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Mapping the landscape of carbon dioxide removal research:
a bibliometric analysisRomain Presty^{1,2,3,*} , Olivier Massol^{3,4}, Emma Jagu¹ and Pascal da Costa¹¹ CentraleSupélec, Université Paris-Saclay, Laboratoire Genie Industriel, 3 rue Joliot-Curie, 91192 Gif-sur-Yvette, France² Center for Energy Economics and Management, IFP School, 228 av. Napoléon Bonaparte, 92852 Rueil-Malmaison, France³ IFP Energies nouvelles, 1 et 4 av. de Bois-Préau, 92852 Rueil-Malmaison, France⁴ Department of Economics, City, University of London, Northampton Square, London EC1V 0HB, United Kingdom

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E-mail: romain.presty@ifpen.fr**Keywords:** carbon dioxide removal, CDR, negative emissions, DACCS, BECCS, biochar, bibliometricSupplementary material for this article is available [online](#)**Abstract**

An intense global research effort on carbon dioxide removal (CDR) technologies is generating a rapidly expanding scientific literature. These contributions stem from various disciplines and investigate various CDR concepts and their potential implications. This study conducts an updated analysis of the international research effort on CDR from 2012 to 2023, examining 7893 publications using bibliometric techniques. We focus on the geographic distribution of technology-specific research and the funding driving this research. Significant publication growth is observed post-2015, particularly after 2018 and in 2023, driven primarily by the EU, China, and the US. Notably, biochar, afforestation/reforestation, and soil carbon sequestration are among the most researched CDR options, with direct air carbon capture and storage, bioenergy carbon capture and storage, and blue carbon also receiving substantial attention, especially in 2023. Analysis of scientific funding patterns aligns with these trends. Based on these findings, the study proposes a knowledge roadmap to elucidate emerging trends in CDR literature, offering insights for future research and policy development.

1. Introduction

The intergovernmental panel on climate change (IPCC) consistently emphasizes the critical role of carbon dioxide removal (CDR) technologies in mitigating the impacts of climate change and enabling a smooth transition to a sustainable future (IPCC 2014, 2018, 2019, 2022). Various CDR options are envisaged, including bioenergy carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), biochar, afforestation/reforestation, soil carbon sequestration, enhanced weathering, blue carbon, and ocean fertilization. These technologies are deployed across different climate scenarios to achieve negative emissions on a global scale, an essential component for genuine carbon neutrality (Ho 2023). In particular, CDR technologies are indispensable

for limiting global warming to 1.5 °C above preindustrial levels and are incorporated into numerous 2 °C pathways (IPCC 2022). Due to their potential, CDR technologies have gained significant attention in policy and scientific arenas (Schneuit *et al* 2021). However, their deployment faces challenges in readiness, scalability, economic viability, and environmental and societal impacts, requiring thorough consideration (Fuss *et al* 2018, Nemet *et al* 2018, Jagu Schippers 2022).

Given the rapid global expansion of CDR research (Minx *et al* 2017), examining its directions and dynamics is timely and offers insights for successful deployment. Structured mapping of the CDR landscape is needed for two main reasons: CDR is evolving quickly and gaining policy momentum, especially with BECCS and DACCS technologies (McCulloch

et al 2019), and its interdisciplinary nature requires cross-disciplinary connections (Rogelj *et al* 2015, Carton *et al* 2020, Grant *et al* 2021). Differing perceptions among professional communities can hinder interactions, making a trans-disciplinary perspective essential. As a result, bibliometric analyses are key for mapping CDR research while mitigating bias (Haddaway *et al* 2015). A triad of systematic reviews on CDR in 2018 (Fuss *et al* 2018, Minx *et al* 2018, Nemet *et al* 2018) coincided with the IPCC's Special Report on 1.5 °C (IPCC 2018), laying a solid foundation for growing CDR research. Since then, bibliometric studies have focused on Carbon Capture and Storage (Omeregbe *et al* 2020, Khosroabadi *et al* 2021, Ritchie and Tsalaporta 2022), carbon sinks (Huang *et al* 2020), specific technologies (Miranda *et al* 2022, Zolfaghari *et al* 2022), and mitigation scenarios (Hilaire *et al* 2019).

This paper provides an updated overview of the CDR research landscape in the years 2012–2023, focusing on the geographic distribution of technology-specific CDR research and the funding driving this research. Using bibliometric analysis, we quantitatively assess the field to offer a structured picture of existing literature and research trends. This approach enables the identification of key institutions, authors, and funding sources while highlighting potential gaps in research efforts. From a policy perspective, our analysis unveils comparative performances among countries engaged in CDR research, reveals specialization patterns, and analyzes differences in funding schemes. Moreover, it identifies national research priorities and their impact on the scope and direction of CDR studies, providing valuable insights for designing research policies that promote the development of CDR technologies and optimize resource allocation.

From a methodological standpoint, the effectiveness of this CDR literature overview depends on the careful selection and analysis of specific datasets, thus ensuring a comprehensive understanding of various CDR technologies and their associated studies. In our study, we consider a large set of CDR techniques, including enhancing forest coverage through afforestation and reforestation, stimulating phytoplankton growth via ocean fertilization, the application of enhanced weathering that grinds up small parts of ground silicate minerals that capture CO₂, blue carbon that focuses on the conservation and restoration of coastal and marine ecosystems, such as mangroves, seagrasses, and salt marshes. We also investigate technologically advanced solutions such as BECCS, where we use biomass for energy and then capture and store the CO₂ they would have released, and DACCS, which directly captures CO₂ from the atmosphere and stores it underground.

Our analysis highlights a growing literature with surges after 2015 and 2018, with the European Union (EU), China, and the United States of America (US) leading the way, followed by Australia, the United Kingdom (UK), Canada, and Germany. CDR research is mainly studied in environmental sciences, while other fields such as agriculture, engineering, energy, and technology show country-specific focuses. Among CDR technologies, biochar, afforestation/reforestation, and soil carbon sequestration have received the most attention in terms of research volume, with DACCS, BECCS, and blue carbon following closely behind, gaining prominence since 2015 and especially after 2018. Our data reveals a focus on specific technologies in different countries. Academic funding has significantly increased over the years, predominantly from China, the EU, and the US, with the UK following. Academic funding patterns show China's strong emphasis on older technologies, while the EU and the US influence academic research towards newer CDR technologies like DACCS, BECCS, and blue carbon, albeit without complete dominance. Our results indicate significant competition, intentional or not, between the US and China in DACCS research investments. The EU has historically led in funding DACCS and BECCS research, but there has been a notable decline in CDR research funding in 2022 and 2023.

The paper is organized as follows. In the next section, we present the data and the methodology. The third section provides a comprehensive analysis supported by graphical visualizations and tables and discusses the findings. Finally, the last section offers a summary and some concluding remarks. For the sake of reproducibility, [appendix](#) presents the search queries employed to obtain the data.

2. Data and methods

2.1. Data

We consider the period covering the years 2012–2023. The choice of a restricted timeframe is consistent with the standard recommendations for bibliometric studies (see, e.g. Luo *et al* 2022) that emphasize the potential shortcomings (e.g. visualizations quality, data comparability) of including previous publications in recent analyses and specifically recommend the use of a decade as the most appropriate time frame for readability and comparability purposes. Moreover, this timeframe is relevant due to the recent development of the CDR literature, as shown in figure 1.

Following AlRyalat *et al* (2019) guidance, our bibliometric data is extracted from Web of Science, using the query presented in [appendix](#) that is the one already used in the landmarks reviews of Minx

