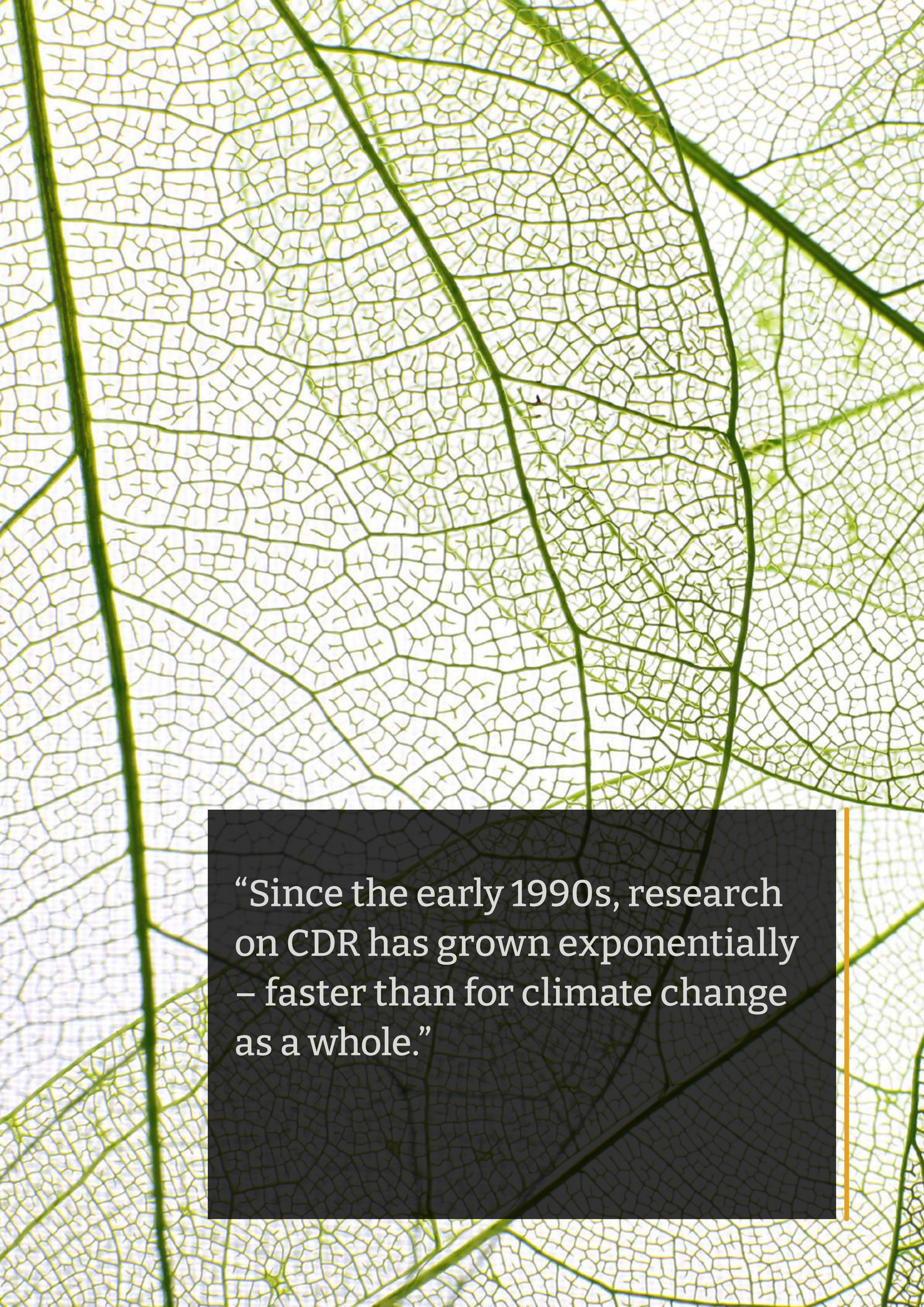

"Since the early 1990s, research on CDR has grown exponentially – faster than for climate change as a whole."

Chapter 2 | Research landscape

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Since the early 1990s, research on Carbon Dioxide Removal has grown exponentially – faster than for climate change as a whole. Most of this rapid growth has been driven by biochar research.

