impacts.

Research must also navigate calls for carbon removal to expand the carbon budget for the Global South to further develop. For some, historical inequalities could provide a rationale for those countries least responsible for historical emissions and most in need of "wriggle room" in their development trajectories to be afforded the same (or greater) status as hard-to-abate sectors. This could be implemented through differential allocation of carbon removal or take-back obligations (Bednar et al., 2021; Jenkins et al., 2021). Whatever the mechanism, obligations might be highest for countries most responsible for historical emissions and/or able to undertake emissions reductions, including in industries bearing additional profits and windfalls from the kind of asset inflation that emerges as carbon budgets become scarcer (see also ***3.1 Architecture and Agency***).

3.4. Adaptiveness and reflexivity

While the two concepts overlap, adaptiveness in the context of earth system governance focuses on the capacity to respond to changing social-ecological conditions, while reflexivity emphases critical consideration of prevailing values and practices in governing processes of change. Some key challenges at the intersection of adaptiveness and reflexivity in ESG are navigating tensions between stability and flexibility, dealing with increasingly globally-networked risks, and the need to reshape governance systems at all scales (Burch et al., 2019).

3.4.1. How can carbon removal be adaptively and reflexively integrated into climate governance?

Adaptiveness is built into the architecture of the Paris Agreement, specifically through the pledge-and-review process of Nationally Determined Contributions (NDCs) and the five-yearly global review of progress. Yet the situation is far from satisfactory, as most Parties have not outlined a credible mitigation path aligned with the long-term temperature goals and appear to utilize the ambiguity of future carbon removal to avoid scrutiny. This can be observed in the rise of net-zero emissions targets, which imply CDR as a "policy option" (Jacobs et al.,

2023). As long as the net-zero target serves as the guiding principle of global climate governance, CDR will remain a central pillar. Its prominence will be strengthened when overshooting the 1.5C target becomes to be viewed as a certainty upon the total exhaustion of carbon budgets, which implies that all future emissions need to be counteracted through more than equal amounts of global net-negative emissions. However, broadening the discussion and generally including diverse human development targets such as the SDGs can help expand and pluralize the needs, benefits and risks of CDR (Honegger et al., 2021a, see also ***3.1 Architecture and Agency***).

Research and action to increase adaptiveness in CDR – and wider climate – governance would entail (1) exploring how planning processes foreseen by NDCs and domestic policies, and iterative revision thereof, could be made more responsive as greater appreciation of issues and challenges emerges. Increasing reflexivity in CDR governance would mean (2) designing processes so that decisions about NDCs and domestic climate policy are made with the input of those affected by them and/or decisions can be made that reflect on the values of those that should have input but cannot (i.e. future generations).

3.4.2. What underpinning knowledge types, values, assumptions and practices are shaping CDR emergence? What is the role of scientific knowledge and practice?

Some CDR activities to date have faced major pushbacks (i.e. iron fertilisation, BECCS) because the socio-political implications of CDR were not taken seriously by those conducting first field trials, and affected stakeholders and publics were often not involved in designing and planning experiments (see e.g. Gannon and Hulme, 2018; Low et al., 2022). Governance responses to CDR activities have often been reactive and shaped by narrow risk management logics, rather than being adaptive and reflexive (see e.g. Boettcher and Kim, 2021).

Moreover, before the rise of net-zero discourse, CDR was largely framed as part of "geoengineering", coupled with solar radiation management (SRM). In the current era of Net Zero, CDR has re-emerged as part of mitigation (Honegger et al., 2021b). Now, given the emerging reality of overshooting the carbon budget, a new type of discourse on CDR might be materializing. Since a phase of global net negative emissions is – in modeling exercises – the last option to bring temperatures back down (setting aside solar radiation modification), CDR could be seen as necessary for "repair" or "recovery". This would have implications for what types of actions can be taken, and what types of actors can be legitimately involved (McLaren, 2018; Boettcher, 2020).

Reflecting on the performative effects of the evolution of CDR discourse should be a key element of future research. Future research through this ESG lens can help learn from past dynamics and debates to inform current and future research and governance developments (see also ***3.5 Anticipation and Imagination***). The role of scientists and engineers has been predominant in putting CDR on the agenda – e.g. through modelling activities and experiments (Anderson and Peters, 2016; Beck and Oomen, 2021; Carton et al., 2020). In the form CDR is generally conceptualized (as a scientifically-defined category), it fits specific assumptions, norms and values about how to think about climate change and its solutions (e.g. technocratic, least cost, top-down approaches). However, alternative conceptualizations may achieve the same physical result (removing CO2), through different public policy paradigms (e.g. locally-owned, benefits shared with the affected communities – see Buck, 2015).