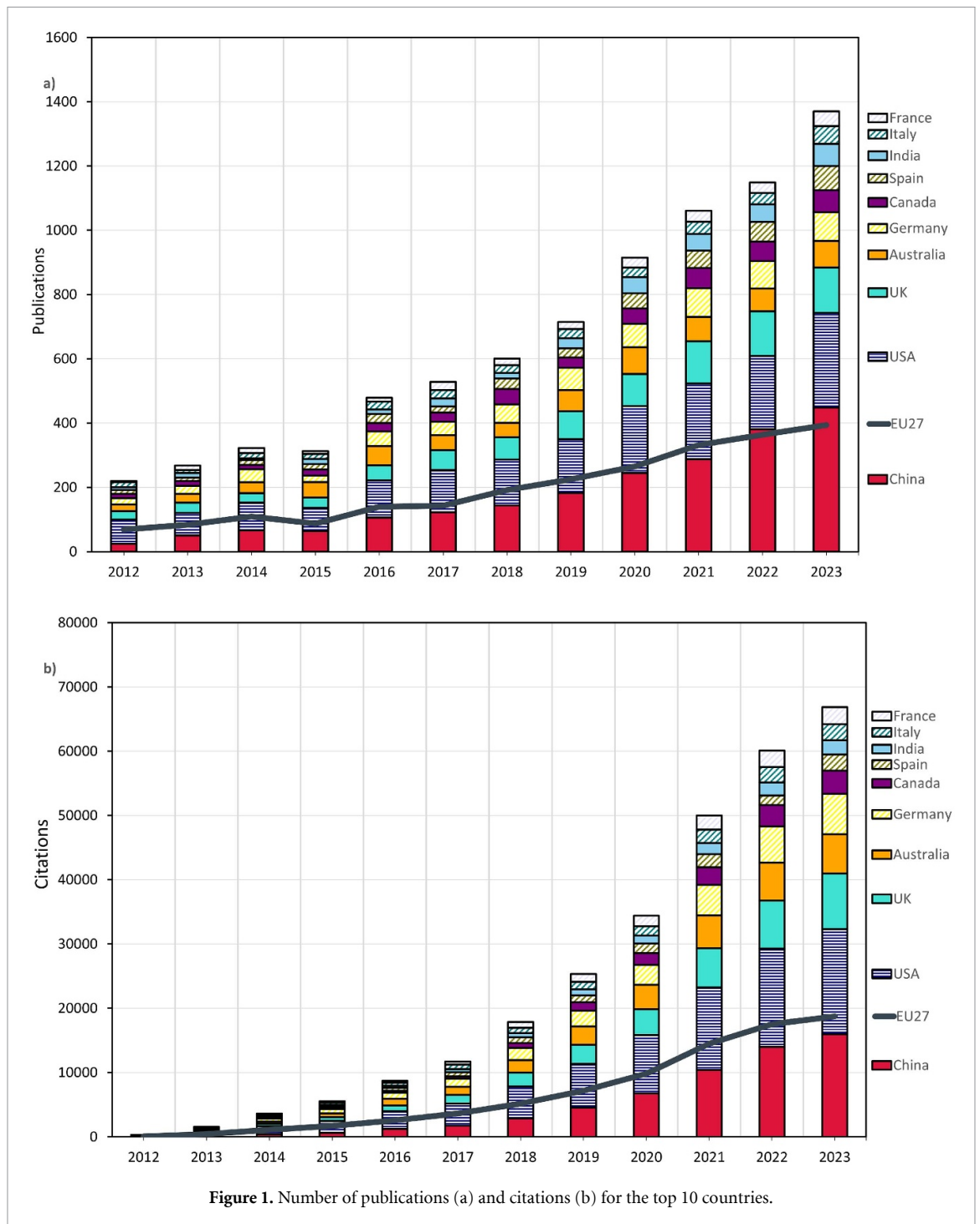


Figure 1. Number of publications (a) and citations (b) for the top 10 countries.

et al (2017, 2018), Fuss *et al* (2018) and Nemet *et al* (2018). This query yields a sample comprising 9806 observations.

To correct for the possible presence of duplicated occurrences in our sample (which could reflect similar works presented in various forms, including conference proceedings or book chapters), we further restrict our sample to include published articles solely. In addition, we use a dedicated algorithm to verify potential duplicates. The algorithm is as follows. Two records are considered the same if they match the first author's last name, the first ten letters of the title, the first ten letters of the source, the

year of publication, the DOI, if any, and the number of pages. If we find duplicates, we keep the Web of Science version. If none of the records is from the Web of Science, we keep the one with more information, i.e. the longer one. We ensure zero duplicates as their presence could introduce bias into our study. This filtering yields a restricted sample that includes 8355 publications. Additionally, we have qualitatively examined the data and detected the presence of publications unrelated to negative emissions or CDR technologies. We removed the inclusion criteria for all fields with less than five publications in order to eliminate unrelated fields such as pharmacology,

medicine, and music publications. The resulting dataset has a total of 7893 observations. Subsequently, this dataset is partitioned into seven subsamples, one for each CDR technology. These subsamples respectively include 1299 publications for soil carbon sequestration, 1573 publications for afforestation/reforestation, 1959 for biochar, 191 for ocean fertilization, 250 for enhanced weathering, 994 for BECCS, 897 for DACCS, and 768 for blue carbon. Note that publications covering multiple technologies can appear in multiple datasets.

2.2. Method

Bibliometric studies are quantitative examinations of the literature that account for the characteristics of a particular publication (Yu *et al* 2017). This methodology inherently allows for a quantitative disclosure of characteristics, evolutionary trends, and research priorities (White 2018). In this paper, we conduct a performance analysis using metrics such as the number of publications, the number of citations, and the average number of citations per publication to determine the productivity and impact of the publications. From a methodological standpoint, our analysis is derived from the literature on bibliometric analysis methods (e.g. metrics) (Donthu *et al* 2021) and software tools (Moral-Muñoz *et al* 2020) that provide guidance for data cleaning.

As a preliminary step, we use the extracted data to gain an overview and a better understanding of our dataset. We visualize the data to gather insights on the macro-level trends within the literature. By examining the characteristics of the literature across different countries, we seek to answer questions such as: which countries, institutions, and authors are active in the CDR research community, and what are their focus areas? Do countries' research activities align with climate objectives and industrial and geographical characteristics? Can we quantify their contributions effectively? We use simple data visualization techniques to investigate these questions and cross-reference them with real-world policies, applications, and projects to glean insights and answers.

In this initial stage of our analysis, we visualize trends and changes in the focus of the research community over time. We illustrate the proportion of publications dedicated to each technology, providing an understanding of the distribution of research effort. Additionally, we demonstrate the growth in the number of publications in the CDR field over the years, offering insights into the evolution and expansion of the field. To demonstrate the country-specific focus on CDR, we use the Herfindahl-Hirschman index (HHI). This commonly used indicator captures in detail the 'concentration' of a portfolio (IEA 2007, Bazilian and Roques 2008a, Löschel *et al* 2010). This index is derived as follows:

$$HHI = \sum_{i=1}^N \left(\frac{\text{Publications}_i}{\sum_{i=1}^N \text{Publications}_i} \right)^2$$

With i being the type of CDR method and Publications_i the number of published studies. This index value sits between $1/N$ (e.g. 12.5% for 8 CDR methods) and 1 (only 1 CDR method has publications).

In the second phase of our analysis, we delve into the allocation of funds for CDR research by extracting funding information from the Web of Science. This funding information includes the names of funding agencies and the associated grant numbers. Investigating the flow of funding offers valuable insights into the strategic planning of various countries or regions regarding specific CDR plans or directions. This, in turn, provides an indication of their response to climate change and sustainability goals. However, this approach has certain limitations. We do not have access to the exact amount of allocated funds, which means that some technologies might receive more substantial financial support than expected from our results. Additionally, the dataset containing funding information is smaller than the initial dataset.

3. Results and analysis

3.1. Preliminary insights: how and where is CDR researched?

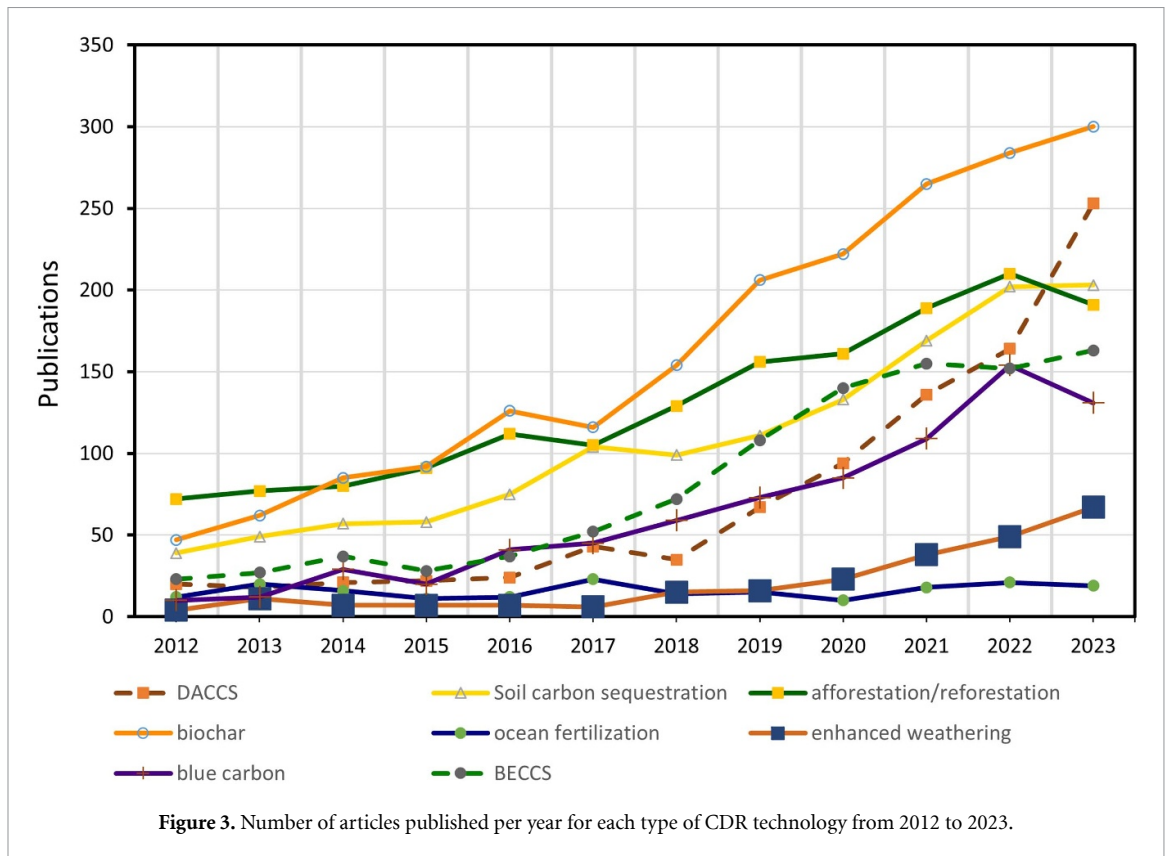
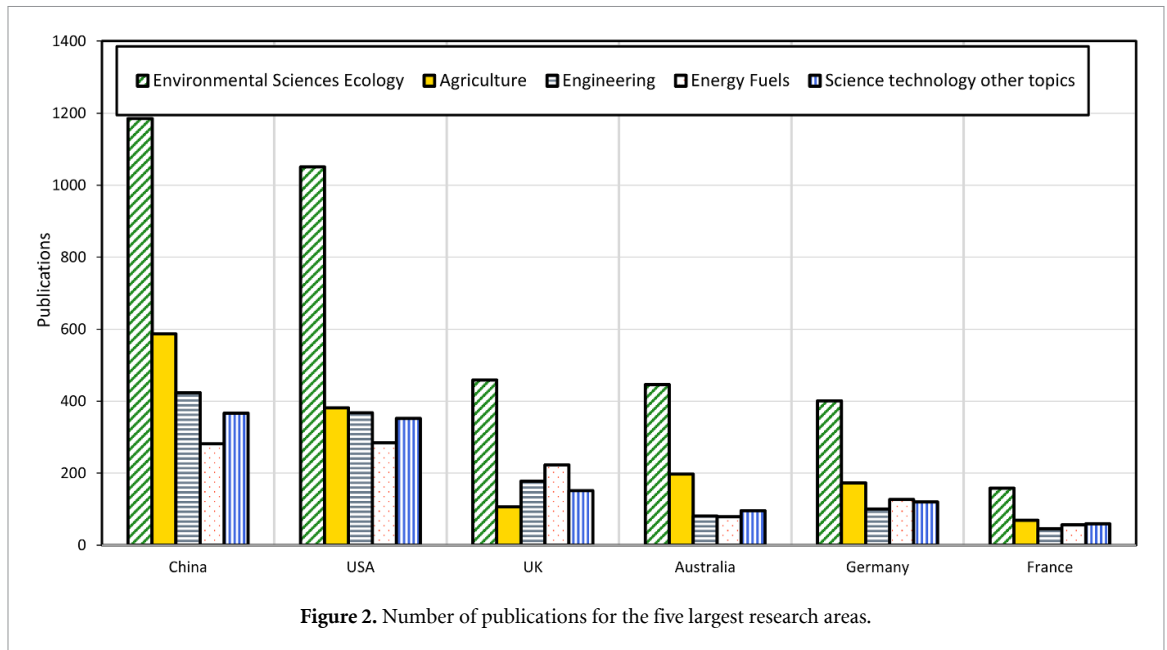
3.1.1. The time dimension

