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Governance of carbon dioxide removal: an AI-enhanced systematic map of the scientific literature

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Introduction: For limiting global warming to well below 2°C rapid and stringent GHG emissions reductions are required. In addition, we also need to actively remove CO_2 from the atmosphere via carbon dioxide removal (CDR). This will require advances in policymaking and governance to incentivise, coordinate and regulate CDR, including strict monitoring to ensure durable, additional removals that do not compete with emission reduction efforts. While it is critical to learn from the existing evidence on CDR policy and governance, there is no overview of this dispersed body of literature right now. IPCC and other science assessments have therefore treated the subject very selectively. This work addresses this lack of overview by systematically mapping the literature assessing policy and governance dimensions of CDR.

Methods: Systematic mapping provides a comprehensive view of a research field by analysing the state of evidence, i.e. how much research is available at any point in time on which topics and geographies studied by whom, when and where. We use an AI-enhanced approach to systematic mapping, trimming down an initial set of about 30,000 documents on CDR to a set of 876 that deal with governance and policy issues.

Results: Our findings show sharply growing attention to CDR policies and governance issues over time, but with limited coverage of the Global South. Long established conventional CDR methods such as afforestation dominate the literatureparticularly in ex-post studies -with little coverage of many novel CDR methods, such as biochar or direct air carbon capture and storage. We observe a shift from an initial discussion on CDR in international agreements towards the planning and implementation phase of national and sub-national policies.

Discussion: Our map can help to inform upcoming science assessments with critical information around CDR policies and governance and might serve as a starting point for generating a rigorous knowledge base on the topic in the future.

KEYWORDS
carbon dioxide removal (CDR), policy, machine learning and AI, systematic literature search, systematic mapping of literature, negative emission, governance

1 Introduction

Immediate and urgent reductions in fossil fuel and deforestation emissions are required to keep warming to well below 2°C in line with the Paris Agreement. But in addition, carbon dioxide removal (CDR) will have a role to play. CDR refers to capturing CO_2 from the

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atmosphere via human intervention and storing it reliably over a period of decades to centuries (Smith et al., 2023). CDR methods can reduce emissions in the near term, compensate for "hard-to-abate" residual emissions in the medium term, and would potentially allow global temperature exceedance to be reversed in the long-term (but would not compensate for the impacts of overshoot).

While CDR methods expand the range of options available to address climate change, it should be clear that they are not a substitute for emissions reductions: scenarios suggest an 8:2 ratio of effort between reducing CO_2 emissions and scaling CO_2 removals by the mid-century (Prütz et al., 2023), and a precautionary approach may suggest even more focus on reductions. Nonetheless, even low estimates of CDR requirements by the mid-century imply several gigatons of removals (Smith et al., 2023). It is therefore important to set the policy conditions for preserving existing levels of CDR while sustainably scaling new methods (Nemet et al., 2023).

CDR refers to a variety of technologies and methods, including those that are relatively well integrated into national policy and planning such as afforestation/reforestation, soil carbon sequestration and harvested wood products. These methods already entered the international climate negotiations discourse under the United Nations Framework Convention on Climate Change (UNFCCC) in the early 2000s (Carton et al., 2020). However, a range of further methods are now emerging that have so far had little exposure to national or international governance and policy regimes. These include bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), biochar, enhanced weathering and blue carbon. Taken all together, current CDR approximates 2 $GtCO_2$ per year, or about 3% of current global net greenhouse gas emissions (United Nations Environment Programme, 2023).

With the new logic of national "net-zero" targets that integrate both reductions and removals, it is becoming increasingly urgent to develop appropriate governance systems for CDR (Schenuit et al., 2021; Schenuit et al., 2023a). Many have discussed, for example, the need to organise separate policy tracks for reduction and removals, to avoid any fungibility and the risk that longer-term ambitions for CDR dilute short-term efforts to reduce emissions (McLaren et al., 2019; Rogelj et al., 2021). Emerging compliance markets under national or regional carbon pricing schemes will need to address such issues, while dealing with the central issues of permanence and how to govern liabilities for removals that expire after a certain period of time (e.g., afforestation/reforestation) (Edenhofer et al., 2023).

Alongside national policy making, corporate net-zero standards and voluntary carbon markets are emerging that could support businesses in decarbonising their operations, but could also offer new avenues for greenwashing. The European Commission's Carbon Removal Certification Framework, which aims to regulate certification of removals in the voluntary market, is particularly concerned with ensuring that CDR is appropriately quantified, that removals are additional, that carbon is durably stored, and that projects meet sustainability criteria (European Commission, 2024).

Certain types of CDR also carry social and environmental risks, such as the risk that a new wave of land appropriation in the global South occurs under the auspices of afforestation/reforestation projects (Dooley et al., 2022). A variety of other trade-offs will need to be addressed by CDR governance, depending on which methods are implemented in different regions. These could include the high levels of electricity demand associated with DACCS, the impacts of mining and material mobilisation with respect to enhanced weathering, or the broader landscape and biodiversity impacts of ocean and ecosystem-based methods (Prütz et al., 2024).

In this article we focus on the literature that has been produced to date on the governance of CDR. It is clear that attention on the topic of CDR has not been absent from the literature, including their role in national climate targets (Buck et al., 2023; Buylova et al., 2021; Smith et al., 2022) and integrated assessment scenarios (Minx et al., 2018; Prütz et al., 2023; Strefler et al., 2018), as well as their projected costs, side-effects and uncertainties (Fuss et al., 2018; Smith et al., 2015). However, we are aware of only a limited volume of studies on the governance of CDR, primarily driven by a recent special issue on the subject (Bellamy et al., 2021).

The primary objective of our article is to develop a "systematic map" of the state of the scientific peer-reviewed literature on the governance of CDR, as a prior step to accumulating knowledge in this domain. A systematic map is a form of systematic evidence synthesis that focuses on identifying and classifying the available literature on a given subject. Our aim is to conduct a descriptive analysis of the scientific literature on governance, providing a comprehensive overview of where evidence might be consolidated through reviews, while also identifying evidence gaps. In doing so, we aim to highlight areas where future research is needed and facilitate a more targeted approach to studying CDR governance in the context of climate policy. Our results reveal significant gaps in the literature in terms of how to integrate CDR into climate governance, including a lack of ex-post policy evaluations, even for mature methods such as afforestation/reforestation, soil carbon sequestration and forest management.