Box 2.1 Key findings

- There is a vast and fast-growing scientific literature on Carbon Dioxide Removal (CDR) of about 28,000 studies in Web of Science and Scopus alone – two of the largest English-language bibliographic databases.

- Studies on CDR make up less than 4% of the scientific literature on climate change but are growing exponentially by about 19% per year (1990-2021). Annual publications are currently doubling every three to four years.

- Scientific studies on CDR are dominated by biochar, soil carbon sequestration and afforestation/reforestation. Such methods account for about 80% of the CDR methods covered in the scientific literature.

- Research on biochar is growing faster than that of any other CDR method, accounting for about 40% of the coverage on CDR methods in the scientific literature overall and about 50% of the studies published in 2021.

- Bioenergy with Carbon Capture and Storage as well as Direct Air Capture and Direct Air Carbon Capture and Storage receive comparatively little attention in the CDR literature – despite dominating discussions on, respectively, the role of CDR in climate change mitigation scenarios and private CDR investment.

- Only about a third of the scientific literature on CDR has a geographical focus, highlighting a potential lack of information tailored to specific local or regional contexts, particularly Africa and South America.

- Based on first author affiliation, 32% of scientific studies on CDR are written in China, 9% in the United States and 4% in Australia. This is particularly driven by a strong dominance of biochar research in China.

- The scientific literature on CDR is mainly published in natural science (49%), agricultural science (25%) and engineering and technology journals (23%). Only 3% is published in social science journals, and a handful in the humanities.

2.1 Overall scientific attention

The scientific literature on Carbon Dioxide Removal (CDR) is small compared with climate change as a whole, but growing faster.

A key indicator of the state of CDR is how much scientific research is being carried out. In this chapter, we use a machine-learning approach to identify, track and analyse the scientific literature published on CDR since the early 1990s (Box 2.2). We find a dynamic picture of the level of scientific attention on CDR over time, both as a general topic and at the level of individual CDR methods.

Box 2.2 Our methods for tracking scientific research on CDR

We use a machine learning-based approach to measure attention to CDR in the scientific literature[24–27].

First, we design combinations of search terms ("search strings") for each CDR method based on a comprehensive list of keywords. We then validate the search strings against a set of studies included in the Intergovernmental Panel on Climate Change's Sixth Assessment Report, ensuring that these studies are returned. These search strings retrieve a total of 60,000 records from two large bibliographic databases: the Web of Science and Scopus. We then manually screen the title, abstract and keywords of 400-600 records per search string and label them with their suitability for inclusion (relevant/irrelevant) and the specific CDR method being studied. In total, we labelled 5,600 documents. Finally, we use this labelled data to train a state-of-the-art machine-learning classifier[28] to predict relevance for inclusion and the specific CDR method for the 56,000 remaining records. Our automated approach enables a comprehensive search for scientific literature in bibliographic databases while still ensuring a high level of precision in terms of the identification of relevant studies.

While the machine-learning methodology allows a more comprehensive assessment of the state of scientific research on CDR than has previously been possible, the analysis presented here has important limitations. First, our use of two major bibliographic databases (Web of Science and Scopus) covers most peer-reviewed literature, including social science studies, but excludes large parts of the non-peer-reviewed literature. Second, the search methodology is limited to returning articles with English-language abstracts. Third, we include not only studies on Direct Air Carbon Capture and Storage but also studies on Direct Air Capture without knowing about the fate of the captured CO_2. Hence, some of those Direct Air Capture studies might not count as CDR, as we define it in this report (see Chapter 1 – Introduction).

By the end of 2021, there were about 28,000 English-language scientific studies on CDR in the Web of Science and Scopus – the two largest commercial bibliographic databases. This is a vast number of publications and a much larger figure than previously indicated in the scientific discussion or any ongoing community effort to track CDR research[29,30]. Based on estimates that the Web of Science covers about 43% of the entire scientific literature[31], and assuming that this share is representative also for the literature on CDR, there could be about 50,000 English-language studies on CDR overall.

The total number of studies on CDR makes up less than 4% of the scientific literature on climate change[26,32,33], but growth has been very rapid. Since the early 1990s, the number of studies on CDR has grown exponentially by about 19% per year – faster than the literature on climate change (13% per year). Right now, the number of annual publications doubles every three to four years. This growth started from a very low level, however: in the 1990s, publications per year reached no more than a few dozen, while almost 4,700 papers on CDR were published in 2021 alone.