We first investigate the temporal progression of CDR literature among countries. The histogram shown in figure 1(a) presents the top 10 countries in volume of publications⁵. A clear trend of increasing publications per year across all countries indicates a growing global interest in CDR technologies, resulting in an exponential growth in citations. From 2012 to 2022, the total number of publications increased fivefold. Significant surges in publication volume occurred after 2015, 2019, and 2023, possibly tied to international events or advancements in the field, such as the Paris Agreement in 2015 and the IPCC reports in 2018 and 2022. Finally, despite China having more publications than the US (and the EU after 2022), we observe fewer citations for Chinese publications.

3.1.2. Insights from a disciplinary clustering

We now explore the disciplinary landscape of CDR research by analyzing publication patterns in the literature. Figure 2 maps out the most influential research areas in CDR, following the disciplinary classifications of Web of Science based on publication volume. The 'Environmental Sciences and Ecology' field dominates the literature across all countries, typically

⁵ Due to collaborative research across countries, our data may contain double-counting. For instance, a publication co-authored by France and the US is counted once for each, thus inflating the total when summing individual country counts.



including soil sciences and marine biology studies. The second dominant field then varies by country. A high focus on ‘Agriculture’ can be observed in China, Australia, Germany, and France. In the UK, the focus is predominantly on ‘Energy and fuels,’ a field that covers BECCS-DACCS and biochar. The remaining research areas include ‘Engineering,’ which is often associated with models and scenarios, and ‘Science technology other topics,’ which includes publications related to the technological aspects of CDR. As

shown in our data, the distribution of research areas highlights a diverse and country-specific disciplinary engagement with CDR technologies.

3.1.3. Insights from a technological perspective

We now investigate the evolution of interest in each CDR technology to explore the heterogeneity among CDR technologies.

Regarding specific technologies shown in figure 3, BECCS and DACCS have seen significant increases

in research activity, especially after 2015 and 2018. Interestingly, the number of BECCS articles surpassed that of DACCS articles until 2022. In 2023, DACCS received unprecedented attention, which could indicate an increasing confidence in the feasibility of the technology. Overall, these results corroborate a recent study showing a relatively high expert support for research on and deployment of BECCS and DACCS (Kerner *et al* 2023).

Soil carbon sequestration and afforestation/reforestation have also seen significant growth in research activity. The relatively higher maturity of these CDR methods (IPCC 2022) may contribute to their popularity. Biochar has also seen an increase in interest, possibly due to its easier access and multiple benefits, such as improving soil fertility in addition to carbon sequestration. Ocean fertilization and enhanced weathering have seen less research activity than other technologies. Lastly, the research on blue carbon has seen an important growth since 2015 and 2022.

These findings provide additional insights into the data presented in figure 1. The first research boom in 2015 marks the beginning of the recognition of CDR and the possibility of new ways of capturing carbon, such as BECCS. After 2018, new technologies began to emerge. Finally, 2023 saw DACCS receiving the largest growth in attention.

3.2. The geography of CDR research

3.2.1. Insights from a country-specific perspective

This section explores the production of articles on each CDR technology across countries.

The distinct emphasis on CDR technologies, as shown in figure 4, highlights national priorities, resources, and policies. This figure presents two scales: the most active countries in CDR research (Graph A) and the countries that are relatively active but not leading the field (Graph B).

The EU, China, and the US show significant research output on biochar, afforestation/ reforestation, and soil carbon sequestration. This focus suggests a potential emphasis on techniques with higher technological readiness levels and multiple co-benefits outside of CDR. In the EU, BECCS also receives an important amount of attention (and DACCS in a smaller way) that corresponds to the EU vision for industrial carbon management, with new CO₂ storage capacity in 2030 for instance (European Commission 2024). The US leads the field in DACCS and Blue Carbon research. The robust focus on DACCS can be linked to the US Department of Energy's dedicated funding for DACCS technology research and development (US Department of Energy 2021). Meanwhile, the extensive research on blue carbon might be associated with the US's vast coastal and marine ecosystems and their potential for carbon sequestration (Kauffman *et al* 2020). China, on the other hand, prioritizes biochar, soil carbon

sequestration, and afforestation/reforestation. This focus may be driven by China's commitment to reforestation efforts and the potential for biochar and soil carbon sequestration techniques to enhance soil health and productivity while also providing carbon sequestration benefits (Majumder *et al* 2019). Australia's research is primarily on blue carbon, likely due to its geographical characteristics (Gulliver *et al* 2020), followed by biochar and afforestation/reforestation. Interestingly, Australia's research activity in BECCS and DACCS is relatively limited. The UK, focusing on BECCS and its access to one of Europe's largest carbon dioxide storage sites (the North Sea), invests a significant portion of its research in BECCS (Drax Group 2023). Similarly, Germany has a significant focus on BECCS.

To ease cross-country comparisons, we also consider a quantitative measure of diversity: the HHI, as presented in the method section. By construction, this indicator reflects both variety (i.e. the number of technologies researched) and balance (the spread among these technologies) (see: Bazilian and Roques 2008b, Massol and Banal-Estañol 2014).

In the US and the EU, we observe a balanced activity across technologies, as shown by the research concentration index (HHI) of 15% and 16%, respectively. Compared to China's high HHI of 22%, the US and the EU have highly investigated emerging technologies (BECCS, DACCS, and Blue carbon) since 2015. On the other hand, China has maintained its historical focus on biochar, afforestation/reforestation, and Soil carbon sequestration.

3.2.2. Impact of CDR research

The top ten countries are detailed in table 1, along with their associated academic characteristics. The h-index is described as follows: a set of papers has an h-index of N if there are N published papers that have N or more citations each. It is an indicator of how many well-cited papers are in this set of papers. A key observation from the data is the prominence of the EU, China, and the USA in CDR research, each demonstrating a substantial volume of publications and a high h-index. This indicates an active and influential literature, with an average citation count of around 20–50 per publication. We also note some differences between the most prolific and influential institutions and authors.

3.2.3. A focus on institutions and individuals

The top 10 institutions presented in table 2 are mostly groups of research departments or universities that facilitate high-volume production. It appears that among the top countries in our rankings, the UK is the only one without a collective research group comprising multiple universities. While Chinese publications have the lowest average citations, France