2 Methods

Systematic evidence synthesis stems from the notion that scientifically-informed policy making requires a rigorous assessment of the available evidence base. In certain fields, especially medicine (Higgins et al., 2022; White et al., 2020) and the environmental sciences (James et al., 2016), various methodologies for systematic evidence synthesis have been developed to gather, organise and synthesise scientific knowledge to inform policy making. As opposed to literature reviews, which tend to be guided by the prior knowledge of the author, these methods aim to minimise inherent biases in the selection and evaluation of the available scientific literature.

A systematic map, also known as an evidence map or gap map (James et al., 2016; Saran and White, 2018; White et al., 2020), is a specific type of evidence synthesis that aims to map out the evidence on entire research fields, asking "What is studied? By whom, where and how?." An important outcome of such an exercise is to identify knowledge gaps, or topics that are underrepresented in the literature that would benefit from primary research. Conversely, they can also highlight knowledge clusters, or subsets of evidence that may be suitable for secondary research, for example through a subsequent systematic review (James et al., 2016).

As in other types of evidence synthesis, systematic maps aim to be comprehensive, transparent and reproducible. Established guidelines (Collaboration for Environmental Evidence, 2018; RepOrting standards for Systematic Evidence Syntheses, 2024; White et al., 2020) distinguish 5–6 steps in this process. We follow these steps, as described in Figure 1 and in the subsequent sections.

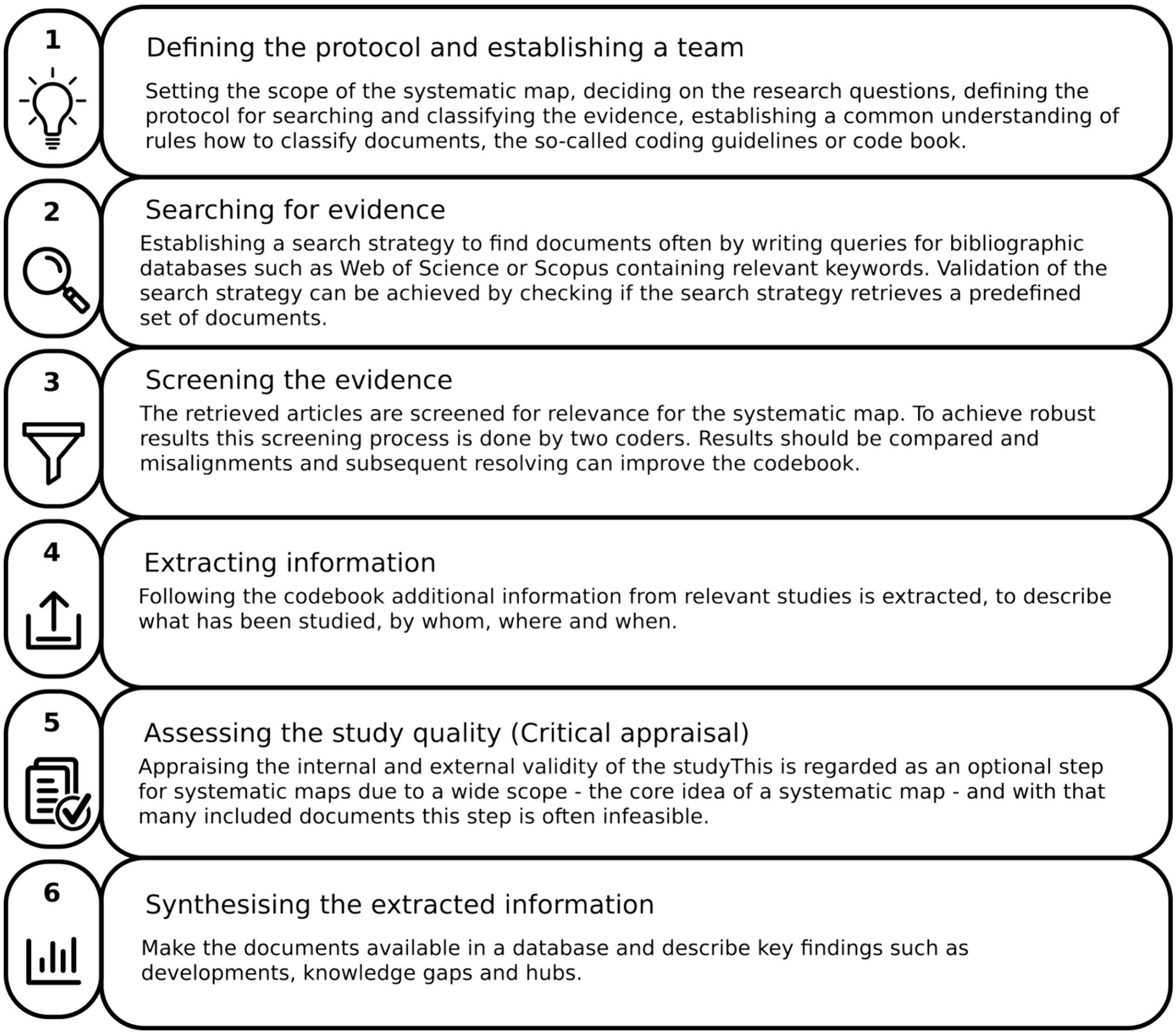

FIGURE 1
Overview of the 5–6 steps of creating a systematic map as established by Collaboration for Environmental Evidence (2018), Higgins et al. (2022), and White et al. (2020).

