



Jan C. Minx,ⁱ Benedict S. Probst,^{ii,iii,iv} Sarah Lück,ⁱ Finn Müller-Hansen,ⁱ Malte Toetzke,ⁱⁱⁱ Laura Diaz Anadon,^{iv} Tim Engelmann,ⁱⁱⁱ Jenna Greene,^v Volker H. Hoffmann,ⁱⁱⁱ Gregory F. Nemet,^v Tim Repkeⁱ

ⁱ Mercator Research Institute on Global Commons and Climate Change

ⁱⁱ Max Planck Institute for Innovation and Competition

ⁱⁱⁱ ETH Zurich

^{iv} University of Cambridge

^v University of Wisconsin-Madison

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Chapter 2 | Research and development

Investments in research and development (R&D) have been increasing steadily. Although there are signs of diversification, R&D remains concentrated in a few countries and on a few carbon dioxide removal (CDR) methods. While the number of scientific publications is growing rapidly, inventive activity has been in decline.

Key insights

- The number of active third party-funded research grants on CDR has grown steadily from fewer than 50 in the year 2000 to more than 1,160 in 2022. Conventional forest-based CDR methods, soil carbon sequestration and biochar continue to dominate CDR research grants.
- The cumulative value of all research grants between 2000 and 2022 is estimated to be \$2.6 (1.9–2.8) billion. Due to their larger project size, novel CDR methods such as direct air carbon capture and storage (DACCS) and bioenergy with carbon capture and storage (BECCS) receive sizeable shares of the financial support for R&D.
- Most third party-funded research grants on CDR are funded in Canada and the US. The number of research grants in non-EU European countries, such as Norway, Switzerland and the UK, are markedly higher than in the EU27, relative to the size of their populations.
- Scientific knowledge on CDR – measured as the number of research publications – has expanded more rapidly than both research funding and inventions.
- Biochar, soil carbon sequestration and afforestation/reforestation continue to dominate research publications on CDR. Over the last decade, publication output has expanded most rapidly for CDR methods such as DACCS, coastal wetland restoration, enhanced rock weathering and biochar.
- Inventions in CDR, measured as the number of international patent families, experienced rapid growth until 2011, but yearly inventions have since declined. This trend is mainly driven by lower growth in patents relating to BECCS. Yet inventions in novel CDR, particularly biochar, are playing an increasingly important role.
- Overall, R&D activities have grown steadily, with the exception of

high-value patents, and there are signs of diversification across CDR methods and geographies. However, this report continues to observe little R&D activity in ocean-based CDR or, geographically, in sub-Saharan Africa, Latin America and the Middle East.

The State of Carbon Dioxide Removal 1st edition highlighted that the pace of innovation in CDR is still modest compared with what is needed to meet the industry's own targets as well as the Paris temperature goal. Scaling up CDR in line with the Paris temperature goal will require a historic acceleration of innovation.^{25,26}

Assessing innovation provides an understanding of how CDR methods are evolving, how fast they might be deployed and how costs are changing. Innovation is a process, and its sequence of stages requires multiple metrics to assess (see also Chapter 1 – Introduction).⁹ However, innovation is not linear; feedback loops between these stages play an integral role.

R&D stands at the beginning of the innovation process and involves the discovery and assimilation of new scientific and technical knowledge.^{9,27,28} It comprises a series of activities that span fundamental research through to applied technology development, closer to commercialization.

This chapter assesses the state of R&D in CDR using three indicators: research grants, scientific publications and patents. The indicators capture different activities and involve multiple actors, such as public funding institutions and researchers and inventors in the public and private sectors. Tracking research grants provides an input-related metric of early-stage investments in R&D that helps characterize the level of effort being made to advance CDR and drive down costs. Numbers of scientific publications and patents are output-related metrics that characterize actual R&D efforts and their efficacy in advancing the knowledge base on CDR (scientific publications) and in driving potential commercialization (patents).

2.1 Investments in R&D for CDR

The number of CDR research grants is growing steadily, investing in an increasingly diversified portfolio of CDR methods.

Awards of research grants is a new indicator in this edition of *The State of Carbon Dioxide Removal*. It comprises information on the number of funded research projects and the amount of research funding (see Box 2.1). As such, it is a metric for early-stage R&D investments in CDR and can shed light on patterns of support for different CDR methods and on how different regions invest in CDR.

There has been substantial research investment in CDR, with 3,840 research grants on CDR in this report's data set between 1991 and 2022 (this does not include research funded via institutional core budgets). These grants come from 131 funding organizations, mainly public funders such as research councils, foundations and ministries, but also philanthropic organizations. The data set shows about 1,600 receiving research

organizations. Almost three-quarters of the research grants also report the value of the funding, which totals \$1.9 billion. This gives an average of about \$670,000 (10th to 90th percentile range: \$25,000–\$875,000) per project. This report therefore estimates the total third-party funding for CDR research to be about \$2.6 (1.9–2.8) billion (see Box 2.1).

Grant making in CDR has grown steadily in terms of the number of projects funded as well as the total financial support provided. The number of research grants for CDR has grown from 35 active grants during 2000 to 1,160 during 2022 (see Figure 2.1a). About 74% of all research grants on CDR in the data set started within the last ten years (2013–2022). This indicates an average annual growth in active CDR research grants of 5% over the last ten years (2013–2022) and about 14% over the last 20 years (2003–2022). The annual amount of research funding spent has grown from about \$5 million in 2000 to about \$190 million in 2022. The average annual growth was faster for the total amount of funding than for the number of projects, at 14% over the last ten years (2013–2022) and 16% over the last 20 years (2003–2022). It is hard to determine from the data why this might be the case, but increased levels of reported funding and a decrease in project duration may contribute to the trend.