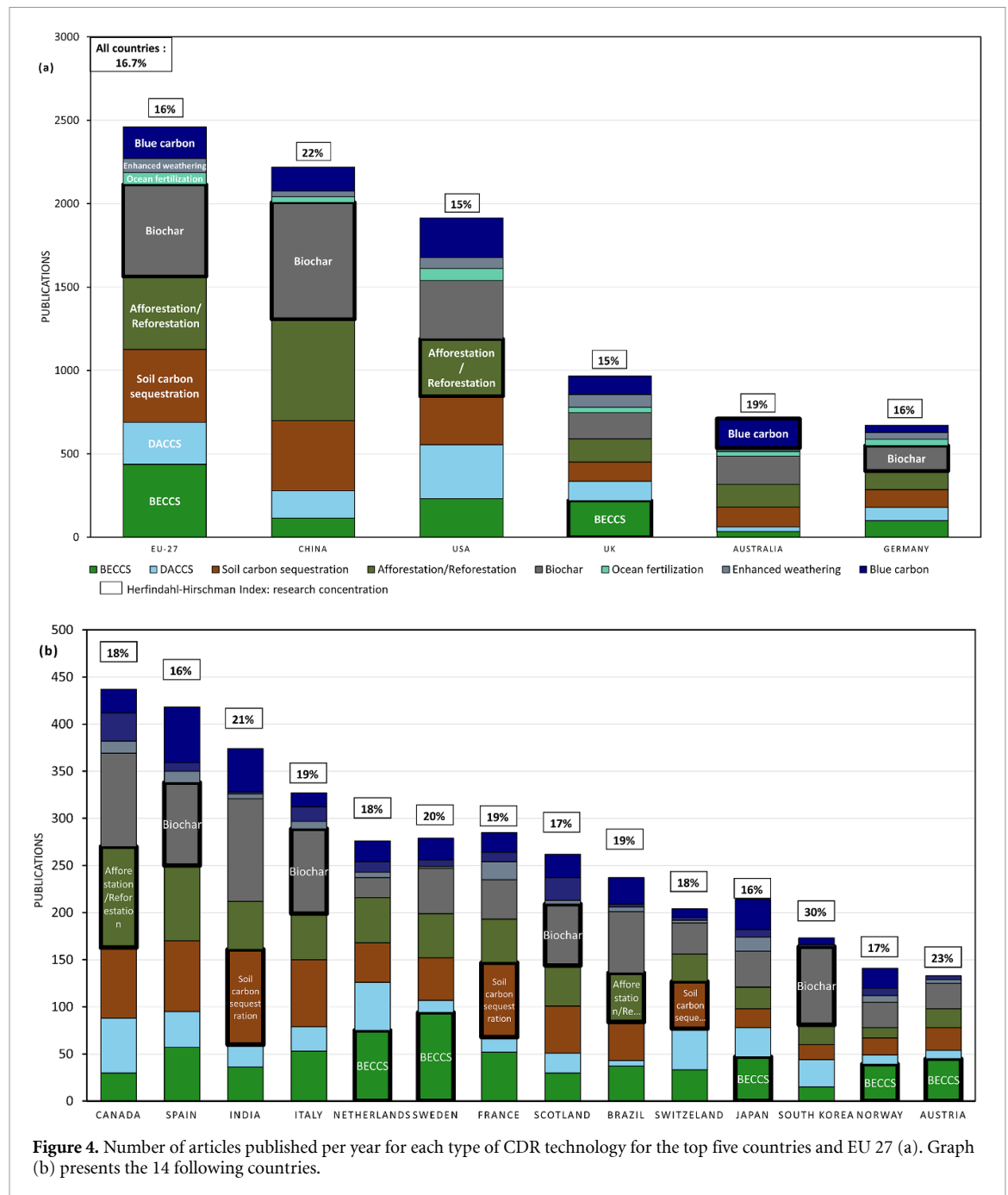


Figure 4. Number of articles published per year for each type of CDR technology for the top five countries and EU 27 (a). Graph (b) presents the 14 following countries.

has the highest ratio for both countries and institutions. Finally, we observe diversity in research focus, even if some technologies are less emphasized. For example, DACCS is only a top focus of the US Department of Energy.

3.3. How is academic CDR research funded?

3.3.1. Funding sources for CDR research

Table 3 illustrates the distribution of funded publications across various institutions from 2012 to 2023. Funded publications are articles with a declared statement of funding in the manuscript. The publications that have not declared any funding are directly stated as ‘unfunded or unknown fund’ in our dataset. From the data, several key trends and observations can be

identified. The National Natural Science Foundation of China has consistently been the leading contributor to scientific publications over the considered time period, with a significant increase in the number of funded publications in 2016.

The EU, the UK Research Innovation (UKRI), and the National Science Foundation (NSF) have also significantly contributed to the total count of funded publications. The UKRI has demonstrated steady growth in its funded research output, with a consistent upward trajectory in the number of publications funded until 2021. However, the NSF and the EU exhibit more variability over the years, possibly indicating shifts in research focus or fluctuations in funding availability.

Table 1. Top ten countries and their respective characteristics. The first column presents the country and its associated h-index. The second column is the actual number of publications published. The third column is the total number of references for those publications, and it only includes external references, with a maximum of one reference per paper. The most prolific institution and author are the ones with the highest number of publications, while influential means the highest number of citations.

Country (h-index)	Total publi.	Total reference	Most prolific institution	Most prolific author	Influential institution	Influential author
EU (125)	2451	52 945	CSIC (Spain)	van Vuuren, D. P. (Utrecht Univ.)	CNRS	Ciais, Philippe (U. Paris-Saclay)
China (108)	2177	37 089	Chinese Acad. of Sci.	Wang, Hailong (Foshan Univ.)	Chinese Acad. of Sci.	Deng, Lei (Tsinghua U.)
USA (125)	1880	50 266	Univ. of California	Jones, Christ. (Georgia IT)	USDA	Lal, Rattan (Ohio U.)
UK (74)	893	25 537	Imperial Coll. London	Smith, Pete (U. of Aberdeen)	Imperial Coll. London	Smith, Pete (U. of Aberdeen)
Germany (85)	679	20 742	Helmholtz Association	Kuzyakov, Yakov (Un. Göttingen)	Helmholtz Association	Luderer, Gunnar (PIK)
Australia (83)	676	21 818	CSIRO	Macreadie, Peter I. (Deakin University)	CSIRO	Macreadie, Peter I. (Deakin U.)
Canada (51)	447	12 708	Univ. of Brit. Columb.	Chang, Scott X (Univ. of Alberta)	Univ. of Brit. Columb.	Angers, Denis A. (AAFC)
Spain (58)	405	10 085	CSIC	Penuelas, Josep (CREAF-CSIC)	CSIC	Marba, Nuria (IMEDEA)
India (45)	364	9075	ICAR	Maiti, Subodh K. (IIT)	IIT System	Mohan, Dinesh (JNU)
Italy (59)	327	10 715	CNR	Tavoni, Massimo (CMCC)	CNR	Tavoni, Massimo (CMCC)
France (54)	274	10 851	CNRS	Ciais, Philippe (U. Paris-Saclay)	CNRS	Ciais, Philippe (U. Paris-Saclay)

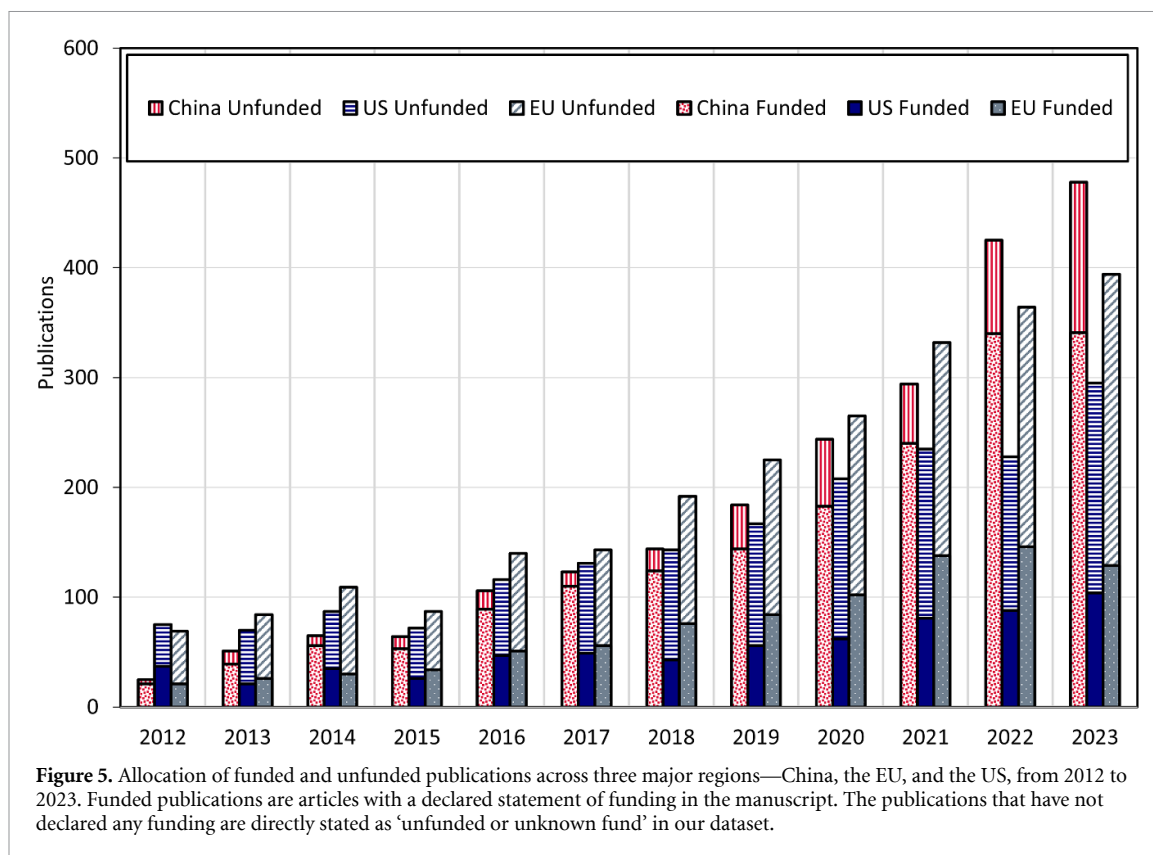
Table 2. Top ten institutions and their respective characteristics. Top ten countries and their respective characteristics. The first column presents the institution and its associated h-index. The second column is the actual number of publications published. The third column is the total number of references for those publications, and it only includes external references, with a maximum of one reference per paper. It finally displays the three main CDR technologies focused on in their research.