Further, in this article we make use of automated methods to enhance the speed and comprehensiveness of our systematic map. This overcomes some inherent constraints with the systematic mapping methodology: since, the growth of the literature in many research areas is rapid and sometimes even exponential, it can be impractical to screen and extract data from all relevant studies by hand. Faced with this problem, one can either narrow the scope of the study to a discrete field with relatively few studies, or retain a broad scope but apply automated methods. We choose to do the latter, and follow techniques established in prior work that have been used to develop comprehensive systematic maps on climate change literature, on climate change adaptation (Berrang-Ford et al., 2021; Sietsma et al., 2021) and climate change and human health (Sietsma et al., 2021). Of course, automated methods can introduce some uncertainties in the analysis, which we highlight in the discussion section of our article. Further, they cannot replace humans when it comes to the qualitative tasks and analysis. As such, we primarily rely on automation to speed up the screening and extraction of information from the literature, rather than the actual synthesis of these studies.

2.1 Study protocol

Our systematic map of governance and policy aspects of CDR is part of a larger sequence of research that aims to track and synthesise the entire literature on CDR, including studies that evaluate the costs, techno-economic potentials, side-effects and risks of these technologies. Accordingly, our study protocol, available in the Supplementary material, refers to this broader effort but is designed to ensure a consistent classification of different CDR technologies.

Our specific research questions are as follows: (1) what is the available scientific evidence on governance and policy aspects of CDR? (2) How is this evidence distributed across different CDR technologies, aspects of policy and governance, and case study locations? (3) What are the key knowledge clusters and gaps on governance and policy aspects of CDR?

2.2 Literature search

We conducted a structured literature search in the Web of Science and Scopus—the two largest bibliographic core collections. We constructed queries of search terms for 11 different CDR technologies, covering BECCS, DACCS, biochar, enhanced weathering, blue carbon, ocean fertilisation, ocean alkalinisation, afforestation/reforestation, forestry management, and peatland/landscape restoration.

In addition to CDR technologies, we include a series of search terms to capture CDR concepts in general, such as "negative emissions," "carbon dioxide removal," "greenhouse gas removal," etc. This is because much of the literature is concerned with broader discussions of how CDR objectives should be pursued in relation to emission reduction efforts, often with only passing mentions of specific technologies (Anderson and Peters, 2016; Geden and Schenuit, 2020; Ho, 2023). Similarly, this category captures broad discussions of geological reservoirs and terrestrial/ocean based sinks, which can be similarly decoupled from technology-focused articles.

The full list of keywords we use for each technology is available in the Supplementary material 1. Our search yields a large number of articles (75,518 after deduplication) that cover the full breadth of scientific discussions on CDR.

2.3 Evidence screening

As we are primarily interested in governance and policy aspects of CDR, we further narrow our search results using a combination of automated classification and hand-coding.

Our procedure was as follows. First, we screened by hand a random selection of results from the initial search query, totalling 400–600 documents per technology, for a total of 5,339 documents. For each document, we read the title and abstract and coded it for relevancy ("does the article refer to CDR?"). Second, and taking only the relevant articles, we further coded technology ("which CDR technology?") and content ("what is the main focus of the article?"). Under the content label we distinguished six categories: "governance and policy" were given for articles on laws, regulations, guidelines, and actions to guide CDR implementation and research, "public perception and acceptance" when opinions or stances in a given population and media coverage was investigated, "equity and ethics" for analysis of the ethical or normative dimensions of CDR technologies and their deployment, "earth system" and "socio-economic pathways" for modelling trajectories of natural or socio-economic development of CDR deployment, and lastly - by far the most commonly given label—"technology" was given for research on understanding and improving the CDR technology from a technical perspective. Articles could be classified with several content labels if they covered several aspects. In this manuscript, we focus on articles marked up as covering "governance and policy" aspects. To ensure a high quality of the labels, an essential pre-requirement for training machine learning classifiers, we coded all articles by at least two persons each, following which any disagreements were discussed and resolved. Decision boundaries were documented in a coding guideline to guide subsequent decisions.

Following this process, we used the hand-coded labels from our set of 5,339 documents to train machine learning classifiers to read the remaining unseen 70,179 documents from our overall search query. We fine-tuned the pretrained language model ClimateBERT (Webersinke et al., 2022) for this purpose, training classifiers to conduct a two step classification—first relevance, second additionally CDR technology, main content of the article—which reproduced our coding strategy (see Supplementary material for further details). The F1 score measures how good a model is by combining its accuracy in identifying positive results and its accuracy in avoiding false alarms. It ranges from 0 indicating least accuracy to 1. The Macro F1 score used for classification tasks with multiple categories averages the F1 scores for each category individually, ensuring each category is equally important, regardless of how often the category appears. We reached a F1 score of 0.91 for relevance and macro F1 scores of 0.7 for the CDR technology and 0.58 for the main content category. The F1 score for "policy and governance" specifically was 0.73. All F1 scores are provided in the Supplementary material. This means that we are confident that the classifiers are able to predict the relevant categories in a sufficient way. We extended the labels to the unseen documents using the machine learning classifiers and collected only documents which were coded as being on policy and governance of CDR. This reduced our final set of documents that discuss governance and policy aspects of CDR technologies to 876 (3% of the 28,976 relevant classified documents on CDR as a whole). We report on the complete literature covering other aspects of CDR in Lück et al. (2024).

2.4 Information extraction

In the final stage of gathering our data, we read all titles and abstracts of the 876 documents and extracted the following information: (1) what aspects of governance or policy are discussed? (2) Is an ex-ante or ex-post evaluation of policy offered? (3) What locations were mentioned? Further, we sub-sampled a set of documents that discussed measurement, reporting, and verification in the context of two technologies: afforestation/reforestation and BECCS (the two most substantively modelled CDR options in the scenario literature).

To classify governance and policy discussions we code the title and abstracts of the documents according to a categorisation scheme inspired by the Grantham Research Institute on Climate Change and the Environment and Sabin Center for Climate Change Law (2022) and the New Climate Institute (2020), but formalised by Callaghan et al. (2024). Adjusting this scheme, we describe three levels of policy effort covering 19 individual codes, as shown in Figure 2 and further described in Supplementary material 1.

To classify whether an article is an ex-ante or ex-post evaluation, we simply record whether it refers to a future or potential governance and policy development (ex-ante), or if it refers to an existing or past arrangement (ex-post).