Almost 70% of all active CDR research grants between 2000 and 2022 focus on soil carbon sequestration (35%) or biochar (33%). However, research grants have been diversifying over time (see Figure 2.1b): The shares of active biochar and soil carbon sequestration projects dropped to 30% and 22%, respectively, in 2022, while shares increased for many other CDR methods, such as direct air carbon capture and storage (DACCS) (11%), peatland restoration (8%), coastal wetland restoration (7%), enhanced rock weathering (5%) and bioenergy with carbon capture and storage (BECCS) (5%).

The amount of funding in monetary terms is more evenly spread across CDR methods, as some methods are more capital-intensive than others (e.g. BECCS, DACCS).

While soil carbon sequestration and biochar receive a sizeable chunk of the allotted funding (22% and 17%, respectively), some other novel CDR methods such as BECCS (18%) and DACCS (21%) receive similar shares (despite accounting for fewer projects), driven by R&D investments in more recent years. Ocean alkalinity enhancement and enhanced rock weathering have received comparatively little early-stage R&D support. Overall, a slight trend towards diversification of CDR research funding is observable over the 20-year analysis period.

Research investments in CDR are markedly higher in Canada and the US than in the EU27. Between 2000 and 2022, 40% of all active research grants on CDR and 59% of the research funding took place in Canada or the US. There are about three times more CDR research grant years, and their total value is about twice as high, in Canada and the US than in the EU27.

In addition, some non-EU European countries, including Norway, Switzerland and the UK, jointly support almost as many research grant years on CDR as all 27 countries of the EU combined. These non-EU European country grants jointly account for about 11% of global funding support, compared with 19% for the EU27. These non-EU European countries have the highest per capita funding levels across all regions. Growth in CDR funding is also

most dynamic in non-EU European countries in terms of both the number of grants and the volume of the funding. While the increase in the number of CDR grants funded in the EU27 between 2000 and 2022 was smaller than in Canada and the US, the amount of funding spent on CDR grew more dynamically. China funds many CDR projects, but the financial support reported is comparatively small. The average funding for a CDR project in China is \$74,000, compared with \$979,000 in Canada and the US, \$1,406,000 in the EU27 and \$582,000 in non-EU European countries. Factors driving these observed differences in the average size of the grants are difficult to determine and may be the result of the funding system, reporting issues or other factors.

Regions broadly follow the global trend of funding more research projects for biological CDR methods, but there are distinct patterns of specialization (see Figure 2.1c). Compared with the global average, there is a larger share of CDR research grants on soil carbon sequestration, DACCS and ocean fertilization in Canada and the US; in China, CDR research projects focus more on biochar and soil carbon sequestration. The EU27 invests in a larger share of CDR grants on BECCS and enhanced rock weathering as well as grants that deal with the broader or cross-cutting aspects of CDR (general CDR) than the global average. CDR research in Africa is more focused on biochar, afforestation/reforestation and coastal wetland restoration.