Institution (h-index)	Total publications	Total references	Main focus	Second focus	Third focus
Chinese Acad. of Sciences (71)	663	15 618	afforest./ reforest.	Soil carb seq.	Biochar
University of California (48)	183	8530	Soil carb seq.	afforest./ reforest.	Biochar
Northwest AF Univ. China (41)	182	5053	afforest./ reforest.	Soil carb seq.	Biochar
US department of Energy (43)	182	7061	DACCS	Biochar	BECCS
US dep. of Agriculture (40)	176	5998	Biochar	afforest./ reforest.	Soil carb seq.
CSIC (Spain) (37)	151	5605	Biochar	enhanced weather.	BECCS
Helmholtz Association (Germany) (41)	147	5020	Ocean fertiliz.	Biochar	afforest. reforest.
CNRS (France) (41)	139	7105	Soil carb seq.	BECCS	afforest./ reforest.
Ministry of Agri. (China)(31)	138	2653	Soil carb seq.	afforest./ reforest.	Biochar

Some institutions, such as the National Basic Research Program of China and the Ministry of Education, Culture, Sports, Science, and Technology Japan, showed a declining trend in the number of publications funded. However, the overall number of publications with a declared statement of funding increased significantly over the

years, from 118 in 2012 to 682 in 2023, suggesting a global growth in public recognition of CDR.

From the data, the NSFC, the EU, the NSF, and UKRI appear to be the top CDR academic research funders in their respective regions. While the NSFC and the EU keep a consistent and growing funding



allocation, the NSF and UKRI do not uniformly fund CDR research, still with a growing trend.

Finally, the funding agencies’ funded publications are consistent with the most active countries in the CDR literature shown previously and the surges in CDR interest after 2015, 2018, and 2023 with our previous analysis.

3.3.2. Funding allocation and technology preferences

Figure 5 presents the allocation of publications funded and ‘unfunded or unknown fund’ across three major regions—China, the EU, and the US, from 2012 to 2023. One striking observation from the data in figure 5 is the close numbers of declared funds (1740) and publications (2177) originating from China. This near-parity may suggest strong central planning that dictates the direction of academic research, which tends to allocate funds to areas that are national priorities and led by central institutions. This is reflected in Soil Carbon Sequestration, Afforestation/Reforestation, and Biochar receiving the highest levels of investment⁶. In contrast, this correlation is less evident in the cases of the US (648 vs 1880) and the EU (1016 vs 2451). This might be indicative of their different approaches to scientific research.

⁶ The main funding agency in China is the NSF of China (table 3) which is directly administered by the Central government. Their main tasks can be found here: (<https://fundit.fr/fr/institutions/national-natural-science-foundation-china-nsfc>).

Figure 6 illustrates the allocation of funds across different CDR technologies in three major regions—China, the EU (which includes EU Bodies), and the US—other regions are also included when they are among the top funders on a specific technology from 2012 to 2023.

An unexpected finding is the technological shift observed in regions outside of China. The EU is allocating relatively more funds towards BECCS than expected, considering the region’s predominance of soil sciences publications. The U.S. presents a similar pattern but towards DACCS; their investment in DACCS exceeds that of biochar by far. In 2023, funds in all technologies except DACCS were stagnant or lowered. The growth in DACCS funding in 2023 corroborates the growth in DACCS publications.

Building on this trend, it is worth noting that the EU is investing in various promising technologies. The allocated funding is fairly distributed across all promising technologies and may even be higher for newer and more technologically sophisticated methods such as BECCS and DACCS since 2018. Surprisingly, blue carbon received enormous attention, specifically during the year 2022 for the EU.

Conversely, the US seems to be allocating its additional funds towards DACCS, BECCS, and Blue Carbon, while Soil Science research stays constant at the top, with 2021 being a special funding-intensive year. This shift could indicate a policy transition towards innovative and potentially scalable CDR

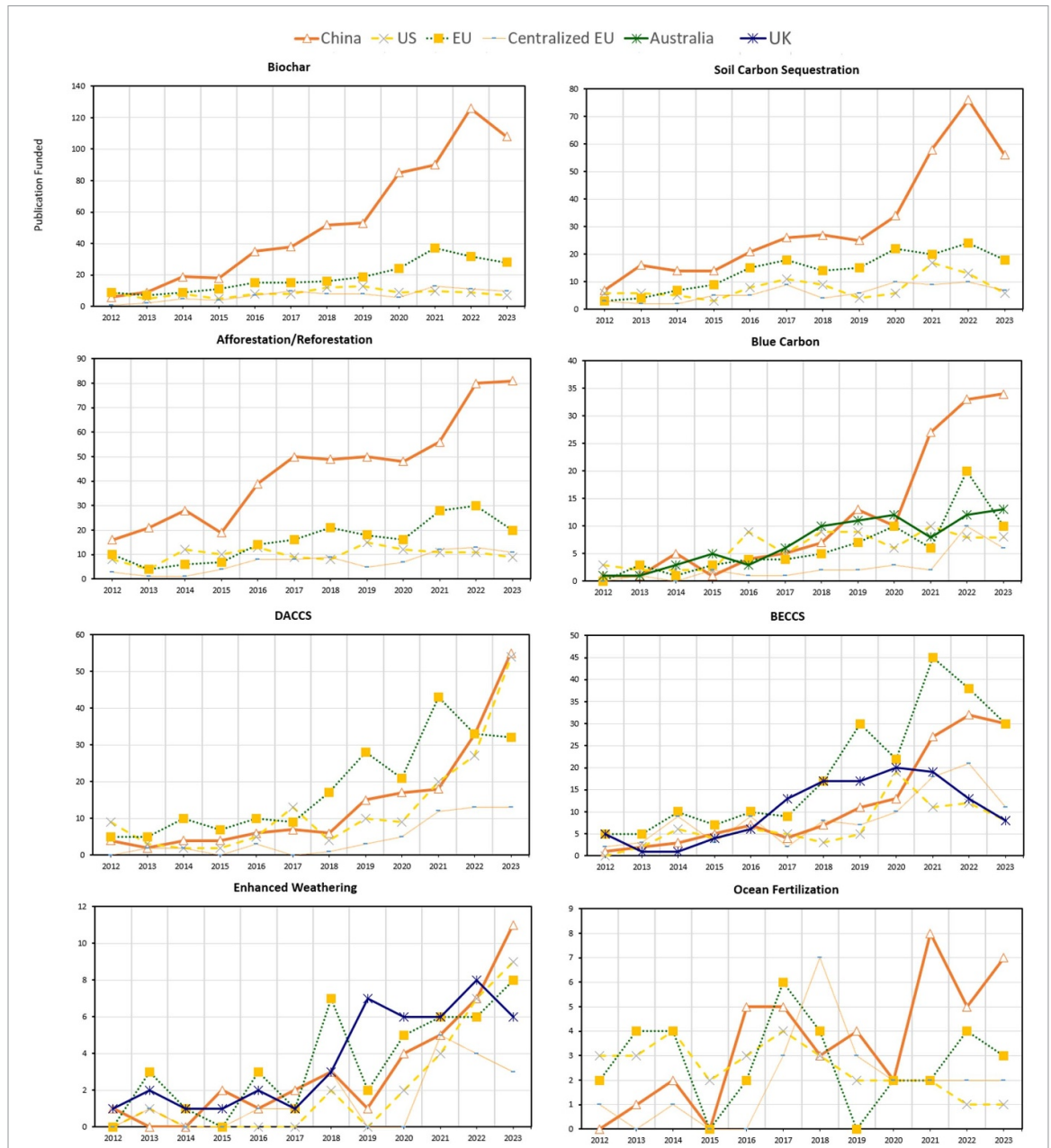


Figure 6. Allocation of funds across different CDR technologies in three major regions—China, the EU (of which includes EU Bodies), and the US—other regions are also included when they are funding a higher amount of research on a technology, from 2012 to 2023. Funded publications are articles with a declared statement of funding in the manuscript. The publications that have not declared any funding are directly stated as ‘unfunded or unknown fund’ in our dataset.

solutions. The stagnation of funding from the US for Soil Sciences technologies may suggest a perceived research saturation in this area or a strategic pivot towards other technologies. The US research does not rely much on grants compared to China and the EU.

In general, both the EU and the United States seem to invest less in maritime technologies. The EU has the smallest investment in ocean fertilization and blue carbon research, while the United States is least involved in funding enhanced weathering studies. Interestingly, smaller regions such as the UK and Australia are making a noticeable impact.

The literature on enhanced weathering is predominantly funded by the UK, which also holds a strong position in BECCS research. When the

funding contributions of the EU and the UK are combined, it becomes clear that BECCS occupies a central and perhaps dominant role in their climate change strategies. Meanwhile, Australia stands out for its significant investment in Blue Carbon research, a focus that aligns with its unique coastal geography.

Despite being the least active and starting with relatively modest funding levels, the European Bodies have increased their funding across all technologies over the past decade. The EU bodies’ funds are predominantly directed toward BECCS research, followed by studies in soil sciences. Other technologies, however, attract significantly less attention from funding agencies. For instance, DACCS receives a considerably smaller portion of the funding but is a

relatively newly funded technology, with funds actively growing since 2018. Despite a growing trend in funding for maritime CDR, particularly focusing on blue carbon in 2022, research in maritime technologies remains significantly underfunded. This highlights a potential area for increased attention and support.

4. Conclusion

In light of the rapid growth and expanding diversity of CDR research, there is a pressing need for a structured interdisciplinary perspective on the existing literature and research trends. This study proposes an updated picture of the CDR research landscape in the years 2012–2023, focusing on the geographic distribution of technology-specific CDR research and the funding driving this research. Through bibliometric analysis, we aimed to facilitate the identification of research trends, key contributors, funding sources, and potential gaps in the research landscape. Our data encompasses all published research on the eight main types of CDR methods, representing approximately 7900 papers.