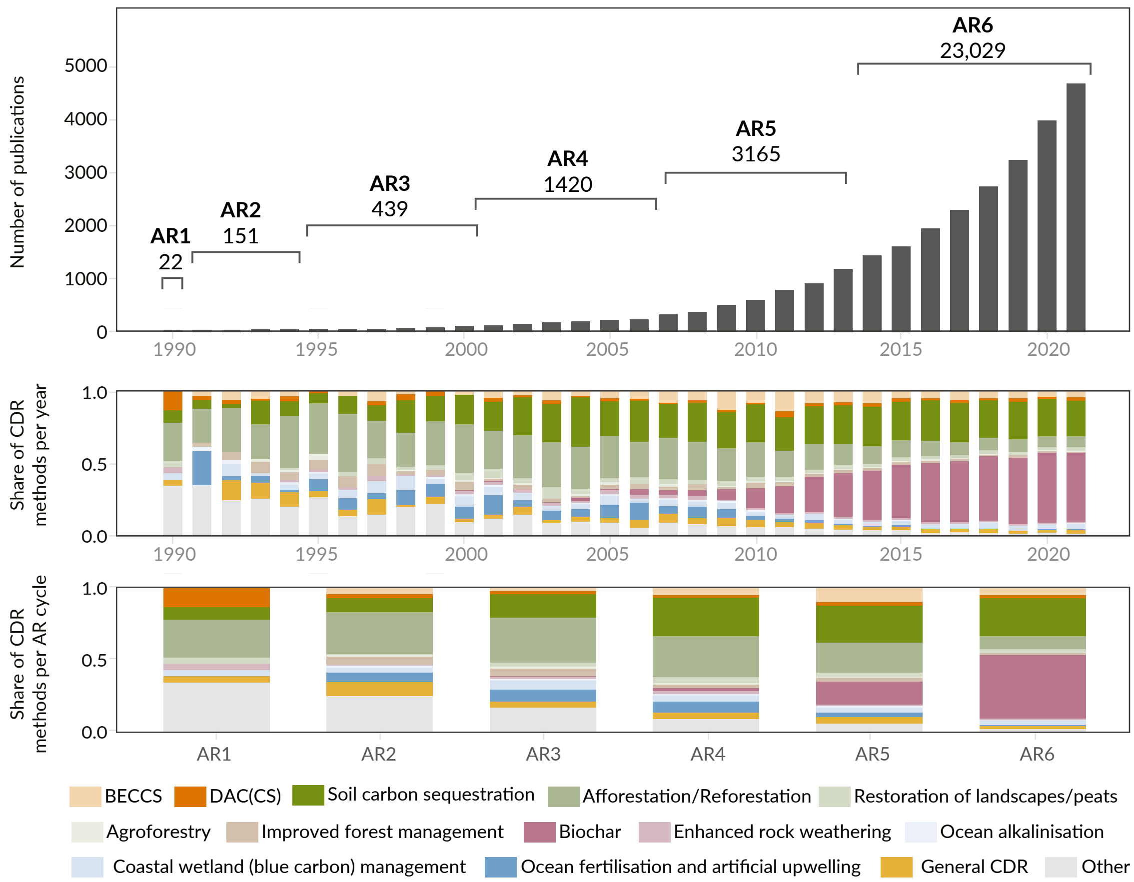

Figure 2.1. *Exponential growth in the scientific literature on Carbon Dioxide Removal (CDR) over time. Total number of scientific publications on CDR per year from 1990 to 2021 in the Web of Science and Scopus (top panel). Share of CDR methods covered in these scientific publications per year (middle panel). Share of CDR methods covered in scientific publications released during each Assessment Report (AR) cycle of the Intergovernmental Panel on Climate Change (bottom panel). Definitions: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS).*

The analysis presented above does not include scientific publications on Carbon Capture and Storage (CCS) nor on biomass harvested for energy without CCS – as these do not, on their own, count as CDR (see Chapter 1 – Introduction, Box 1.2). The growth rate of the CCS literature, however, provides an interesting contrast with that of CDR (see Box 2.3).