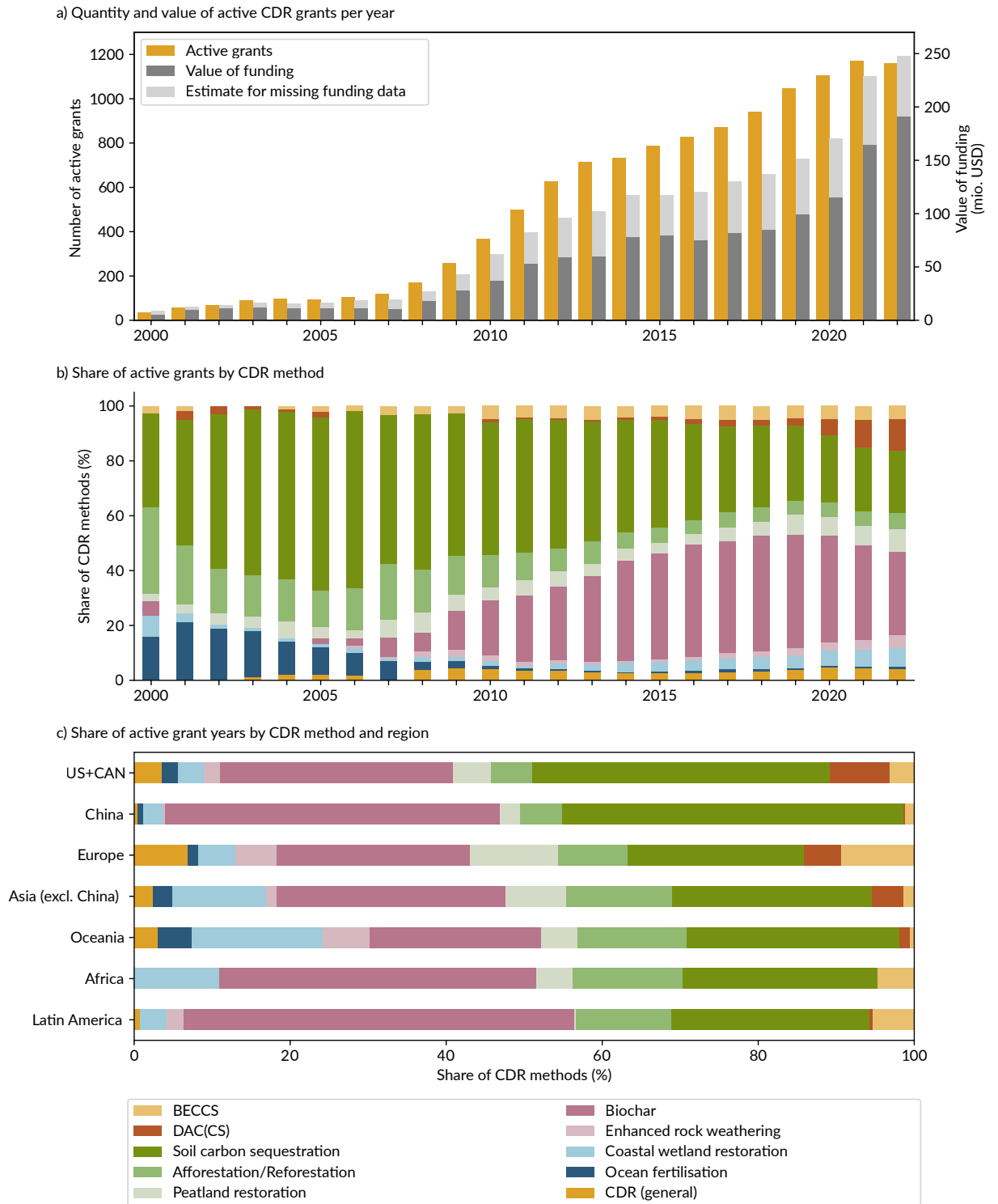


Figure 2.1 Growth in the number and value of grants for carbon dioxide removal (CDR) research: (a) Total number of active research grants and their total value between 2000 and 2022; (b) CDR methods being researched in these grants over time as a share of the total number of all active grants; (c) CDR methods by region of funding organization as share of active grant years. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).

Box 2.1 Methods: Tracking early-stage R&D investments through third-party research grants

This report assesses early-stage, third-party R&D investments in CDR using data on research projects granted by funding bodies as listed in the Dimensions database.^{29,30} Comprehensive keyword searches were conducted for each of the CDR methods considered to download an initial set of about 9,600 grants potentially relevant to CDR research. A machine-learning classifier (ClimateBERT based on DistilRoBERTa),³¹ fine-tuned on a large set of annotated scientific abstracts, was then used to differentiate between CDR grants and grants related to CDR. A manually annotated test sample was used to evaluate this classifier, and good performance (F1-score = 0.8) was found. A multi-class model was used to annotate the CDR methods that each grant covers, which worked with moderate performance (F1-score = 0.67).

Other aspects analysed in the report – including the value of grants, the country of the funder and the receiving research organization, and the research fields – are provided directly in the Dimensions data. Data on the amount of funding were missing for 28% of the projects; these data were imputed using the average project funding and tested against CDR method-specific mean values. The 10th and the 90th percentile of the project value distribution were used to estimate a range that should reflect the uncertainties in the calculations.

While this report provides the most expansive effort to date to track early-stage third-party R&D investments in CDR, there are some important limitations (see Box 2.4).

2.2 Growth in scientific publications

Scientific publications on biochar and soil carbon sequestration continue to dominate CDR research. But publications on some other (novel) CDR methods – particularly DACCS, coastal wetland restoration and enhanced rock weathering – are increasing rapidly.

R&D comprises a series of activities to increase the stock of knowledge in a certain area and devise new applications from it. While the research grant indicators detailed in Section 2.1 focus on how early-stage R&D activities for CDR are supported across the world, this section examines indicators that try to measure R&D outputs.

The section first estimates research output on CDR as the total number of (English-language) scientific publications. While growth in scientific publications may not necessarily reflect an increase in the available knowledge, it is an indication of the interest in a field, the development of that interest over time and the opportunity for knowledge expansion. This edition of *The State of Carbon Dioxide Removal* sources the data from OpenAlex³² – a publicly available bibliographic database – rather than the Web of Science and Scopus, as used in the first edition. The numbers here are therefore different to those in the first edition of the report (see Box 2.2). But despite the overall numbers being lower in this edition, they

remain broadly comparable with the first edition in terms of the observed numbers and trends.

Overall, this report finds a large body of scientific literature on CDR of about 27,000 English-language publications between 2000 and 2022 – mostly peer-reviewed articles, working papers and books. The entire universe of scientific publications, including all peer-reviewed and non-peer-reviewed sources, could be as large as 50,000 publications.^{25,33}

Publication output on CDR continues to grow rapidly. The total annual number of scientific publications on CDR increased by 19% from about 3,900 in 2021 to about 4,700 in 2022 (see Figure 2.2a). Preliminary evidence suggests that growth will continue to about 5,300 scientific publications in 2023.

Research output in 2022 was 1.4 times larger than in 2020, eight times larger than in 2010 and more than 50 times larger than in 2000, when 77 scientific studies on CDR were published. High growth rates in CDR research publications have been maintained over the last two decades. The 19% increase in publication output between 2021 (the reference point in *The State of Carbon Dioxide Removal* 1st edition) and 2022 is broadly in line with the average annual growth during the last ten years (18%; 2013–2022) and the last 20 years (21%; 2003–2022). This rate is higher than the average growth in research output on climate change as a whole²⁵ and the growth in active CDR research grants and associated funding over the last ten and 20 years (see Section 2.1).

Three groups of CDR methods continue to dominate the scientific literature on CDR: biochar, soil carbon sequestration and afforestation/reforestation. Their joint overall share in the scientific CDR literature has increased from about 73% during the 2000s to about 83% during the 2010s (see Figure 2.2b). This increase has been driven by the rapid growth in biochar research over the last 20 years. Hence, while publication output is growing across all CDR methods, a long-term trend towards concentration rather than diversification is evident in CDR research publications.