To classify locations and case studies, we use named entity recognition to extract place-names from titles and abstracts and resolve these to a list of corresponding geographic entities (Halterman, 2017).

2.5 Synthesis

Our evaluation of the literature is descriptive, focusing on broad trends across different categories of technologies, governance aspects

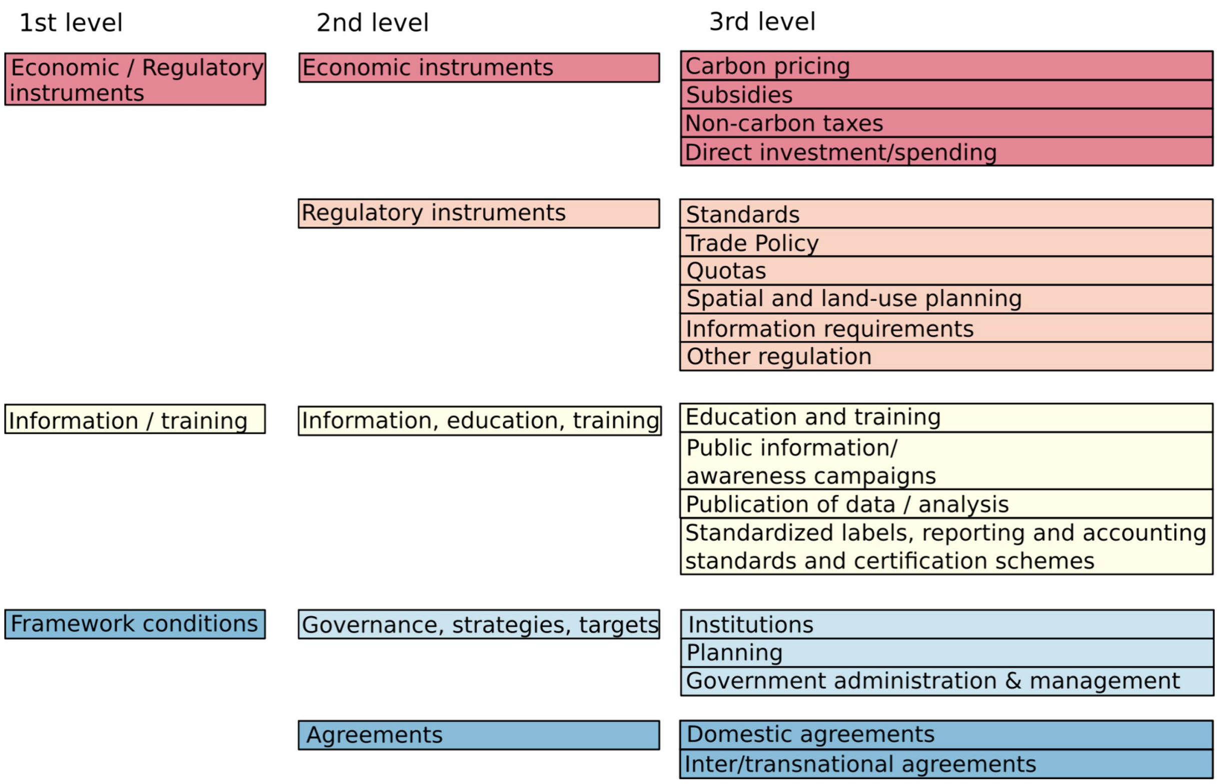

FIGURE 2
Hierarchical scheme of governance and policy instruments which was used to code scientific literature, adapted from Callaghan et al. (2024). Colour scheme is used in subsequent figures.

and policy instruments. In doing so, we focus on evidence clusters, evidence gaps, and the distribution of research—sometimes in comparison to the broader CDR literature that does not only cover governance and policy aspects.

3 Results

3.1 Research on policy and governance aspects of CDR is growing, following the overall growth of the CDR literature, albeit unevenly across different technologies

We found in total 876 documents that discuss governance and policy aspects of CDR. The literature has grown since the early 90s with an average growth rate of 13% in the past 10 years. Only a small proportion of the overall CDR literature deals with governance, but the share remains stable with 1–3% per year (Figure 3).

Land-based and longer established technologies constitute the largest part (51% of all policy papers) of policy literature, such as afforestation/reforestation (235 publications, 27% of policy papers), soil carbon sequestration (87 publications, 10%), restoration of landscapes such as peatlands (51 publications, 6%) and coastal wetland (blue carbon) management (74, 8%). The general literature that is not specific to any single technology is covered by 297 scientific publications (34%). Technologies where CO_2 is either captured from the flue gas of burned bio-material (Bioenergy Carbon Capture and Storage or BECCS) or from ambient air (Direct Air Carbon Capture and Storage or DACCS) and then stored underground are reflected in 9 and 3% of all publications on governance. Only 28 publications (3%) cover ocean alkalinity enhancement.

When compared to the technology distribution of the total CDR literature we found strong differences. Although the CDR literature as a whole strongly focuses on biochar (56% of scientific publications overall), specific research on governance aspects of biochar is almost entirely absent (22 scientific publications, 3% of publications on governance). Afforestation/reforestation on the other hand is more strongly represented in scientific publications on governance, 27% compared to 12% in the total CDR literature. This is not unexpected, as afforestation is one of the oldest CDR technologies (Minx et al., 2018) and is already recognised by many policies and agreements, including mitigation efforts under the Paris Agreement (von Hedemann et al., 2020).