Box 2.3 Tracking scientific literature on Carbon Capture and Storage

While fossil Carbon Capture and Storage (CCS) does not count as CDR (see Chapter 1 – Introduction, Box 1.2), it is still instructive to also track the literature on CCS, as many critical aspects of CCS are not comprehensively discussed in the dedicated CDR literature.

We find approximately 16,000 scientific publications on CCS in the Web of Science and Scopus overall (see Box 2.2), with a notably different growth pattern to that of CDR and the different CDR methods. The literature base on CCS grew steadily during the 2000s, peaking at about 1,500 publications annually in 2017. Annual publications subsequently declined to about 900–1,300 publications in subsequent years. Compared with total publications on CDR, as well as the climate change literature as a whole, there appears to be a recent levelling out of scientific literature dedicated to CCS. This is despite the strong reliance on CCS in climate change mitigation scenarios that are consistent with meeting the Paris temperature goal[34–36] (see Chapter 7 – Scenarios).

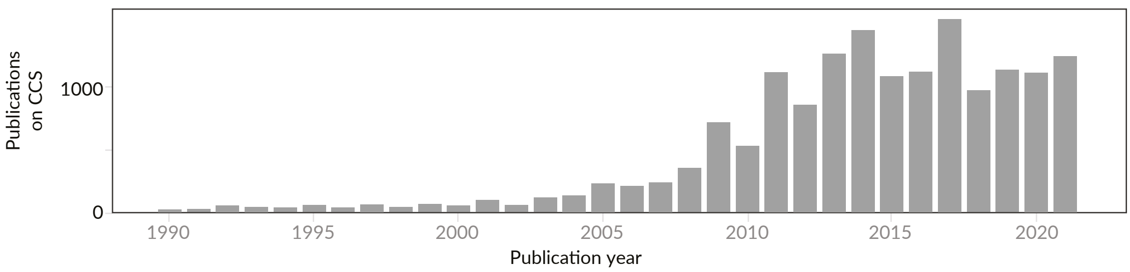

Figure 2.2. *Total number of publications on Carbon Capture and Storage (CCS) per year from 1990 to 2021. Growth in the scientific literature on CCS appeared to peak in 2017 with around 1,500 publications per year.*

2.2 Individual CDR methods, geographical focus and scientific disciplines

Scientific studies on CDR are concentrated on particular methods and regions, with others receiving little attention. Natural science and engineering perspectives heavily dominate over the social sciences.

Individual CDR methods

Biochar accounts for almost 40% of the coverage on CDR methods in the approximately 28,000 scientific publications on CDR (Figure 2.1). Biochar is material made from harvested biomass that has removed CO_2 from the atmosphere during plant growth and has been pyrolysed (heated in an oxygen-limited environment), with a portion of the CO_2 being locked into the char.

There is also a sizeable scientific literature on soil carbon sequestration (accounting for 26% of the coverage on CDR methods) and afforestation/reforestation (12%). Bioenergy with Carbon Capture and Storage (BECCS) represents only about 5% of the CDR methods covered in the scientific literature, despite being the dominant novel CDR method in most scenario pathways for meeting the Paris temperature goal[4,37,38] (see Chapter 7 – Scenarios) and having received considerable space in high-level editorials and commentaries on CDR[39–41]. Three per cent is on coastal wetland (blue carbon) management. Direct Air Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS), which have received a lot of attention in the CDR innovation and investment space, only make up about 2% of the CDR methods covered in the scientific literature. There are several hundred studies on peatland and wetland restoration (2%), ocean fertilisation (1%), enhanced rock weathering (1%) and improved forest management (1%). Scientific literature on ocean alkalinisation and agroforestry in the context of CDR is still in its infancy, with about 100–200 studies each. There are about 1,000 studies (3%) dealing with CDR in a generic sense, without focusing on a specific method.

During most of the 2000s, only 3-5% of the discussion of CDR methods was on biochar. But over the last decade (2011-2021), biochar research grew by about 32% annually – faster than any other CDR method and than the average growth across all methods (19% per year). In 2021, biochar accounted for about 50% of the CDR methods covered in the scientific literature (2,900 studies) – most of these being laboratory studies or field experiments. Growth in the literature on other CDR methods has been more moderate. Research on coastal wetland (blue carbon) management, enhanced rock weathering and soil carbon sequestration has grown by about 25%, 23% and 21% per year, respectively. The remaining CDR methods have developed slower than the average growth in scientific publications on CDR as a whole: research on DAC(CS) by 14% per year and on BECCS by 6% per year.