Our exploration highlights the diversification and expansion of CDR research, marked by three notable surges in activity after 2015, 2018, and 2023. We observe a growing literature driven by the EU, China, and the US, followed by the UK, Australia, Canada, and Germany, with significant attention given to Biochar, afforestation/reforestation, and soil carbon sequestration historically. Emerging technologies such as DACCS, BECCS, and Blue Carbon have gained prominence since 2015, with DACCS receiving unprecedented attention in 2023. Each country appears to pursue its own goals and objectives regarding CDR, reflecting varying technological focuses.

One striking observation is the differences in research portfolios. The US and the EU exhibit the most diversified approaches to CDR research, whereas China's strategy focuses on CDR methods that present high co-benefits for agriculture. In developing their research strategies, the US and the EU focus on BECCS and DACCS in distinct ways. The US primarily concentrates on DACCS, directing about half of its efforts towards BECCS, whereas the EU does the opposite. This divergence may stem from the US viewing CDR as a pathway to innovation, supported by the Inflation Reduction Act and the willingness to continue fossil energy (Bigger *et al* 2022). At the same time, the EU considers it primarily as a climate neutrality tool (Tatarewicz *et al* 2021).

The analysis of academic funding reveals that the EU and the US have adopted a diverse research strategy in a range of technologies, particularly DACCS and BECCS, since 2018. Investigating funds highlights greater diversification in CDR research than merely examining research volume for those two regions. In contrast, the NSF of China funds the

vast majority of Chinese research, indicating strong central planning due to the strategy of 'command and control' (Liu *et al* 2021) and a less diversified approach, as evidenced by the concentration index. The results on the funding for DACCS indicate significant competition, intentional or not, between the US and China in DACCS research investments. Historically, the EU has been the leading region in funding DACCS research. However, in 2023, there was a noticeable reduction in the funds allocated to DACCS and other CDR methods. Based on the EU's climate objectives (IPCC 2022), the EU should be careful not to under-invest in CDR research compared to other regions. After 2021, the EU failed to remain the most productive region in BECCS and DACCS research. China and the US did the opposite for DACCS by investing in almost three times more publications in 2023 than in 2021.

Our study is limited by several factors. First, our data are limited by including only English-speaking studies. We may leave out a big portion of Asian, South American, and even European parts of the literature (Linkov *et al* 2021). A second factor to consider is the metric used for publication; we used the number of articles published, with no access to the differences in publishing strategies or the quality of published articles. In a similar way, we have access to the declaration of funds within each study; some studies may not disclaim any funds, even if some were perceived. In addition, we do not have access to the monetary amount of those funds.

It should also be noted that some of the publications included in this study may not primarily focus on CDR but rather on other co-benefits. For example, biochar provides numerous benefits for agriculture (Tisserant and Cherubini 2019, Campion *et al* 2023) and biodiversity (Tammeorg *et al* 2017). Afforestation and reforestation offer co-benefits such as habitat provision, biodiversity enhancement, soil retention, water conservation, and reduction in non-point source pollution (Li *et al* 2021). Soil carbon sequestration improves soil health, which is beneficial for food production (Eddy and Yang 2022). Blue carbon contributes to coastal protection and habitat restoration (Morris *et al* 2023), and enhanced weathering mitigates ocean acidification (Taylor *et al* 2016). In contrast, other CDR methods may have minimal or no co-benefits or even negative side effects. BECCS mostly has negative side effects beyond energy production, and DACCS primarily presents negative impacts (Prütz *et al* 2024).

In conclusion, this study underscores the need for continued interdisciplinary research efforts to address the challenges and opportunities in the field of CDR. Leveraging bibliometric analysis can advance knowledge and offer timely insights to inform research policy decisions aimed at achieving carbon neutrality and mitigating climate change. Future research directions could include a more

extensive analysis of the CDR research landscape by visualizing collaboration and influence dynamics within the literature, enriching the understanding of the field. Another potential extension could involve comparing our data on research funding with patents to examine whether funding impacts patenting, thereby documenting the interactions between funding, published research, and patented innovation in CDR. Finally, one could explore whether the interplay between funded and unfunded academic research preserves a diversified portfolio compared to the 'innovation mercantilist' strategy that solely involves publicly funded research (Atkinson 2020, 2021).

Data availability statement

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

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Appendix

A1. Full search query

(TS = (biochar* AND ((carbon OR CO2) NEAR/3 (sequest* OR storage OR stock OR accumulat* OR capture))) OR TS = (ocean NEAR/5 iron NEAR/5 (fertiliz*ation OR enrichment) NOT natural NOT ice* NOT glaci*) OR TS = ((soil NEAR/3 (carbon OR CO2) NEAR/3 (sequest* OR storage)) AND ('climate change' OR 'global warm*')) AND (manag* OR practice* OR restoration OR land-use)) OR TS = ((afforestation OR reforestation) AND ((carbon OR CO2) NEAR/3 (sequest* OR storage))) OR (TS = (('ocean liming') AND (removal OR storage) AND (CO2 OR carbon*)) OR TS = ((geoengineer*) AND (silicate OR olivine OR albite OR CaCO3)) OR TS = ((silicate OR olivine OR albite OR CaCO) AND (mitigat* NEAR/3 ('climate change' OR 'global warming'))) OR TS = (('ocean alkalin*') AND (remov* OR storage OR mitigat* OR sequest*) AND (CO2 OR carbon*)) OR TS = (((enhance* OR artificial*) NEAR/2 weathering) AND ((carbon OR CO2 OR 'climate change' OR 'global warming') NEAR/3 (remov* OR sequest* OR storage OR sink OR mitigat* OR reduc*)))) NOT TS = (glaci* OR ice* OR ordovic* OR Aptian OR Cenozo* OR Paleo* OR Mezo*) OR (TS = (((capture OR extraction OR absorbtion) NEAR/3 (air OR atmosph*)) AND (ambient OR 'atmosph* pressure*')) AND (CO2

OR carbon)) OR TS = (((captur* OR extract) NEAR/3 (direct* OR 'carbon dioxide') NEAR/3 (air OR atmosph*)) AND (CO2 OR carbon)) OR TS = ((*sorber OR amine) AND capture AND (carbon OR CO2) AND ('ambient air')) OR TS = ((captur* NEAR/3 CO2 NEAR/3 (air OR atmosph*)) AND solar)) NOT TS = (phenolic OR PCB* OR particulate OR NOx OR isotope OR 'heat pump' OR polycyclic OR *bacteria* OR lignin OR sink OR pollution OR photosynth* OR biofuel* OR sugar) OR TS = (BECCS OR ((biomass OR bioenerg*) AND ('CCS' OR 'Carbon capture and Storage' OR 'Carbon dioxide capture and Storage' OR 'CO2 capture and storage')) NOT 'co-fir*' NOT 'co-generat*' NOT cogeneration NOT coal) OR TS = ((seagrass OR mangrove* OR macroalgae OR 'blue carbon') AND ((carbon OR CO2) NEAR/3 (sequest* OR accumulat* OR storage OR capture)) AND (deforest* OR afforest* OR conserv* OR restor* OR manag*)) OR (TS = ((CDR AND (CO2 OR carbon*)) OR 'negative carbon dioxide emission*' OR 'negative CO2 emission*' OR 'negative GHG emission*' OR 'negative greenhouse gas emission*' OR 'carbon-negative emission*' OR ('negative emission*' NEAR/10 carbon) OR ('negative emission*' NEAR/10 CO2)) OR TS = (geoengineering AND ((carbon OR CO2) NEAR/3 (sequest* OR accumulat* OR storage OR capture))) OR TS = (('geoengineering' OR 'climate engineering') AND CDR)) NOT TS = (N2O OR nitrogen OR NOX)) NOT TS = ('bioactive equivalent combinatorial components' OR 'bandwidth-efficient-channel-coding-scheme' OR 'bronchial epithelial cell cultures' OR 'california current system' OR comet OR Mars OR exoplanet* OR 'competition chambers' OR gastric OR (mercury NEAR/3 capture) OR (image NEAR/3 capture) OR 'canary current system' OR 'heavy metal' OR eicosanoid OR 'companion cells' OR 'calcium carbonate sand' OR 'copper chaperone' OR 'commercial cane sugar' OR 'Cindoxin reductase' OR 'coupled dissolution reprecipitation' OR 'carbon dioxide reforming' OR rats OR 'complementarity determining regions' OR deoxycytidine).

A2. Soil carbon sequestration

TS = ((soil NEAR/3 (carbon OR CO2) NEAR/3 (sequest* OR storage)) AND ('climate change' OR 'global warm*')) AND (manag* OR practice* OR restoration OR land-use)).

A3. Afforestation/reforestation

TS = ((afforestation OR reforestation) AND ((carbon OR CO2) NEAR/3 (sequest* OR storage))).

A4. Biochar

TS = (biochar* AND ((carbon OR CO2) NEAR/3 (sequest* OR storage OR stock OR accumulat* OR capture))).

A5. Ocean fertilisation

TS = (ocean NEAR/5 iron NEAR/5 (fertilisation OR enrichment) NOT natural NOT ice* NOT glaci*).