However, signs of diversification in more recent years indicate that this trend might be changing. The share of research publications on biochar, soil carbon sequestration and afforestation/reforestation has started to decline, from 83% in 2020 to 81% in 2022. Publication output has tended to grow faster for novel CDR methods, with some exceptions. Fast annual average growth over the last decade (2013–2022) can be observed for DACCS (26% per year) and biochar (21% per year), but also coastal wetland restoration (25% per year) – all growing faster than the CDR field as a whole (18% per year). Strong growth is also observed in research outputs for the CDR methods with some of the smallest annual publication levels. Since 2020, scientific publications on ocean fertilization have more than quadrupled, while research output on DACCS, enhanced rock weathering and ocean alkalinity enhancement has more than doubled, strengthening these less developed bodies of scientific knowledge. Looking at the diversification trend of research funding across CDR methods in Figure 2.1 (panel b), there is good reason to believe that research publications could follow a similar pattern in coming years.

Almost 50% of all CDR research publications between 2000 and 2020 are from Asia – particularly China (30% of all CDR research publications) – mainly driven by research

on biochar and soil carbon sequestration. The share of CDR research publications from Europe (25%) is considerably higher than from Canada and the US (15%). The most dynamic growth patterns in CDR research publications over the last decade (2013–2022) can be observed for Africa (32% per year), China (26% per year) and the rest of Asia (30% per year), and Latin America (26% per year). Europe's growth in CDR research output (17% per year) tracks just below the average and remains higher than the rates observed for Canada and the US (10% per year). This report does not assess the quality of any of the publications.

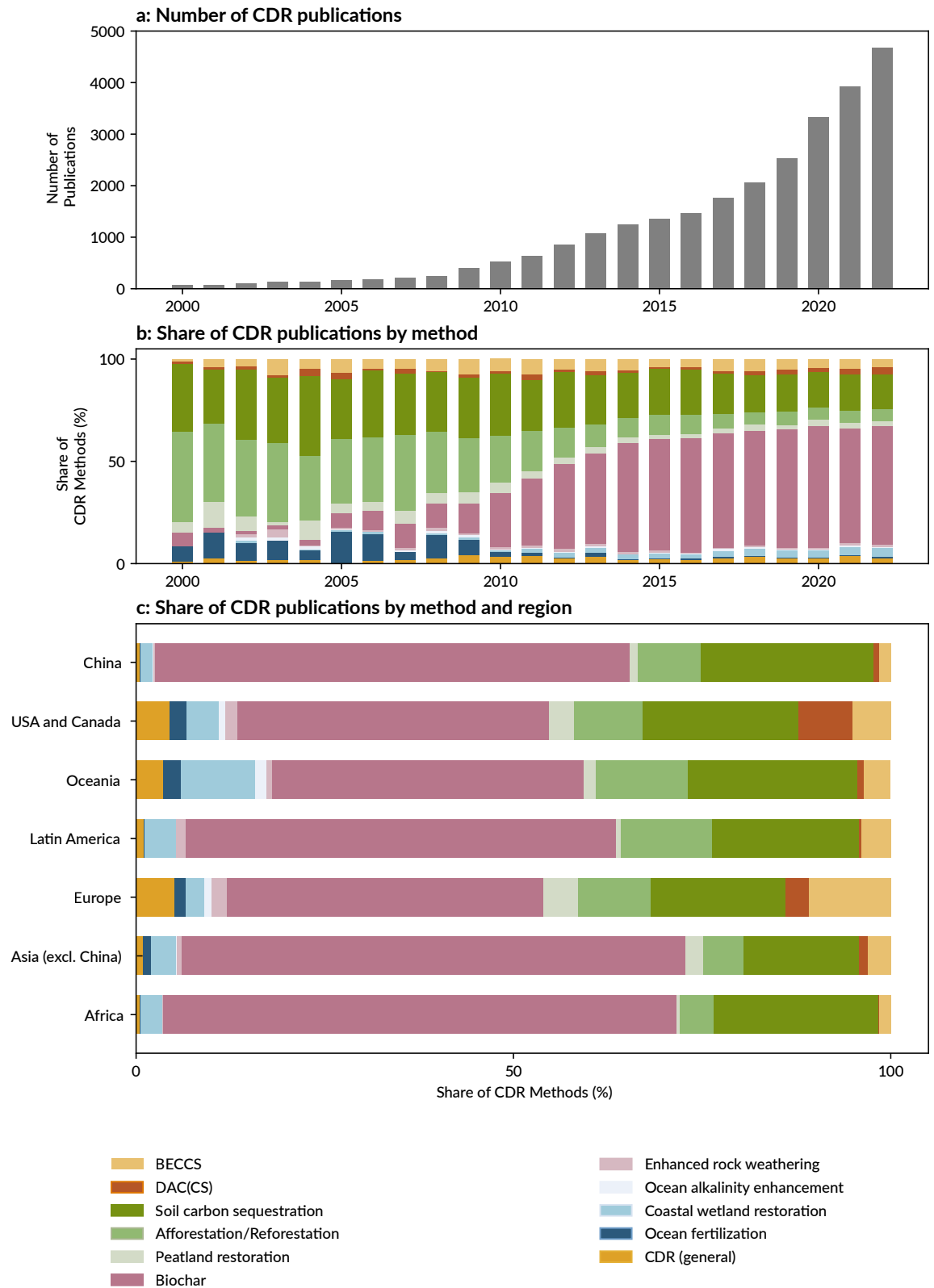


Figure 2.2 Exponential growth in research output on carbon dioxide removal (CDR) over time: (a) Total number of scientific publications on CDR per year from 1990 to 2022 in the open-access bibliographic database OpenAlex; (b) Share of CDR methods mentioned in these scientific publications per year; (c) Share of CDR methods mentioned in scientific publications by region of first author. BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).