Geographical focus

Research on CDR that is specific to a geographical location (place-specific) is important as it can consider the local circumstances that determine the efficacy of CDR methods; their potential co-benefits and adverse side effects; and their equitable implementation, operation and governance. However, less than a third of the English-language scientific publications on CDR covered here (8,900 out of 28,000 studies) mention a location in the title or abstract. Of those 8,900 studies, 69% mention national-level locations and about 30% subnational locations. Few studies mention broader regions or continents in their abstracts (Figure 2.3). The distribution of study locations mentioned is very uneven across major world regions (Figure 2.4). More than 40% of all place-specific CDR research refers to locations in Asia (~3,700 studies), 24% in North America (~2,100 studies) and about 18% in Europe (~1,600 studies). Only 5-6% of place-specific CDR research focuses on South America, Oceania and Africa (~500 studies or fewer). This indicates that there is a potential gap in site-specific knowledge with respect to CDR methods in Africa and South America – despite their importance for carbon storage from land-use change and the provision of biomass for various CDR pathways in global integrated assessment models[42,43].

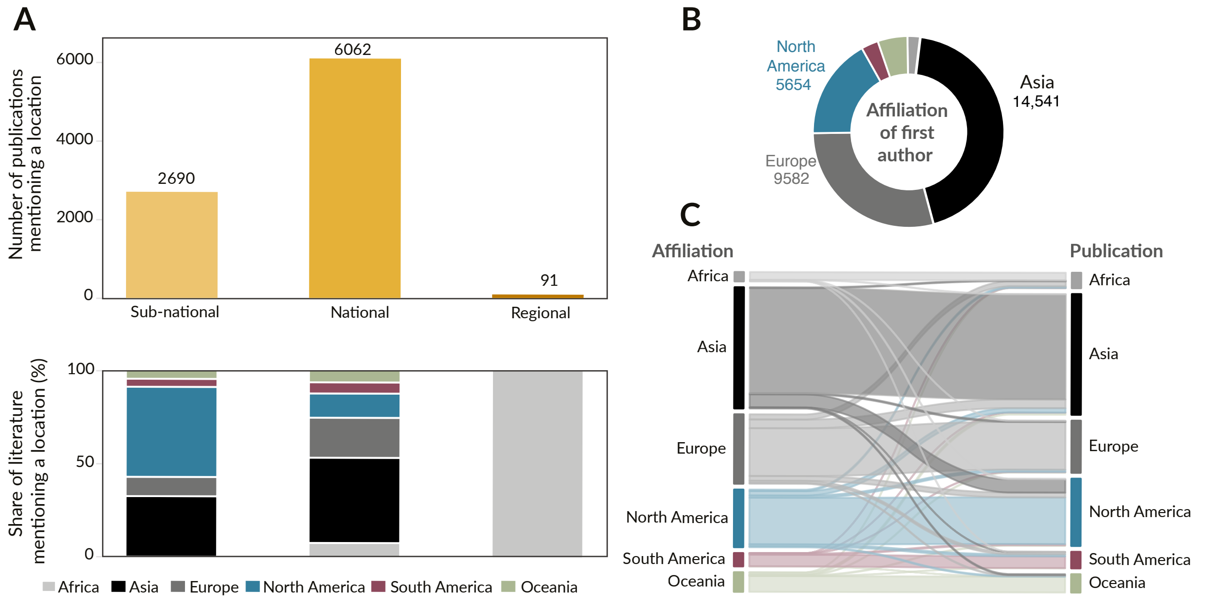

Figure 2.3. *Geographical locations mentioned in the abstract and/or title of Carbon Dioxide Removal (CDR) research publications, shown by level of analysis (subnational, national or regional – for example, Western Africa, North Africa) and by world region (panel A top and bottom, respectively). Continent in which CDR research is produced, derived from the first author's affiliation (panel B). How geographical locations mentioned in the abstract/title of a CDR research publication are related to the first author affiliation (panel C).*

The geographical focus of place-based CDR research also differs strongly for different CDR methods. The vast majority of place-based CDR research is on CDR methods involving biological storage on land or in biochar – soil carbon sequestration (32%), biochar (24%) and afforestation/reforestation (20%) together make up more than three-quarters of place-specific CDR research. Other CDR methods such as DAC(CS) (1%; ~40 studies) feature only marginally, partly because the overall size of the scientific literature on these methods is much smaller.