A6. Enhanced weathering

(TS = (('ocean liming') AND (removal OR storage) AND (CO2 OR carbon*)) OR TS = ((geoengineer*) AND (silicate OR olivine OR albite OR CaCO3)) OR TS = ((silicate OR olivine OR albite OR CaCO3) AND (mitigat* NEAR/3 ('climate change' OR 'global warming'))) OR TS = (('ocean alkalini*') AND (remov* OR storage OR mitigat* OR sequest*) AND (CO2 OR carbon*)) OR TS = (((enhance* OR artificial*) NEAR/2 weathering) AND ((carbon OR CO2 OR 'climate change' OR 'global warming') NEAR/3 (remov* OR sequest* OR storage OR sink OR mitigat* OR reduc*)))) NOT TS = (glaci* OR ice* OR ordovic* OR Aptian OR Cenozo* OR Paleo* OR Mesozo*).

A7. Bioenergy carbon capture and storage

TS = (BECCS OR ((biomass OR bioenerg*) AND ('CCS' OR 'Carbon capture and Storage' OR 'Carbon

dioxide capture and Storage' OR 'CO2 capture and storage')) NOT 'co-fir*' NOT 'co-generat*' NOT cogeneration NOT coal).

A8. Direct air capture

(TS = (((capture OR extraction OR absorption) NEAR/3 (air OR atmospher*)) AND (ambient OR 'atmospher pressure*') AND (CO2 OR carbon)) OR TS = (((capture* OR extract) NEAR/3 (direct* OR 'carbon dioxide') NEAR/3 (air OR atmospher*)) AND (CO2 OR carbon)) OR TS = ((*sorber OR amine) AND capture AND (carbon OR CO2) AND ('ambient air')) OR TS = ((capture* NEAR/3 CO2 NEAR/3 (air OR atmospher*)) AND solar)) NOT TS = (phenolic OR PCB* OR particulate OR NOx OR isotope OR 'heat pump' OR polycyclic OR *bacteria* OR lignin OR sink OR pollution OR photosynth* OR biofuel* OR sugar).

A9. Blue carbon

TS = ((seagrass OR mangrove* OR macroalgae OR 'blue carbon') AND ((carbon OR CO2) NEAR/3 (sequest* OR accumul* OR storage OR capture)) AND (deforest* OR afforest* OR conserv* OR restor* OR manag*)).

A10. Funding data**Table 3.** Allocation of funds across different CDR technologies in three major regions—China, the EU (*of which* represents EU Bodies), and the US—other regions are also included when they are funding a higher amount of research on a technology, from 2012 to 2023.

Tech.	Instit.	12	13	14	15	16	17	18	19	20	21	22	23	TOTAL
All	China	34	50	71	64	110	130	148	172	214	287	391	381	2054
	EU	25	31	38	36	62	59	86	95	114	155	165	150	1016
	(<i>Of which</i>)	8	11	18	18	29	24	38	32	37	66	68	58	407
	US	39	23	35	26	48	54	46	56	62	81	88	103	648
Soil Carbon Sequestration	China	7	16	14	14	21	26	27	25	34	58	76	56	374
	the EU	3	4	7	6	12	15	14	12	21	19	24	18	155
	(<i>Of which</i>)	2	3	3	3	5	8	5	4	10	9	10	7	69
	US	6	6	5	3	8	11	9	4	6	17	13	6	94
Afforest. / Reforest.	China	16	21	28	19	39	50	49	50	48	56	80	83	448
	the EU	7	4	5	7	13	12	19	17	13	25	28	20	170
	(<i>Of which</i>)	2	1	1	4	7	5	11	5	6	11	11	11	75
	US	8	4	12	10	13	9	8	15	12	11	11	9	122
Biochar	China	6	9	19	18	35	38	52	53	85	90	126	113	645
	the EU	7	7	9	11	17	15	16	20	23	35	30	26	216
	(<i>Of which</i>)	0	1	4	4	6	10	8	7	5	12	10	9	76
	US	0	1	4	4	6	10	8	7	5	12	10	9	76

(Continued.)

Table 3. (Continued.)

Tech.	Instit.	12	13	14	15	16	17	18	19	20	21	22	23	TOTAL
	US	9	5	8	5	8	8	12	13	9	10	9	7	103
Ocean fertilization	China	0	1	2	0	5	5	3	4	2	8	5	7	42
	US	3	3	4	2	3	4	3	2	2	2	1	1	30
	the EU	2	4	4	0	2	6	3	0	1	1	4	2	29
	(Of which)	1	0	1	0	0	4	2	0	1	1	2	1	13
Enhanced Weather.	UK	1	2	1	1	2	1	1	3	7	6	8	6	44
	the EU	0	3	1	0	2	1	8	2	5	5	4	7	38
	(EU Bodies)	0	1	0	0	0	1	3	0	0	4	3	2	14
	China	1	0	0	2	1	2	3	1	4	5	7	11	37
US	0	1	0	0	0	0	0	0	2	4	7	9	25	
BECCS	the EU	4	3	10	6	9	8	15	29	19	41	36	29	209
	(Of which)	1	1	9	2	8	1	9	8	7	14	19	10	89
	China	1	2	3	5	7	4	7	11	13	27	32	30	142
	UK	5	1	1	4	6	13	17	17	20	19	14	8	125
	US	0	2	6	4	6	5	3	5	19	11	12	8	81
	China	4	2	4	4	6	7	6	15	17	18	33	55	171
DACCS	US	9	3	2	2	5	13	4	10	9	20	27	54	160
	the EU	2	1	1	1	4	3	4	9	14	18	22	31	110
	(Of which)	0	1	1	0	2	0	1	3	4	7	12	12	43
	China	1	1	5	1	4	5	7	13	11	27	33	34	142
Blue Carbon	Australia	1	1	3	5	3	6	10	11	12	8	12	14	86
	US	3	2	2	2	9	5	9	9	6	10	8	8	73
	the EU	0	3	1	3	5	3	5	7	10	5	19	9	70
	(Of which)	0	1	0	3	2	1	1	2	3	1	9	5	28

Table 4. Number of publications funded by different agency by year. The top 30 funding agencies is represented.

Institution	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	TOTAL
National Nat. Sci. Found. Of China	17	32	45	40	76	92	98	124	139	195	235	253	1383
European Union	10	13	17	16	27	22	30	30	32	42	47	53	339
UK Research Innovation	9	13	14	11	16	24	33	39	33	49	32	30	319
National Science Foundation	23	15	16	14	27	27	19	25	29	35	28	41	305
United States DOE	13	8	9	6	7	17	16	13	16	28	28	58	231
Nat. Key R and D Prog. Of China	0	0	0	0	0	7	27	32	50	54	62	38	206
Natural Env. Res. Council	6	10	6	6	9	12	21	27	24	30	14	11	183
Fundamental Research Funds...	5	2	3	6	13	16	12	14	17	16	27	34	171
Spanish Government	5	7	3	5	8	3	10	10	16	16	17	26	163
Chinese Academy Of Sciences	4	10	18	11	15	11	11	11	9	17	15	18	132
Australian Research Council	4	3	7	10	13	15	15	11	16	12	14	9	120
Natural Sci. and Engi. RC Of Canada	4	2	4	7	11	7	8	8	10	20	19	15	119
Engineering Physical Sc. RC	4	4	6	6	4	14	13	19	12	20	14	8	116
United States Dep. Of Agri.	7	2	8	4	8	6	7	14	13	20	14	9	103
Conselho Nac. De Desenvolvimento	1	0	2	2	8	6	14	14	13	14	13	14	101
China Postdoctoral Science Found.	2	1	2	2	5	5	7	10	10	15	20	20	100
German Research Foundation Dfg	1	4	6	3	11	6	14	15	9	8	8	11	99
Federal Minis. Of Educ. Research	5	2	5	3	7	5	10	8	12	11	14	18	82
National Basic Res. Prog. Of China	7	10	12	6	8	12	13	4	2	2	0	0	78
China Scholarship Council	0	2	1	2	3	3	9	10	14	16	13	15	91
Ministry Of Educ. Culture, Jap.	4	0	3	3	6	3	5	9	7	15	11	11	78
CGIAR	0	1	0	2	10	6	5	6	9	12	8	7	67
Japan Society For The Prom. Of Sci.	4	0	3	3	5	3	5	9	4	12	10	8	67
Coordenacao De Aperfeicoamento...	0	0	0	4	4	5	7	8	9	11	5	6	62
National Research Found. Of Korea	2	1	1	1	5	4	4	3	4	12	14	15	58
Australian Government	1	5	8	10	10	5	3	4	4	0	4	1	57
European Commission Joint RC	1	1	6	7	3	7	5	5	4	5	9	2	54
Total	118	125	174	269	296	322	394	462	593	620	695	731	4884