Concrete suggestions for future research in this area include: Designing formats and processes to (1) increase reflexivity and accountability among those researching and developing CDR, about the role their own knowledge types, worldviews, assumptions, norms and values shape their work and (2) bring different knowledge types and worldviews into conversation at key points in CDR research and development processes, to increase the reflexivity of research trajectories and (3) designing visioning work aimed at developing on alternative CDR (policy) futures – e.g. a "charming Anthropocene" wherein people are empowered to do their own kind of removal (Buck, 2015) vs. "radical degrowth" where societal change removes the need to counterbalance emissions (Keyβer and Lenzen, 2021).

3.5. Anticipation and Imagination

The key earth system governance issues the Anticipation and Imagination can help to examine include: How to govern diverse anticipation processes (modelling, scenarios, assessments etc.); how anticipation itself becomes a site of politics; how anticipation processes and practices shape and limit what futures can be imagined, and how dominant social imaginaries shape and limit which new approaches to governance can be considered (Burch et al., 2019).

3.5.1. How can new scenarios and pathways be developed for carbon removal that focus on lived experiences and local implications of 'global cockpit' strategies?

We can improve how justice and equity are represented and distributed in emissions targets, technology selection, scenario construction, and pathway prioritization (Klinsky and Winkler, 2018; Jafino et al., 2021). Proposals range from fine-tuning existing integrated assessment modelling (IAM) work (O'Neill et al., 2020) to more fundamental reform towards combining IAMs with more qualitative, stakeholder-engaged work (Salter et al., 2010; Mach and Field, 2017). At the 'back end' of dissemination, many have pointed out mismatches in priorities between knowledge producers (e.g., IAM modelers) and their envisioned users (e.g., policy-makers) (Petersen et al., 2015). Research should understand the diverse demands in governmental and industry planning under which carbon removal-heavy emissions pathways already are and could be further mis-used (Brecha et al., 2021). While recognizing the steering power of global pathways, we must acknowledge the importance of mission-driven local-to-national modeling for policy planning. Where this is embedded in broader deliberation processes and combined with real-time observation, these can aid with monitoring, reporting, and verification (MRV) and carbon accounting, understanding carbon storage capacities, local conditions, and side effects (Low et al., 2022a,b).

In addition, there is a need to explore formats and processes that bring different knowledge types into conversation at key points in CDR research and development processes, and to increase reflexivity of research and governance trajectories (i.e. participatory futuring methods, deliberative engagements) - see also ***3.4 Adaptiveness and Reflexivity***. We might consider the 'situated', local interests of actors (polities, industries, organizations) regarding carbon removal, to supplement the top-down global planning view (e.g. Boettcher et al., 2023), as well as new knowledge communities (stakeholder groups, expansion of sectoral and academic perspectives beyond innovation; indigenous and traditional knowledge) in building assumptions on whether carbon removal is 'feasible' (Thoni et al., 2020). Such formats and processes might aim at (1) the development of inclusive imaginations of future (e.g., net-zero) economies and backcasting-based policy planning – for example, through mixed-methods that combine stakeholder engagements with systems-modeling to test technology and policy mixes (Low et al., 2022a,b; Muiderman et al., 2022), and other templates for expanding the creative, stakeholder-driven use of IAMs and scenario frameworks (Braunreiter et al., 2021). Many CDR approaches are immature or hypothetical. We can anticipate their challenges by extrapolating or imagining fully deployed CDR systems, and using them to engage stakeholders, and explore feasibility and desirability as well as needed policies and legal processes (e.g. Boettcher, 2023; Satterfield et al., 2023). We might also (3) map how discourse on CDR has evolved in order to learn from past challenges, as well as anticipate future developments to inform governance (see i.e., Boettcher, 2020).

3.5.2. How can these efforts challenge or improve established global assessment processes at IPCC, IPBES, and other science-policy interfaces?