Box 2.2 Methods: Tracking scientific research on CDR

This report uses an AI-based approach to identify research publications on CDR in the English-language scientific literature.³⁴⁻³⁷ First, combinations of search terms (or search strings) were designed for each CDR method based on a comprehensive list of keywords. The search strings were then validated against a set of studies included in the IPCC Sixth Assessment Report, ensuring that these studies were returned by the literature search. Using these search strings, about 100,000 records were retrieved from OpenAlex – the largest open-access bibliographic database. The analysis in *The State of Carbon Dioxide Removal* 1st edition queried the Web of Science and Scopus. The results in the two editions are therefore not directly comparable.

For this edition, after the 100,000 records were retrieved, the title, abstract and keywords of 400–600 records per search string were manually screened and labelled with their suitability for inclusion (relevant/irrelevant) and the specific CDR method being studied. The labelled data were then used to train state-of-the-art machine-learning classifiers^{31,38} to predict a total of 27,000 relevant CDR research publications as well as the CDR methods covered within them. This automated approach enables a comprehensive search for scientific literature in bibliographic databases while still ensuring a high level of precision in the identification of relevant studies. This edition identifies slightly fewer studies than *The State of Carbon Dioxide Removal* 1st edition because of using a single bibliographic database and restricting the sample to the CDR methods specifically searched for.

While the machine-learning methodology used in this report allows a more comprehensive assessment of the state of scientific research on CDR, the analysis presented here has important limitations (see Box 2.4).

2.3 Patents: Inventive activity

After a period of rapid growth, inventions in CDR have declined, but novel CDR is playing an increasingly important role in inventive activity.

Like scientific papers, patents measure the output of the invention effort but are even closer to eventual commercialization. Inventors file patents at the end of the invention process once they plan to use their invention. While this is no guarantee of eventual commercialization, it can signal the intent to progress to commercial use. A patent grants an inventor exclusive right to the new technology but forces the inventor to reveal its underlying technical process. Patent documents therefore contain detailed descriptions of the technology, which allows researchers to identify, technically categorize and measure inventive dynamics over time. Box 2.3 describes how this report uses machine learning to analyse patent data, how this methodological approach has changed since *The State of Carbon Dioxide Removal* 1st edition, and how this report addresses the limitations inherent in patent data.

The filing of patents for CDR inventions experienced rapid growth between 2000 and 2010 but then started to slowly decrease (Figure 2.3a). The number of inventions grew

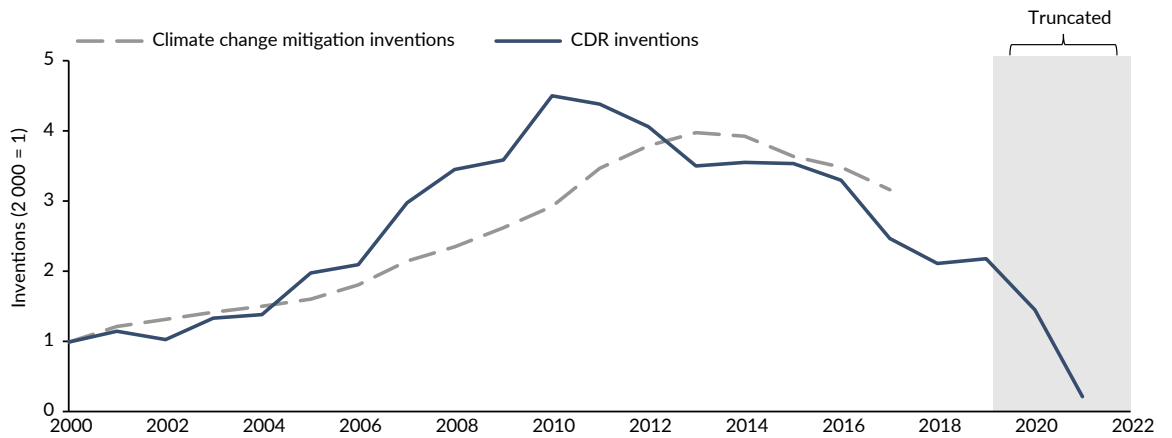
fairly steadily between 2000 and 2010, with annual patent filings more than quadrupling during that period. Since 2011, there has been a moderate decline in the average number of inventions per year, but annual patent filings in 2019 were still twice the average filings in 2000. The invention trend is in line with the evolution of high-value inventions observed across all climate technologies until 2017,³⁹ but climate-tech inventions have rebounded recently. The decline is partly driven by a fall in patenting efforts in BECCS (fuelled by those in carbon capture and storage more broadly), potentially due to overblown expectations of its large-scale deployment in the 2000s. Macroeconomic factors, such as fossil fuel and carbon prices declining around the same time, could also have played a role, but the exact reasons are unclear.