In general, CDR methods that involve biological storage on land are much more likely to feature place-specific research. For example, about 50% of studies on afforestation/reforestation have an explicit geographical focus. In contrast, only about 6% of scientific studies on DAC(CS) have a specific regional focus. About a quarter of all research on enhanced rock weathering is place-specific, while this is the case for only 8% of studies on ocean alkalinisation. This may be primarily due to institutional challenges involved in setting up experimental research in the ocean.

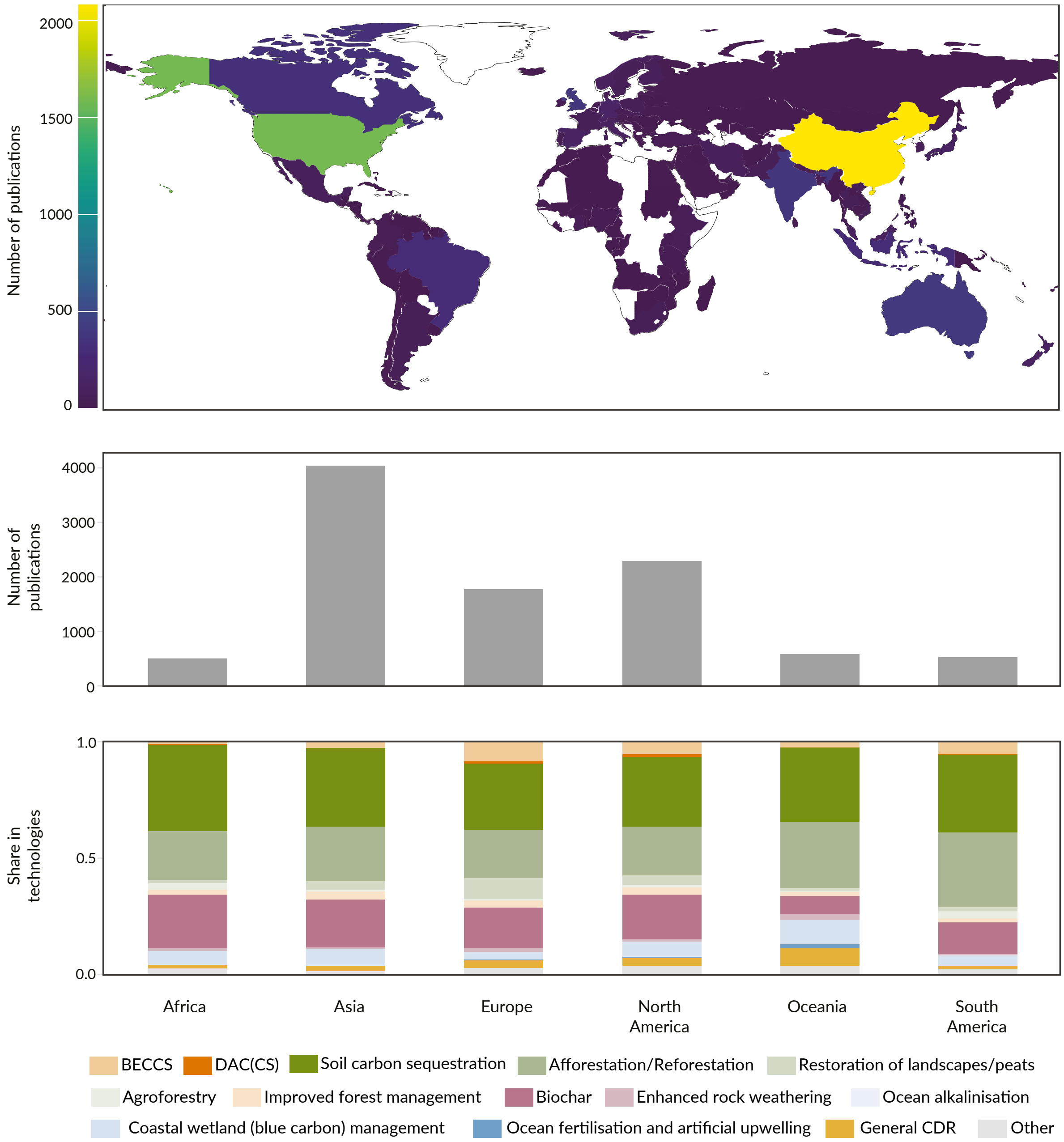

Figure 2.4. *The distribution of place-based Carbon Dioxide Removal (CDR) research is very uneven across major global regions. Total number of CDR research publications that mention a geographic location in abstract or title, shown by country (top) and world region (middle). Share of CDR methods in scientific research publication that refer to a specific geographic location, shown by world region (bottom). Definitions: Bioenergy with Carbon Capture and Storage (BECCS), Direct Air Carbon Capture (DAC) and Direct Air Carbon Capture and Storage (DACCS).*

Analysing the affiliations of the (first) authors of English-language peer-reviewed research on CDR, we find that Asia – and in particular China – is a hotspot in terms of producing CDR research. This is mainly driven by high levels of research activity on conventional CDR methods on land, as well as biochar. Overall, there are about 8,900 publications on CDR for which the first author's affiliation is in China, followed by the United States (2,600) and Australia (1,200). This finding is particularly driven by a strong dominance of biochar research in China. This is also reflected when looking at research organisations. Of the research organisations with the largest numbers of first-authored publications on CDR, nine of the top ten are in China.

In general, place-based CDR research is led by research teams from the country under investigation. Studies led by European research organisations are the most likely to cover regions outside Europe (28% of their total publications), while research organisations based in Asia dedicate a smaller fraction of their CDR research to other regions (13%).

Scientific disciplines

About half the CDR research is taking place in the domain of the natural sciences. About 49% of the scientific discussion around CDR is published in academic outlets that classify themselves as natural science journals. These also include a range of interdisciplinary journals such as *Science* or *Nature*. Two other scientific domains attract substantive CDR research: about 25% of research papers are published in agricultural science journals and 22% in journals on engineering and technology. This highlights the focus of the CDR research community to date on studying the workings of individual CDR methods.