Expanding how carbon removal and other mitigation efforts are conceived challenges the broader structure of global environmental assessments away from technocracy, imbalances towards the natural and technical disciplines, siloing, and the information-deficit model (Castree et al., 2020). A strong network within IPBES, one of the Convention on Biological Diversity's advisory bodies, has deliberately resisted the 'IPCC template' of science-first assessment, and constructed numerous alternative frameworks incorporating qualitative, societal scenarios, non-economic values toward nature, and non-scientific knowledge (Borie et al., 2021). There are further arguments for heightening the IPCC's potential to galvanize action: from modeling top-down, techno-economic strategies as part of comprehensive but non-policy-prescriptive assessment, to being an 'issue advocate' for transformational change, driven by policy-driven Special Reports and serving as a hub for bottom-up practices (Asayama et al., 2023). With special regard to biogenic forms of CDR, assessment should include diverse values of nature and human-nature relationships, which are gaining increasing prominence in sustainability policy discourses due to the IPBES Values Assessment (IPBES et al., 2022) - see also ***3.3 Justice and Allocation***).

We can also seek shared spaces between and within global environmental assessments – collaboration on cross-cutting issues that integrate different communities and assessment practices. The AR6 process created Cross Working Group issues, including carbon removal, to bridge disciplinary siloing within the IPCC (Vardy, 2023). The IPCC's Special Report on Land involved all three Working Groups as well as several other UN bodies examining land-use (and implicating carbon removal), in light of adaptation, food security, climate justice, and developing countries perspectives. IPBES has similarly begun a "nexus assessment" for the intersections of biodiversity with health, food and water security, and climate change, and IPBES and the IPCC have recently published a joint report on biodiversity and climate change (Pörtner et al., 2021, see also ***3.1 Architectures and Agency***).

Finally, of relevance is a flurry of reports on carbon removal, as expert networks and intergovernmental organizations map its implications for the audiences they deem relevant – for example, the International Energy Agency's Net Zero Report (International Energy Agency, 2021), the UNEP Emissions Gap Report (United Nations Environment Programme, 2022), and the GESAMP (2019) report on marine CDR. Future research might especially (1) compare two academic efforts: the State of CDR Report (innovation and policy-facing) vs. the Land Gap Report (Dooley et al., 2022 - critical, aimed more at agrarian/developing country concerns). We can ask (2) what types of assessments are able to innovate new modes of assessment, serve as templates and connections to established processes, or entrench established, neoliberal modes of environmental assessment and industry support (see also ***3.3 Justice and Allocation***, and ***3.4 Adaptiveness and Reflexivity***).

4. Conclusion: cross-cutting issues in an integrated ESG research agenda on carbon removal

In this perspective, we have sketched a broad set of CDR research questions through the ESG lenses, based on a mapping exercise that involved a diverse range of perspectives. As with any such exercise, the questions identified reflect the perspectives of those involved, and are far from exhaustive. In conclusion, with a bird's eye view over the research questions scoped in this perspective (summarized in Table 1), it is possible to identify key cross-cutting and inter-related issues that we believe are implicated in – and should be addressed through – multiple ESG lenses, and that can come to form the basis of an integrated earth system governance research agenda on carbon removal.

The first issue is the need to *move past an ecological modernist, techno-economic paradigm, whether in the assessment of carbon removal options, the construction of mitigation and emissions pathways, or policy planning* that narrowly caters to market mechanisms and entrenched industry interests. We must remain aware of particular interest capture and policy diversion regarding carbon removal development, accounting and offsets, and construction of NDCs and policies that feed into logics of delaying decarbonization, or that entrench (carbon) colonialism through land-grabs (for 'nature-based' approaches) or carbon waste exports (for direct air capture or BECCS). We can assess emissions pathways driven less by cost-effective, supply side technological innovations, and more by alternative dimensions of well-being and sustainability (e.g., the SDGs).

The second is the need for *governance that reflects globally networked challenges across sectors, levels, and issue areas* that pertain to biogenic and engineered forms of carbon removal, across marine and terrestrial landscapes worldwide. There is a need to bridge polycentric (embracing the agency and diversity of decentralized, locally grounded efforts) and integrated governance (linking and even steering efforts across levels, sectors, and issue areas). Such efforts must also navigate historic responsibilities as well as current and emerging capacity, allocating 'fair shares' in emissions commitments, financing, and compensation regarding the impacts of and solutions to climate change - including carbon removal.

The third recognizes the steering role of experts in governance

Table 1
An Earth System Governance research agenda for carbon removal.