Inventions in CDR have diversified over the last two decades, but conventional CDR (e.g. afforestation/reforestation) continues to make up a sizeable share of inventions (see Figure 2.3b). The growth in patents until 2010 was primarily driven by BECCS (with annual filings growing approximately ten times between 2000 and 2010) but also by a broader portfolio of technologies, such as biochar, enhanced rock weathering and DACCS. Despite all CDR methods having seen an absolute decline in inventions over the last decade, several novel CDR methods (apart from BECCS) have seen a relative increase in importance (in terms of share of patents). This increase is particularly striking for biochar (growing from 14% in 2010 to around 24% in 2019) and coastal wetland restoration (growing from 1% to 11% in the same period). Yet several other CDR methods have continued to play a minor role: ocean fertilization and ocean alkalinity enhancement jointly accounted for only 3% of CDR inventions during the last decade. Overall, CDR inventions constitute around 1% of all inventions of climate change mitigation technologies.³⁹ The patent application process and data gathering process leads to truncated data; therefore, the last three years should not be seen as representative.

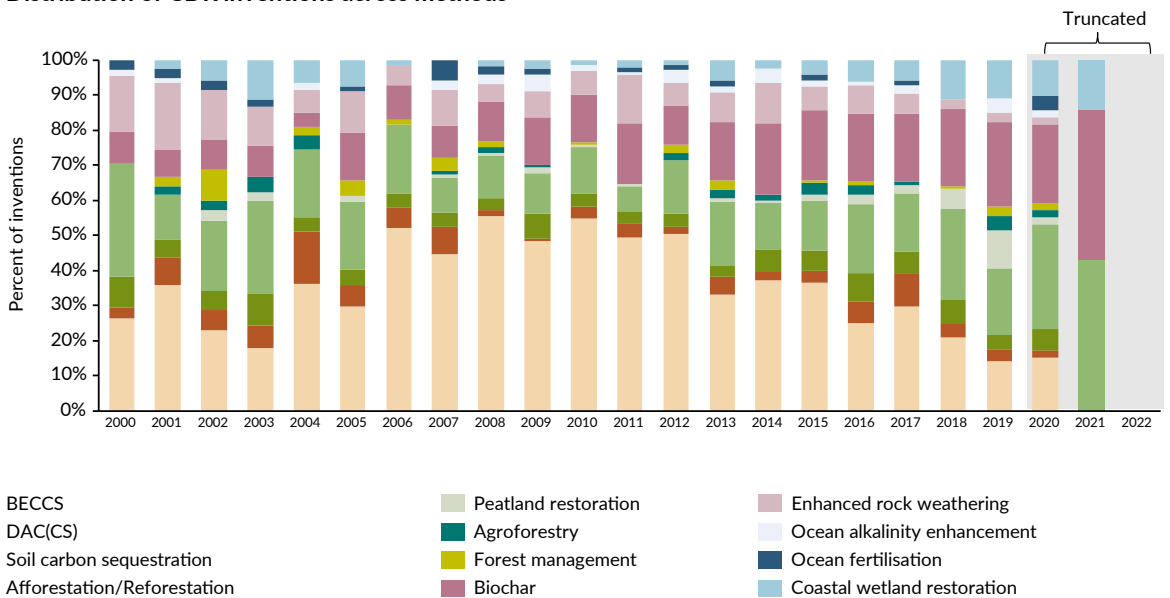
Regions show different patterns of specialization (see Figure 2.3c). Whereas Europe and Canada and the US focus heavily on inventions in BECCS (accounting for 41–48% of CDR patents in both regions), China and the rest of Asia show a greater emphasis on conventional CDR, such as soil carbon sequestration and afforestation/reforestation (together accounting for 33–39% of CDR patents in these regions). Biochar plays an important role across all regions, but it has the highest relative invention share in China (approximately 20% of all CDR inventions). DACCS is most important in Canada and the US, accounting for 7% of all CDR inventions. Coastal wetland restoration plays a more important role in China and the rest of Asia (accounting for 8–10% of CDR inventions). All other CDR methods (e.g. enhanced rock weathering, ocean fertilization) only account for approximately 10–15% of the global total of CDR inventions.

Geographically, CDR inventions are heavily concentrated in Canada and the US and in Europe. Both regions account jointly for 78% of CDR inventions, with Canada and the US featuring 44% and Europe 34% of inventions. Asia (excluding China) accounts for 12% of CDR inventions. China plays a minor role, with only 5% of all CDR inventions, but the country has recently seen increasing numbers of inventions across several CDR methods. The share of CDR patents in China is the same as its global share of climate change mitigation inventions more generally (approximately 5%).³⁹ Latin America, Africa and Oceania each account for less than 3% of inventions.

a) Annual patenting trends in CDR and all climate change mitigation inventions



b) Distribution of CDR inventions across methods



c) Distribution of CDR inventions across geographies (2000 - 2022)

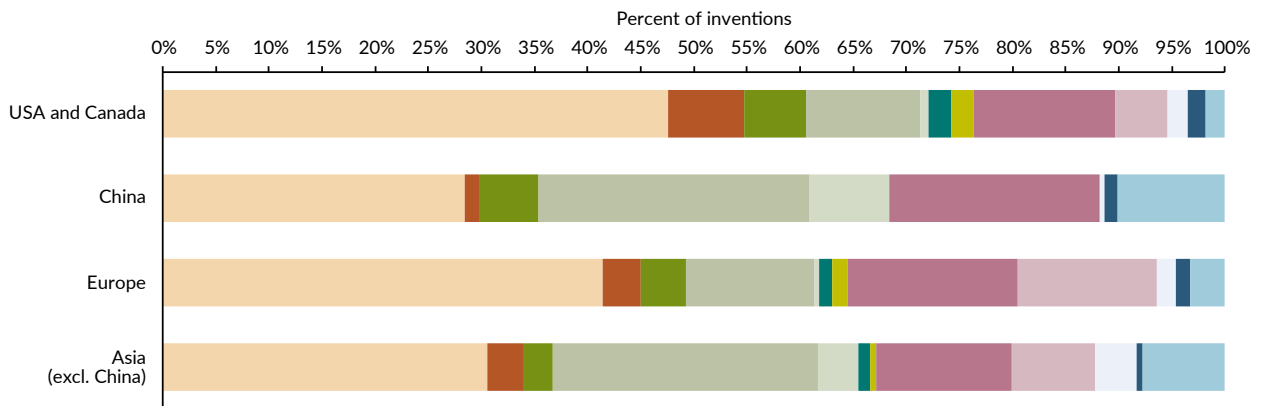


Figure 2.3 Technological and geographic trends in carbon dioxide removal (CDR) inventions as represented by patents: (a) Annual high-value inventions in CDR and climate change mitigation inventions (from Probst et al., 2021)³⁹ from 2000 to 2022; (b) Share