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References

- AlRyalat S A S, Malkawi L W and Momani S M 2019 Comparing bibliometric analysis using PubMed, Scopus and Web of Science databases *J. Vis. Exp.* **152** e58494
- Atkinson R D 2020 How China's mercantilist policies have undermined global innovation in the telecom equipment industry *Technical Report* (Information Technology and Innovation Foundation)
- Atkinson R D 2021 China's 'innovation mercantilism' reduces the rate of global innovation *Technical Report* (Information Technology and Innovation Foundation)
- Bazilian M and Roques F (eds) 2008a *Analytical Methods for Energy Diversity & Security (Elsevier Global Energy Policy and Economics Series)* (Elsevier) pp 305–15
- Bazilian M and Roques F 2008b Introduction: Analytical approaches to quantify and value fuel mix diversity *Analytical Methods for Energy Diversity & Security (Elsevier Global Energy Policy and Economics Series)* ed M Bazilian and F Roques (Elsevier) p xxv–xlii
- Bigger P, Bozuwa J, Cha M, Cohen D A, Fleming B, Freemark Y, Hassan B and Riofrancos T 2022 Inflation reduction act: the good, the bad, the ugly *The Climate and Community Project* (available at: www.climateandcommunity.org/inflation-reduction-act)
- Campion L, Bekchanova M, Malina R and Kuppens T 2023 The costs and benefits of biochar production and use: a systematic review *J. Clean. Prod.* **408** 137138
- Carton W, Asiyabi A, Beck S, Buck H J and Lund J F 2020 Negative emissions and the long history of carbon removal *Wiley Interdiscip. Rev. Clim. Change* **11** e671
- Donthu N, Kumar S, Mukherjee D, Pandey N and Lim W M 2021 How to conduct a bibliometric analysis: an overview and guidelines *J. Bus. Res.* **133** 285–96
- Drax Group 2023 Progressing global BECCS opportunities (available at: www.drax.com/financial-news/progressing-global-beccs-opportunities/) (Accessed 8 July 2024)
- Eddy W C and Yang W H 2022 Improvements in soil health and soil carbon sequestration by an agroforestry for food production system *Agric. Ecosyst. Environ.* **333** 107945
- European Commission 2024 Proposal for a council decision on the position to be adopted, on behalf of the European Union, within the general council of the World Trade Organization on the accession of Turkmenistan to the World Trade Organization (available at: <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2024:62:FIN>) (Accessed 8 July 2024)
- Fuss S et al 2018 Negative emissions—part 2: costs, potentials and side effects *Environ. Res. Lett.* **13** 063002
- Grant N, Hawkes A, Mittal S and Gambhir A 2021 The policy implications of an uncertain carbon dioxide removal potential *Joule* **5** 2593–605
- Gulliver A, Carnell P E, Trevathan-Tackett S M, Duarte de Paula Costa M, Masqué P and Macreadie P I 2020 Estimating the potential blue carbon gains from tidal marsh rehabilitation: a case study from south eastern Australia *Front. Mar. Sci.* **7** 403
- Haddaway N R, Woodcock P, Macura B and Collins A 2015 Making literature reviews more reliable through application of lessons from systematic reviews *Conserv. Biol.* **29** 1596–605
- Hilaire J, Minx J C, Callaghan M W, Edmonds J, Luderer G, Nemet G F, Rogelj J and del Mar Zamora M 2019 Negative emissions and international climate goals—learning from and about mitigation scenarios *Clim. Change* **157** 189–219
- Ho D T 2023 World view *Nature* **616** 9
- Huang L, Chen K and Zhou M 2020 Climate change and carbon sink: a bibliometric analysis *Environ. Sci. Pollut. Res.* **27** 8740–58
- IEA 2007 *Energy Security and Climate Policy—Assessing Interactions* (IEA) (available at: www.iea.org/reports/energy-security-and-climate-policy-assessing-interactions)
- IPCC 2018 An IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development and efforts to eradicate poverty *Global Warming of 1.5 °C* accepted
- IPCC 2014 *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed O Edenhofer et al (Cambridge University Press)
- IPCC 2019 Summary for Policymakers *Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security and Greenhouse Gas Fluxes in Terrestrial Ecosystems* ed P R Shukla et al (accepted)
- IPCC 2022 *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* ed P R Shukla et al (Cambridge University Press)
- Jagu Schippers E 2022 Addressing climate change with carbon dioxide removal: insights from industrial economics and cooperative games *PhD Thesis* Université Paris-Saclay
- Kauffman J B, Giovanonni L, Kelly J, Dunstan N, Borde A, Diefenderfer H, Cornu C, Janousek C, Apple J and Brophy L 2020 Total ecosystem carbon stocks at the marine-terrestrial interface: blue carbon of the Pacific Northwest Coast, United States *Glob. Change Biol.* **26** 5679–92
- Kerner C, Thaller A and Brudermann T 2023 Carbon dioxide removal to combat climate change? An expert survey on perception and support *Environ. Res. Commun.* **5** 041003
- Khosroabadi F, Aslani A, Bekhrad K and Zolfaghari Z 2021 Analysis of carbon dioxide capturing technologies and their technology developments *Clean. Eng. Technol.* **5** 100279
- Li K, Hou Y, Andersen P S, Xin R, Rong Y and Skov-Petersen H 2021 Identifying the potential areas of afforestation projects using cost-benefit analysis based on ecosystem services and farmland suitability: a case study of the grain for green project in Jinan, China *Sci. Total Environ.* **787** 147542
- Linkov V, O'Doherty K, Choi E and Han G 2021 Linguistic diversity index: a scientometric measure to enhance the relevance of small and minority group languages *Sage Open* **11** 21582440211009191
- Liu L, Jiang J, Bian J, Liu Y, Lin G and Yin Y 2021 Are environmental regulations holding back industrial growth? Evidence from China *J. Clean. Prod.* **306** 127007
- Löschel A, Moslener U and Rübbecke D 2010 Indicators of energy security in industrialised countries *Energy Policy* **38** 1665–71
- Luo W, Deng Z, Zhong S and Deng M 2022 Trends, issues and future directions of urban health impact assessment research: a systematic review and bibliometric analysis *Int. J. Environ. Res. Public Health* **19** 5957
- Majumder S, Neogi S, Dutta T, Powel M A and Banik P 2019 The impact of biochar on soil carbon sequestration: meta-analytical approach to evaluating environmental and economic advantages *J. Environ. Manag.* **250** 109466
- Massol O and Banal-Estañol A 2014 Export diversification through resource-based industrialization: the case of natural gas *Eur. J. Oper. Res.* **237** 1067–82
- McCulloch S, Keeling S, Malischek R and Stanley T 2019 *IEA. 20 Years of Carbon Capture and Storage. Accelerating Future Deployment* (International Energy Agency (IEA))
- Minx J C et al 2018 Negative emissions—part 1: research landscape and synthesis *Environ. Res. Lett.* **13** 063001
- Minx J C, Lamb W F, Callaghan M W, Bornmann L and Fuss S 2017 Fast growing research on negative emissions *Environ. Res. Lett.* **12** 035007

- Miranda A M, Hernandez-Tenorio F, Ocampo D, Vargas G J and Sáez A A 2022 Trends on CO₂ capture with microalgae: a bibliometric analysis *Molecules* **27** 4669
- Moral-Muñoz J A, Herrera-Viedma E, Santisteban-Espejo A and Cobo M J 2020 Software tools for conducting bibliometric analysis in science: an up-to-date review *Prof. Inf.* **29** 1
- Morris R L, Fest B, Stokes D, Jenkins C and Swearer S E 2023 The coastal protection and blue carbon benefits of hybrid mangrove living shorelines *J. Environ. Manag.* **331** 117310
- Nemet G F, Callaghan M W, Creutzig F, Fuss S, Hartmann J, Hilaire J, Lamb W F, Minx J C, Rogers S and Smith P 2018 Negative emissions—part 3: innovation and upscaling *Environ. Res. Lett.* **13** 063003
- Omogbe O, Mustapha A N, Steinberger-Wilckens R, El-Kharouf A and Onyeaka H 2020 Carbon capture technologies for climate change mitigation: a bibliometric analysis of the scientific discourse during 1998–2018 *Energy Rep.* **6** 1200–12
- Prütz R et al 2024 A new taxonomy to map evidence on carbon dioxide removal side effects *Commun. Earth Environ.* **5** 197
- Ritchie S and Tsalaporta E 2022 Trends in carbon capture technologies: a bibliometric analysis *Carbon Neutrality* **1** 38
- Rogelj J, Luderer G, Pietzcker R C, Kriegler E, Schaeffer M, Krey Y and Riahi K 2015 Energy system transformations for limiting end-of-century warming to below 1.5 °C *Nat. Clim. Change* **5** 519–27
- Schenuit F, Colvin R, Fridahl M, McMullin B, Reisinger A, Sanchez D L, Smith S M, Torvanger A, Wreford A and Geden O 2021 Carbon dioxide removal policy in the making: assessing developments in 9 OECD cases *Front. Clim.* **3** 638805
- Tammeorg P et al 2017 Biochars in soils: towards the required level of scientific understanding *J. Environ. Eng. Landsc. Manag.* **25** 192–207
- Tatarewicz I, Lewarski M, Skwierz S, Krupin V, Jeszke R, Pyrka M, Szczepański K and Sekuła M 2021 The role of BECCS in achieving climate neutrality in the European Union *Energies* **14** 7842
- Taylor L L, Quirk J, Thorley R, Kharecha P A, Hansen J, Ridgwell A, Lomas M R, Banwart S A and Beerling D J 2016 Enhanced weathering strategies for stabilizing climate and averting ocean acidification *Nat. Clim. Change* **6** 402–6
- Tisserant A and Cherubini F 2019 Potentials, limitations, co-benefits and trade-offs of biochar applications to soils for climate change mitigation *Land* **8** 179
- US Department of Energy 2021 DOE announces \$14.5 million supporting direct air capture and storage coupled to low carbon energy sources (available at: www.energy.gov/articles/doe-announces-145-million-supporting-direct-air-capture-and-storage-coupled-low-carbon)
- White H D 2018 Pennants for Garfield: bibliometrics and document retrieval *Scientometrics* **114** 757–78
- Yu D, Xu Z, Kao Y and Lin C-T 2017 The structure and citation landscape of IEEE Transactions on Fuzzy Systems (1994–2015) *IEEE Trans. Fuzzy Syst.* **26** 430–42
- Zolfaghari Z, Aslani A, Moshari A and Malekli M 2022 Direct air capture from demonstration to commercialization stage: a bibliometric analysis *Int. J. Energy Res.* **46** 383–96