So far, only a very small share (~3%) of CDR studies are published in social science journals, and there are only a handful of studies in humanities journals. The social sciences and humanities are crucial for discussions on implementation, equity and governance of CDR, but scientific discussion in the English-language peer-reviewed literature is not yet fully developed in these areas[29].

2.3 Building understanding

Closing the evidence gap requires research on CDR methods where it is missing or scarce as well as improvement in our understanding of local and regional aspects of deploying and upscaling CDR.

There are very large differences in scientific attention to different CDR methods. While there is a very large amount of evidence on certain CDR methods, such as biochar or soil carbon sequestration, a range of other CDR methods are still the subject of relatively few studies, such as peatland and wetland restoration, ocean alkalinization and DAC(CS). This suggests great differences in the detailed understanding of the various CDR methods, which needs to be addressed for a sound understanding of the entire portfolio of CDR methods.

Critically, place-specific research on CDR is still underdeveloped for almost all novel CDR methods except biochar. Regional and local circumstances will determine the costs, mitigation potentials and side effects of specific CDR methods and also relate to important governance aspects. Place-specific research will be critical for advancing scientific evidence on CDR, notably in regions that are typically projected to provide substantial deployments of specific CDR methods in global mitigation pathways that limit warming to well below 2°C[37]. Finally, only a very small share of research is published in social science journals – and almost none in the humanities. This is an indication that CDR research still mainly focuses on the development and application of CDR methods. There is a need within the scientific community to give more attention to issues around policy, governance and equity.

Our results suggest that the size of the literature on CDR – already vast and fast-growing – may make it difficult to keep an overview of developments in research. This suggests the need for tracking CDR research in quasi real time. Moreover, there is a growing need for this evidence to be continuously synthesised and presented in an accessible format, requiring rigorous systematic review work to ensure that the best-available CDR knowledge can be considered in science and policy.