3.2 Recent growth in the literature has focused on national implementation, rather than international agreements. However, ex-post evaluations remain scarce

Our evaluation of climate policies in the CDR literature is split into three broad categories: (1) studies on policy instruments

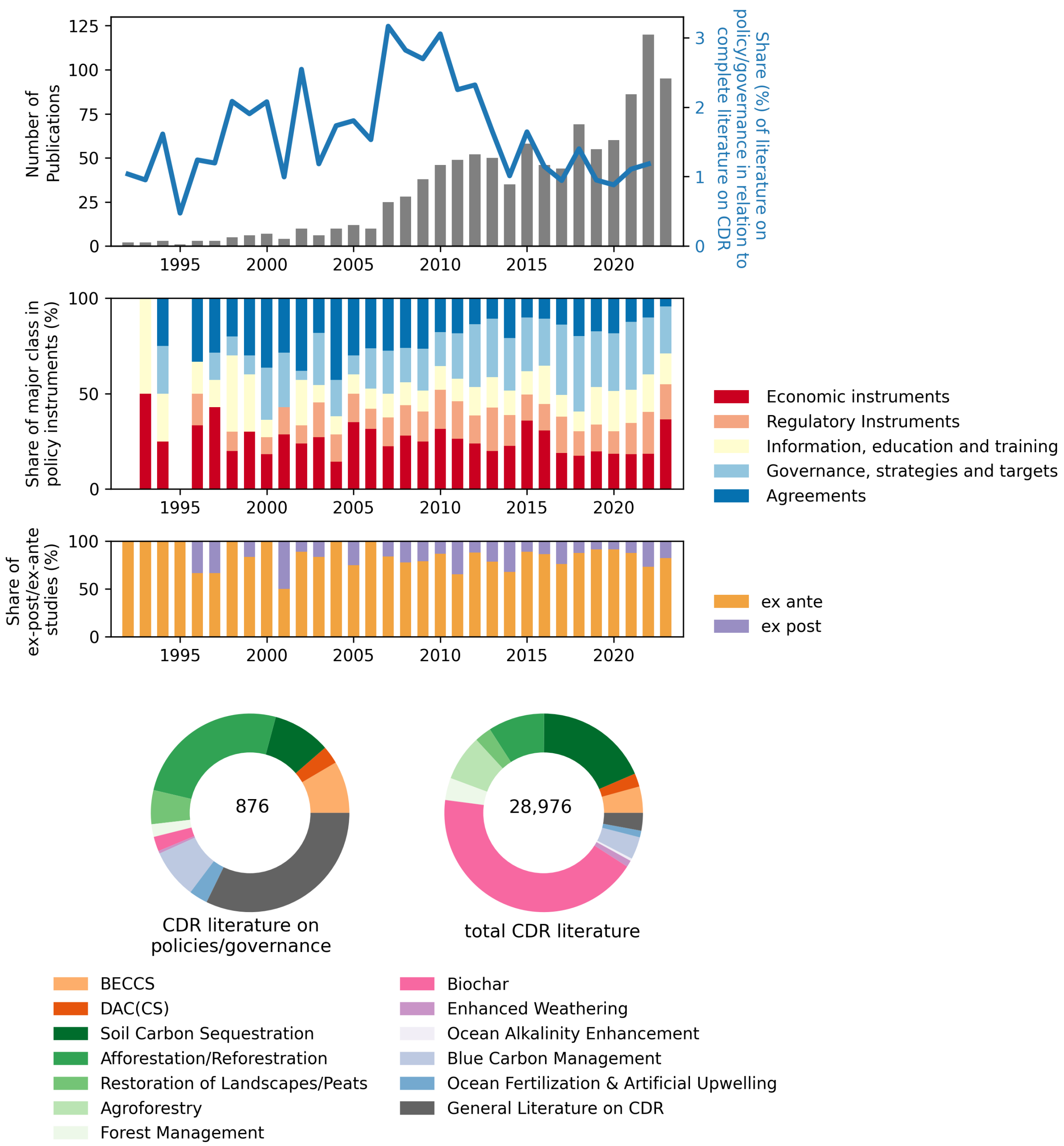

FIGURE 3
Time development of policy research on CDR and its coverage of different technologies compared to the total scientific literature on CDR Top panel: total number of publications on CDR with a focus on policies/governance per year between 1992 and 2023. Additionally, we show the share these documents have of the overall publications. Middle Panel: share of policy instruments covered in the scientific publications per year. Multiple instruments per publication are possible. Second middle panel: Share of scientific publications with ex ante/ex post evaluations per year. Bottom panel: shares of CDR technologies in the scientific literature on governance and policies aspects (left) and in the complete set of CDR literature (right).

themselves (economic and regulatory instruments); (2) studies on information, education and training; (3) studies that focus on the framework conditions for policy making (agreements, and governance, strategies, and targets) (see Figure 2). The literature to date has mainly focused on the first (77%) and second (71%) of these categories, while the third has received relatively less attention (23%), respectively (Note that where articles cover more than one of these areas, we double-count it in the total).

Policy instruments refer to studies on economic instruments, such as carbon pricing (179 documents, 20%), subsidies (76 documents, 9%), and direct investments (82 documents, 9%). Interestingly, we find only five studies on non-carbon taxes, which may be relevant in the land sector. In general, we observe a tendency in the literature to focus more on economic instruments compared to regulatory instruments (252 documents, 29%) (Figure 3), with the latter mainly focusing on spatial and land-use planning and standard setting (see Supplementary Figure 1).

Information, education and training concerns topics such as public information campaigns, education and training, and data transparency around CDR (237 documents, 27%). This overarching category also captures discussions of measurement, reporting and verification (MRV) (139 documents, 16%). MRV will be instrumental for integrating CDR into policy discussions, as it will form the basis for standardised and verified accounts of CO_2 storage, its durability and additionality (Schenuit et al., 2023b).

Concerning framework conditions, a large quantity of literature has focused on CDR in the context of international agreements (257 publications, 29%), such as the UNFCCC regime and the Paris Agreement. However, since about 2010, an increasing share of studies is concerned with national policy making contexts (Figure 3), including the development of national institutions (206 publications, 24%), and national strategies and targets (180 documents, 21%).

Overall, the literature has been relatively stable in terms of its focus on framework conditions, policy instruments and information, education and training. The last 5 years has started to see the focus shift away from international agreements towards national policy making contexts, as might be expected when policies begin to move into an implementation phase. However, we still observe that most scientific publications (821, 94% of all publications) are ex-ante evaluations. Therefore, actual evaluations of implemented policies are still in the minority—similar to other fields of public policy research (Lamb et al., 2020).