Lenses	Recalling key issues in CDR assessment and governance	Research questions	Examples of (future) research efforts
Architecture & Agency	Diverse sectors & regimes: Climate, biodiversity, food systems, energy access and security, marine pollution, development	How to confront CDR as globally networked challenge? How to expand governance beyond ecological modernization?	Templates for governance across scales, issues, levels Scrutinize corporate agendas, monitoring (false) carbon accounting
Democracy & Power	Lack of information on public priorities esp. in global South Misidentification of challenges; backlash	How to enhance links between local and global democracy, or between democracy and sustainability?	Knowledge exchange processes Frameworks for feasibility, desirability and sustainability
Justice & Allocation	Competing uses of land, resources (e.g. food vs. fuel) Unequal capacities, vulnerabilities	How to address carbon colonialism (e.g. land grabs, monocultures, hazardous siting)? How navigate trade-offs in space and resources?	Distribution of kinds of CDR across different economies and geographies Fair shares frameworks
Adaptiveness & Reflexivity	Techno-economic agenda setting, innovation bubble forming Over-reliance on land CDR in national long-term strategies	How can CDR be integrated into Paris Agreement, national and corporate commitments? What knowledge is privileged in shaping CDR?	Knowledge pluralism and enhancing public agency to make bottom-up decisions Accountability and reflective processes
Anticipation & Imagination	Speculative or unscaled approaches Address shortfalls: society/social science, publics, national agendas, global South, multi-issue synthesis	How to move beyond techno-economic 'global planner' pathways? How to improve global assessment processes?	Anticipate 'whole systems' of CDR in different locales Re-imagine IPCC pathways, as well as global assessments as sites of production

processes: to develop *assessments that similarly reflect networked challenges, through inclusive participation, and mixed methods that bridge technical and societal scoping*. There is a need to reflect critically on past courses of action (e.g., the neoliberal, techno-economic paradigm), as well as to proactively develop pathways and assessments of options that repair the structural marginalization of various communities and demographics, and to include the knowledge systems and perspectives that they represent in authoritative assessment processes and reports that steer policy-making. We should create or adapt shared spaces – processes and outputs that bridge issues or sectors – for such activity, and maintain an orientation towards polycentric action and engagement.

Each of the above recognizes a fourth issue: *the significance of situated (actor- and locale-oriented) knowledge*. This is necessary to supplement global pathways and assessments that miss much of the polycentricity and agency of climate action or latent perspectives on carbon removal. It also recognizes structural inequities in who is (under)represented in authoritative assessments and governance processes, and can inform technocratic decision-making in both governments and industry. At the same time, we must navigate the power dynamics, or information and policy failures, that emerge with movements towards polycentricity. Emphasizing the 'bottom up' in carbon removal assessment is a corrective action, not a panacea; it must come with information and practice sharing and policy coordination across levels and borders.

Carbon removal is an unfolding field – subject to the push-and-pull of agendas and actors across academia, civil society, innovation, and policy. As a multi-disciplinary authorship group, we reflect this diversity ourselves. By proposing this research agenda, we aim to bridge many perspectives, from critical reflection, to expanding new kinds of knowledge and participation, to policy-design. We take an expansive view on carbon removal across the fullest, systemic scope of earth system governance – implicating energy politics, innovation and technology governance, food systems, biodiversity, marine spaces, even conflict, human, and state security. Finally, we hope that these insights and calls for action will not be taken as exhaustive, but indicative – and that the research agenda advanced here will be expanded and refined by others in years to come.

CRediT authorship contribution statement

Sean Low: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Miranda Boettcher:** Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Shinichiro Asayama:** Formal analysis, Writing – original draft, Writing – review & editing. **Chad Baum:** Formal analysis, Writing – original draft, Writing – review & editing. **Amanda Borth:** Formal analysis, Writing – original draft, Writing – review & editing. **Calum Brown:** Formal analysis, Writing – original draft, Writing – review & editing. **Forrest Clingerman:** Formal analysis, Writing – original draft, Writing – review & editing. **Peter Dauvergne:** Formal analysis, Writing – original draft, Writing – review & editing. **Kari De Pryck:** Formal analysis, Writing – original draft, Writing – review & editing. **Aarti Gupta:** Formal analysis, Writing – original draft, Writing – review & editing. **Matthias Honegger:** Formal analysis, Writing – original draft, Writing – review & editing. **Dominic Lenzi:** Formal analysis, Writing – original draft, Writing – review & editing. **Renate Reitsma:** Formal analysis, Writing – original draft, Writing – review & editing. **Felix Schenuit:** Formal analysis, Writing – original draft, Writing – review & editing. **Celina Scott-Buechler:** Formal analysis, Writing – original draft, Writing – review & editing. **Jose Maria Valenzuela:** Formal analysis, Writing – original draft, Writing – review & editing.

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

No data was used for the research described in the article.

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