of high-value inventions across CDR methods; (c) Share of high-value inventions across inventor locations (i.e. where inventors currently work and live, which may be different from their country of birth). This report does not use the patenting office as a location as patents are territorial, and inventors may therefore gain patents directly in the most lucrative market (rather than their home country). The patent application process and data gathering process leads to truncated data; therefore, the last three years should not be seen as representative. Latin America, Africa and Oceania all account for 3% of inventions or less and are therefore omitted. Carbon capture and utilization and carbon capture and storage are not included, unless the underlying patent specifically refers to the use of CO₂ directly captured from ambient air or to biogenic CO₂. DAC(CS) = direct air capture (with or without carbon storage).

Box 2.3 Methods: Tracking invention in CDR

The analysis in this report applies machine learning to patent data to measure inventive activity in CDR. Patents are a common metric used in the economics and innovation literature to measure inventions.⁴⁰⁻⁴² Patent abstracts contain a detailed description of the underlying technology. Patenting activity is one measure of innovation, and one with accessible data, but innovation can also occur outside what firms choose to patent. Invention, experimentation and learning can be retained as tacit knowledge and trade secrets.

This report uses patent data from the Worldwide Patent Statistical Database PATSTAT, which the European Patent Office maintains. The database contains more than 100 million patents from 90 patent authorities and is widely used in academic and industrial research. The coverage of the data is particularly comprehensive for industrialized countries but may underrepresent certain regions of the world (e.g. Africa).

This analysis used machine learning, and specifically natural language processing, to identify and classify relevant CDR inventions. Two machine-learning classifiers were used to identify and classify CDR patents. The first, a *relevance classifier*, determines for each patent in the database whether that patent relates to a CDR method. The relevance classifier uses the supervised learning model ClimateBERT. To train the ClimateBERT model,³¹ the research team manually annotated over 1,000 patents that covered all CDR methods, as well as patents not related to CDR. To ensure high-quality annotations, each patent was classified by at least two authors. Differences in individual annotations were resolved via discussion. After the relevance classifier identified potentially relevant patents, the more compute-intensive GPT-4 model⁴³ was used as a *technology classifier* to map each potential CDR patent to specific CDR methods. In contrast to *The State of Carbon Dioxide Removal* 1st edition, which relied on keywords and patent codes, this machine learning-based approach enabled the identification of substantially more relevant patents.

The analysis follows Probst et al., 2021,³⁹ in using international patent families to provide an international comparison of patenting activity. An invention is typically protected by multiple individual patents, referred to as a patent family. International patent families cover this invention in at least two jurisdictions. Monitoring international patent families – rather than simply counting individual patents – addresses two limitations inherent in patent data: the heterogeneity of patent value (i.e. some patents are very valuable, but many are not) and cross-country differences in the propensity of

inventors to patent.

The analysis included all patents that could be used in the context of CDR, including technology components. However, carbon capture and storage patents were only included if they were explicitly used in the context of BECCS or DACCS. If the classifier put an invention into several categories (e.g. both afforestation/reforestation and soil carbon sequestration), the fractional counts were used to account for multi-classification (i.e. 0.5 was assigned to each technology class).

Box 2.4 Limitations and knowledge gaps

This report has identified areas on which future assessments can build, including:

- The estimates of investment in CDR research projects (Section 2.1) do not reflect all research funding on CDR, as the Dimensions database only includes third-party projects and does not cover institutional funding from universities and other research institutes.
- The search strategy for research projects includes all major CDR methods but is not fully exhaustive. Most importantly, the search does not cover carbon capture and utilization with long-term storage in products, or forest management or methods that have more recently gained attention, such as direct ocean carbon capture and storage.
- The geographic coverage of the Dimensions database for tracking research grants is not fully transparent, and uncertainties remain over the scope of investments covered in some regions, such as Latin America, Africa and Asia. The same applies for the patent data from PATSTAT.
- The classification of research grants by CDR method is not performed with very high accuracy, particularly for less frequently studied CDR methods as there are fewer annotations with which to train the machine-learning classifier.
- The machine-learning methodology for searching scientific research on CDR (Section 2.2) only returns articles with English-language abstracts.
- Although OpenAlex is one of the largest bibliographic databases, covering most peer-reviewed literature and including some of the major working paper collections, it is limited in its coverage of other non-peer-reviewed studies.
- For all indicators, this machine-learning approach does not work equally well across all CDR methods and across time, which could lead to some biases in the numbers, particularly for CDR methods for which there is currently little research.
- Patents are only one measure of inventive activity, and many inventors choose to protect their inventions with secrecy rather than patents.
- This analysis uses international patent families to control for differences in patent quality, yet even within this high-quality invention group, patent quality may be highly skewed.