3.3 Economic instruments are investigated across all technologies, research on policies of land-based technologies reflect stronger active policies and their implementation

CDR methods are rather diverse in terms of sectors, stakeholders and technologies and thus present distinct policy and implementation challenges (Honegger et al., 2022; Schenuit et al., 2021). For instance, afforestation requires substantial land resources, whereas DACCS entails substantial energy consumption and the need for storage facilities. Furthermore, technologies vary in their readiness for deployment, from those in the early stages of innovation and research investments (DACCS, BECCS), to more mature approaches (afforestation).

Research on economic instruments is high across almost all technologies, from 30 to 54% of studies per technology, except ocean fertilisation. Specifically, articles tend to focus more on carbon pricing instruments compared to direct investments or subsidies (Supplementary Figure 2). Discussions of carbon pricing are especially prominent for BECCS (54% of all policy papers on BECCS), which is strongly represented in the techno-economic scenario literature (Fuss et al., 2018; Hilaire et al., 2019; Riahi et al., 2022).

Setting strategies and targets and involving institutions such as stakeholders can be important framework conditions for steering policies. However, these discussions have been rather unevenly distributed in the literature to date, with a focus on governance and stakeholder engagement for mainly land-based CDR methods. In fact, studies on afforestation, the restoration of landscapes, soil carbon sequestration and blue carbon are primarily focused on topics related to governance, strategies and targets (Figure 4). Notably, blue carbon, despite being considered as a marine CDR option, is often conducted on land through mangrove restoration projects and as such has a long implementation history similar to other land-based CDR options. In light of that, for the aforementioned technologies the share of ex-post evaluations is generally higher, from 17% for blue carbon to 39% for restoration of landscapes, compared to other CDR methods, such as BECCS (10% of papers on BECCS investigate ex-post evaluations) or DACCS (3%).

Research covering international agreements is particularly prominent for ocean fertilisation (46%, 13 documents) and afforestation (36%, 84 documents), as both technologies have been the subject of international agreements, including REDD+ and other UNFCCC agreements focusing on deforestation and land use emissions, as well as the London Protocol to regulate ocean fertilisation under the International Maritime Organisation.

Research classified under information, education, and training predominantly focuses on Monitoring, Reporting, and Verification (MRV), with 53% of documents on documents on information falling under the sub-category MRV (see Supplementary Figure 1). This emphasis is evident in the majority of the technologies, reflecting its importance (see Supplementary Figure 1). However, ocean fertilisation and upwelling - a marine-based CDR option - stands as exception, with only one document addressing MRV. This indicates a significant gap, likely due to the challenges associated with conducting accurate measurements in the ocean.

3.4 Research on CDR policies covers mainly United States, China, and Europe

About two thirds of CDR research on policies and governance relates to a specific geographic location. Such place-based research is important as it can consider national or local circumstances that determine the effectiveness of CDR policy implementation.

In total, we find in 525 out of 876 scientific documents refer to place-names in the title/abstract (Figure 5). That is significantly more compared to the overall research on CDR where only about one third of the documents are place-based research. A total 109 of those mention more than one country.

89% of place-based studies (466 documents) cover Asia, including China (159 documents), Indonesia (83 documents) and India (73 documents) as the largest focal points. North America is covered in 444 documents, Europe in 411 documents, especially the United Kingdom (158 documents) and Norway (47 documents). By contrast, few articles mention locations in Africa (84 documents) and or South America (51 documents), even though these regions are home to highly productive biomes that would support land-based CDR efforts.

While the broader pattern of governance and policy research persists also in place-based research (i.e., with a tendency to focus on economic instruments and framework policies), we find some divergences by region. While the differences are not large we find that international agreements are mentioned 10% more often for Africa

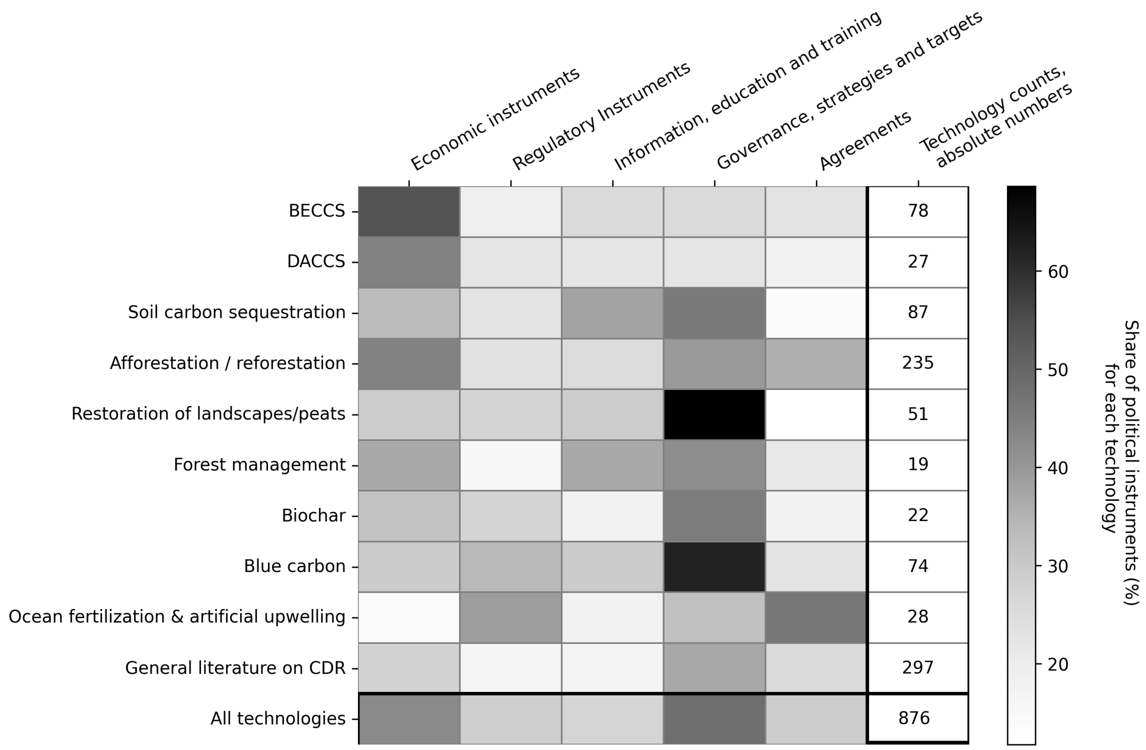

FIGURE 4
Profiles of research on governance and policy aspects for the different CDR technologies. For each technology we show the share of political instruments found in the papers. All shares of one row add up to 100%. The last row shows the shares for all technologies together. The last column displays the absolute number of documents per technology. One document can mention several technologies and/or political instruments and is then shown for each technology or instrument, respectively.

and 6% more often for South America than compared to all place-based literature.

4 Discussion

In this article we presented a comprehensive evidence map of the scientific literature on governance and policy aspects of carbon dioxide removal. We followed an established and rigorous procedure to be as comprehensive as possible and in order to avoid any knowledge driven biases, while using a novel machine learning approach to assist in the screening of thousands of scientific articles. In principle, these methods would allow us to continuously track the literature on governance and policies aspects of CDR going forward, enabling the rapid synthesis of newly emerging evidence.

As it stands, we find that research on governance and policy aspects of CDR is growing fast but remains a minor topic in the overall literature on CDR. The energy transitions literature consistently highlights the importance of policy regimes in structuring the growth of new technologies, alongside institutional rules and cultures, and stakeholder knowledge, engagement and opposition (Geels et al., 2017; Sovacool and Hess, 2017). The relative dearth of research in these areas with respect to CDR technologies, even in the case of quite mature approaches, underlines their nascency in the political domain. However, the political landscape is also rapidly developing, particularly in the United States and European Union, where the Inflation Reduction Act and the European Green Deal include a suite of supportive instruments for CDR technology development. Academia can independently observe and evaluate such measures, as has been done already in 174 ex post studies found in our systematic map, mainly concerning afforestation and restoration of landscapes (for a full list, see Supplementary material). Those could provide a starting point for an evidence synthesis to evaluate under which local conditions and constraints CDR development can be successful.

One important area of CDR governance concerns MRV, which is widely perceived as a prerequisite to developing market-based policies or integrating CDR into existing instruments. To what extent has the literature developed sufficiently to characterise MRV schemes in terms of key criteria, such as quantification, additionality, permanence, leakage, and sustainability (Paul et al., 2023)? Sub-sampling the studies in our systematic map, we find just 12 articles covering a novel CDR method (BECCS), wherein issues of quantification are acknowledged to be highly complex: complete system boundaries would require standardised quantification methods that include biomass growth, biomass transport and processing, interaction with the carbon cycle, biomass combustion, CO_2 capture, and CO_2 transport and storage (Fajardy et al., 2019; Torvanger, 2019). However, specific guidelines remain absent from the literature. By contrast, we identify at least 41 MRV articles on afforestation/reforestation, building from a rich evaluation literature on REDD+, CDM and forestry offset schemes, and suggesting that further evidence synthesis in this domain would be feasible.

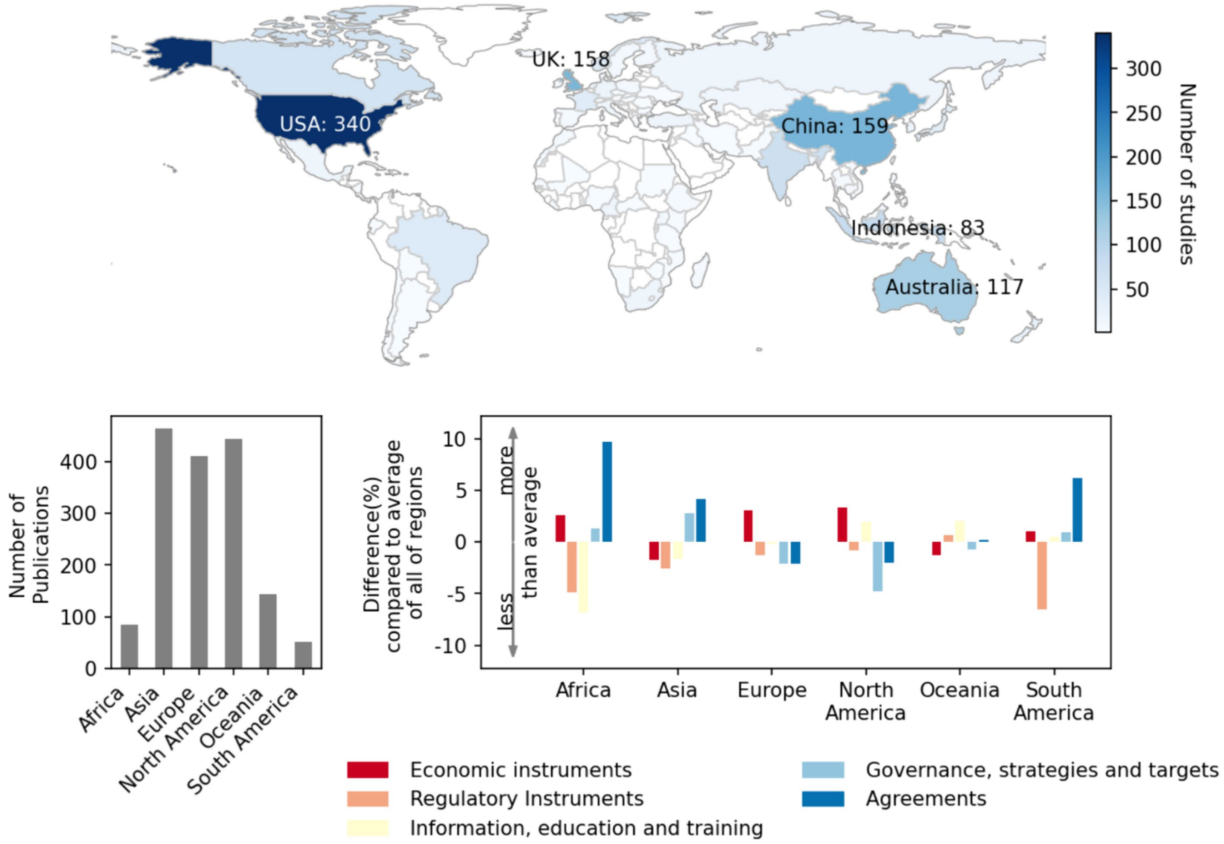

FIGURE 5
Place-based research is concentrated in China and OECD countries. Upper panel: number of studies per country based on places mentioned in title and abstract. A study can mention several places and is then counted for each country mentioned. The five most common study counts are added. Lower left panel: number of studies per continent. Lower right panel: for each world region we compare the percentage difference of the governance/ policy aspect against the average found for all world regions.