- While inventive activity as proxied by international patent families has been in decline, the raw number of patent filings has increased steadily. But due to concerns around patent quality, this report only shows international patent families.
- Patent data are truncated due to the application process, so the data are less reflective of inventive activity from 2020 onward.

2.4 Outlook

Innovation activity has increased and diversified across CDR methods and geographies, but some CDR blind spots remain.

Spurring innovation in CDR is essential to close the CDR gap and meet the Paris temperature goal. Early-stage R&D efforts are a prerequisite to incentivizing continued inventive activity and pushing CDR methods towards greater commercialization and upscaling. Grants, scientific publications and high-value inventions are important – although not exhaustive – metrics with which to track the innovation process. The report’s findings are synthesized in Figure 2.4, which indicates distinct countries, CDR method distributions, and growth trends across the three indicators.

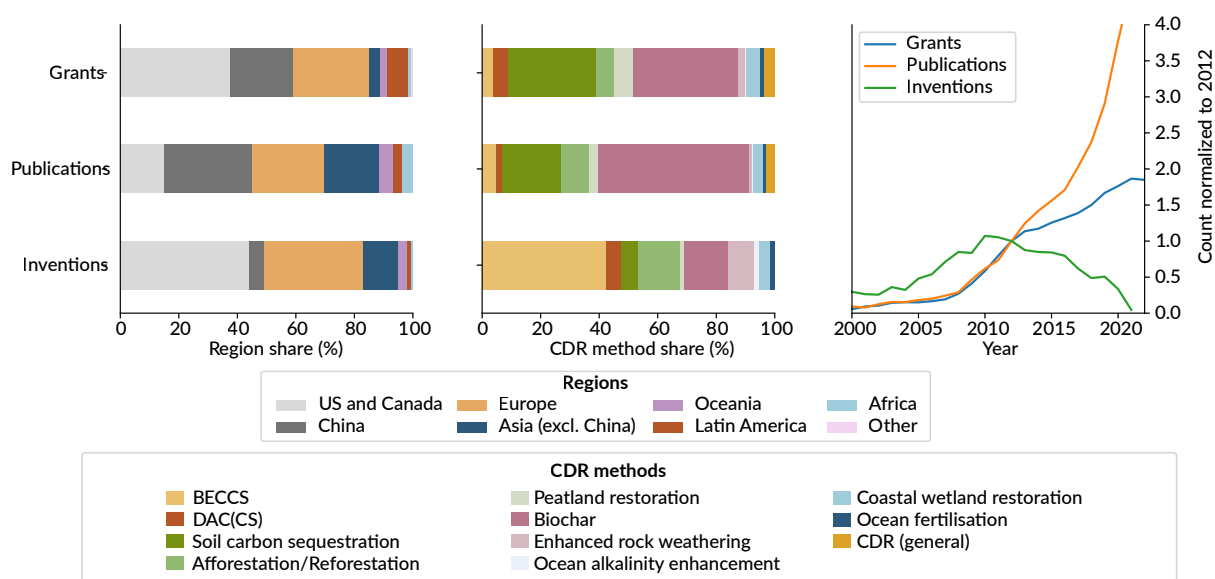


Figure 2.4 Comparison of regions, carbon dioxide removal (CDR) methods and growth over time across three key CDR innovation metrics (research grants, scientific publications and high-value inventions). BECCS = bioenergy with carbon capture and storage; DAC(CS) = direct air capture (with or without carbon storage).

In terms of geographic differences, three distinct R&D/innovation profiles seem to emerge, exemplified by Canada and the US, China, and Europe. These profiles are consistent, geographically, with recent research on the design of public institutions for energy innovation more generally. Like this report, that research found three different innovation models – the Asian, European and US models. Whether differences in the design of public institutions are partly responsible for different CDR innovation profiles could be an area of future research.⁴⁴

While Canada and the US account for almost half of CDR-related grants and high-value inventions, the region's importance is less critical in the scientific publishing domain. This might indicate a more applied nature of Canadian and US grants or easier commercialization routes for Canadian and US scholars and inventors. For China, the reverse appears to be true. China produces more publications relative to grant volume but very few high-value inventions, which might indicate struggles to commercialize academic findings, possibly related to incentives for deployment. Europe, in contrast, looks relatively balanced across all three metrics. Asia (excluding China) features low levels of grants but high levels of publications and commercialization, potentially driven by private sector R&D, which is more difficult to track. Other world regions currently represent a small share of each of the three metrics. The low levels of grants in regions with little inventive activity (Africa, Latin America, and Oceania) could be a sign of inertia and indicate that the observed dynamics are unlikely to change in the foreseeable future.

In terms of CDR methods, diverging profiles can be observed across the three indicators. Grants and scientific publications are heavily focused on conventional CDR (around 40–50% relate to these methods), but novel CDR is a much stronger focus for inventions. Novel CDR methods might be easier to patent than conventional CDR methods as hardware-based technology inventions are more readily patentable than, for instance, a digital monitoring tool for carbon stores in forests.⁴⁵ Inventors might protect such inventions by secrecy rather than patents. Biochar is playing an increasingly important role across all indicators. The invention portfolio across CDR methods is more balanced than the grant and publication portfolios, indicating more diverse inventive activity relative to grants and publications.

Overall, over the last decade, a strong growth can be observed in CDR-related grants and publications, but a slowdown in inventions. The slowdown in inventions could be driven by multiple factors, such as global trends (e.g. low oil and carbon prices) or factors more specific to CDR. It is only possible to speculate on the CDR-specific reasons for the slowdown. Grants may have become less applied or may focus on novel CDR methods that are less mature, leading to a stronger increase in publication activity, but less patenting, as these methods are further away from commercialization.



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