In general, the limited scope of governance and policy research on novel CDR methods contrasts with the predominance of these methods in techno-economic assessments. Indeed, BECCS is the most common CDR method in most scenario pathways for meeting the Paris temperature goal (Fuss et al., 2018; Hilaire et al., 2019; Riahi et al., 2022) and has received considerable attention in high-level editorials and commentaries (Anderson and Peters, 2016; Fuss et al., 2014; Galik, 2020). However, we find that the existing governance and policy literature mainly focus on how to incentivise research, and evaluations of carbon pricing schemes to incentivise BECCS deployment. Similarly, governance and policy studies of biochar are almost absent in the CDR literature despite its strong prominence in the overall literature on CDR, as well as its perceived co-benefits for waste management and soil fertility (Schmidt et al., 2021). DACCS is also the third lowest studied technology in a governance context, even though it attracts the largest share of current start-up investments (Smith et al., 2024). Among the most pressing of governance needs for novel methods is to ensure early and consistent policy support in their formative phases of technology development (Nemet et al., 2023). Without this policy support, it seems unlikely that niche voluntary markets can sustain novel CDR in the long-term. It would be therefore important to fill a current gap in the literature on evaluations of on-going policy experiments to support early novel CDR deployment, such as the UK-based CCS hubs or the DACCS credit scheme in the United States. A specific governance challenge in this context is whether DACCS plants should be required to connect to new, rather than existing, renewable energy production. This would on the one hand incentivise system-wide transitions to net zero, but could also raise barriers to scaling, mirroring challenges around the emerging governance of green hydrogen.

Finally, it is important to note the low coverage of location-specific literature on countries in the Global South. This is problematic insofar as CDR comprises a suite of technologies that may bring tangible benefits to local communities, such as flood protection from mangrove restoration, or enhanced soil fertility and agricultural co-production in sustainably implemented land-based measures. On the other hand, numerous risks have been highlighted, such as human health impacts from CO_2 transportation and storage (DACCS, BECCS) or in mining operations for enhanced weathering. Indirect risks are also undoubtedly present, as emerging voluntary and compliance markets could stimulate a new wave of land commodification and dispossession in the Global South (Dooley et al., 2022). Accordingly, we see a strong need to further evaluate the social outcomes of CDR implementation, with a specific focus on Global South contexts and justice aspects.

Automation through machine learning can accelerate information extraction and document categorisation in systematic maps such as this. Importantly, automation streamlines the management of large document volumes and allows reviewers to move beyond restricted searches or a focus on niche topics to cover large and comprehensive volumes of literature. However, despite its benefits, automation is not flawless, as acknowledged widely, and requires rigorous testing of machine learning models during development. Our machine learning approach varies in accuracy among tasks. While we can predict BECCS with a F1-score of 0.92 predictions of other technologies such as agroforestry are much poorer.

Constructing automated classifications demands substantial resources, particularly high-quality labels, prompting consideration of whether the effort matches the volume of documents to be classified. Smaller datasets may benefit from manual labelling, as demonstrated in our classification of different policy instruments. Moreover, cultural factors play a crucial role, as applying machine learning requires a skill set not commonly taught in social science curricula, potentially hindering interdisciplinary collaborations due to limited networks and disparities with quantitative disciplines where such techniques are more prevalent. Cultural acceptance of machine learning in science remains a challenge, as scepticism persists regarding machines replacing humans in research tasks (Haddaway et al., 2020), potentially impacting the publishability of scientific work.

While our aim is to identify all available literature, we must acknowledge certain inherent limitations. We conducted searches in two of the largest bibliographic databases, Web of Science and Scopus, which encompass a significant portion of scientific literature, focusing on English-language articles, which constitute the majority of relevant scientific texts. However, a substantial amount of scientific literature exists in other languages, as well as a sizable body of grey literature. Indeed, grey literature, particularly from private sector entities such as reports from consulting firms or non-profit organisations such as NGOs, can play a vital role, particularly for emerging technologies. This may contribute to the observed imbalance in location coverage and in certain engineered approaches such as BECCS or DACCS. Further, scientometric research estimates that Web of Science only comprises 40% of the total scientific literature (albeit with the last estimate in 2014) (Khabsa and Giles, 2014). With this in mind the complete literature on governance with respect to CDR might be more than twice as large as we report here.

5 Conclusion

The rollout of CDR is in progress and gaining recognition from a growing number of countries as a key strategy to confront climate change and support (but not replace) greenhouse gas emissions reductions. To effectively incentivise research and development, as well as to manage and monitor CDR implementation, it is imperative to establish robust policies. However, our findings indicate that there is currently low coverage in the policy and governance literature concerning the Global South, which may hinder the development of inclusive and globally applicable CDR strategies. Additionally, the literature on biochar is almost absent, highlighting a critical gap that needs to be addressed through targeted research. Furthermore, bioenergy with carbon capture and storage (BECCS) is predominantly discussed in terms of incentivising research and integrating into the carbon market, suggesting the need for broader discussions on its practical implementation, scalability, and environmental and social impacts. Research will play a pivotal role in assessing the outcomes of these policies, including their effectiveness, social outcomes and their implications for distributive and procedural justice. The evaluation presented here represents just the initial phase of a broader assessment process that must be sustained and expanded upon in the future.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

SL: Conceptualization, Data curation, Investigation, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing. AM: Conceptualization, Formal analysis, Investigation, Visualization, Writing – review & editing. WL: Conceptualization, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fclim.2024.1425971/full#supplementary-material

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