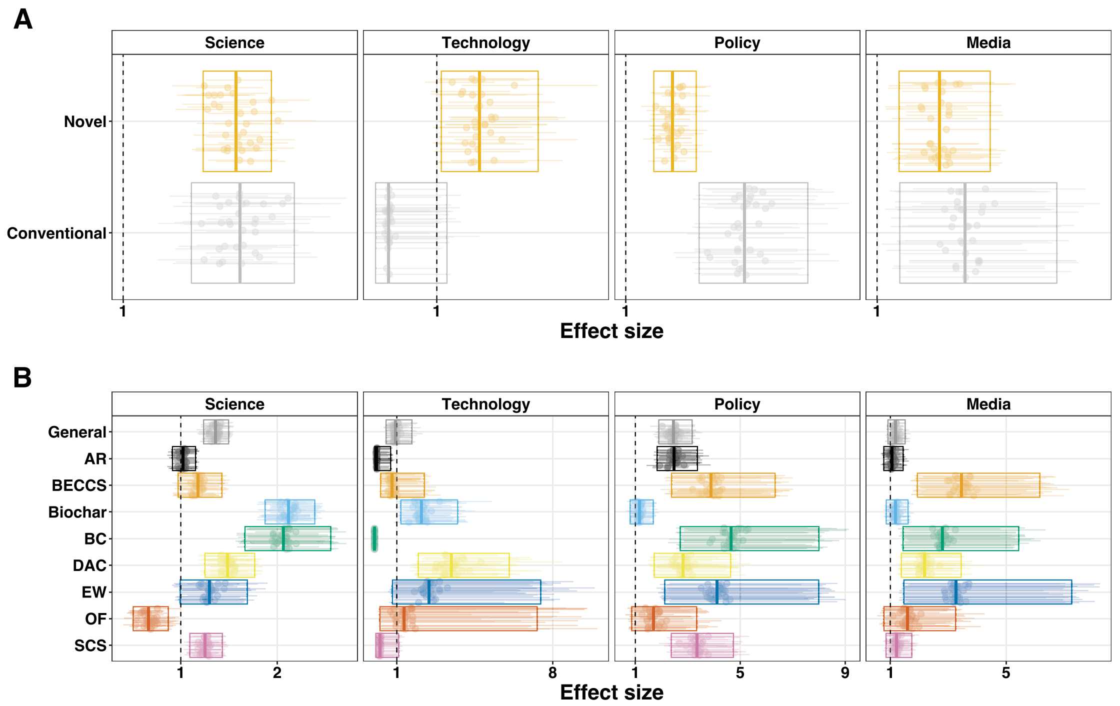

Figure 4. CDR spillovers in science, technology, policy, and media. (A) Effect sizes for novel and conventional CDR solution vs. baseline controls. (B) Effect sizes for each CDR solution (and for the *General* CDR category) vs. baseline controls. (A), (B) Exponentiated coefficients estimates are shown as dots and corresponding 95% confidence intervals as horizontal segments. These represent Incident Rate Ratios for the negative binomial regression relative to **Science**, and Odd Ratios for the logistic regressions relative to **Technology**, **Policy** and **Media**. Results are from repeated fits of the regressions on 30 data sets augmented with different matched control groups (non-CDR articles). Boxes are drawn as to highlight average estimates (mid-lines), lower end of CIs (left margin) and upper end of CIs (right margin) across the 30 fits. For each regression, boxes entirely to the right of 1 (dashed vertical line) indicate CDR solutions whose spillovers are stably significant across different selections of matched controls. In the regression relative to technology, the BC box is collapsed because no valid estimates are produced (BC articles have no mentions in patents). All regressions are based on equation (1) and include fixed effects for publication year and further control covariates—e.g. to take into account whether articles are open access, the team size (number of authors), and the number of references (to capture articles of different types, such as long reviews or shorter pieces, especially relevant in general audience journals).

Table 1. CDR spillovers in science, technology, policy, and media. Average exponentiated coefficient estimates, lower ends of CIs, and upper ends of CIs across the 30 fits of the four regressions, as described in the legend of figure 4. Year dummies and other control covariates are included in all regressions, and the number of articles in each of the 30 augmented data sets (CDR articles + matched control group), i.e. the sample size for each fit, is 3136 (see Sections 2.1 and 2.2 for details). The lower end of the CI above 1 signals positive and significant results.

	Science		Technology		Policy		Media	
CDR	exp β	*CI*	exp β	*CI*	exp β	*CI*	exp β	*CI*
General	1.36	[1.24,1.5]	0.93	[0.52,1.68]	2.45	[1.89,3.16]	1.18	[0.92,1.51]
AR	1.02	[0.91,1.15]	0.10	[0.01,0.72]	2.48	[1.83,3.37]	1.05	[0.77,1.44]
BECCS	1.18	[0.97,1.43]	0.78	[0.27,2.24]	3.88	[2.38,6.33]	3.45	[1.93,6.17]
Biochar	2.12	[1.87,2.39]	2.10	[1.18,3.73]	1.16	[0.8,1.68]	1.17	[0.86,1.61]
BC	2.06	[1.67,2.56]	✘		4.65	[2.71,8]	2.79	[1.44,5.43]
DAC	1.49	[1.25,1.77]	3.45	[1.97,6.05]	2.82	[1.72,4.63]	2.18	[1.38,3.45]
EW	1.30	[0.99,1.69]	2.45	[0.8,7.46]	4.12	[2.12,7.99]	3.27	[1.47,7.27]
OF	0.66	[0.51,0.87]	1.23	[0.24,7.3]	1.69	[0.86,3.34]	1.59	[0.78,3.25]
SCS	1.25	[1.09,1.43]	0.25	[0.06,1.08]	3.35	[0.86,3.34]	1.22	[0.85,1.74]
Year dummies	✔		✔		✔		✔	
Control covariates	✔		✔		✔		✔	
Matched control groups	30		30		30		30	
Sample size	3136		3136		3136		3136	

Note: No valid estimates for BC in Technology (no mentions in patents).

showing positive and significant spillovers in every dimension. Other solutions only stand out in some dimensions. This signals a crucial difference (between DAC and other methods) in terms of coordination effectiveness of science, technology, policy, and media coverage. Interestingly, a positive, although not statically-significant, signal characterizes EW. Indeed, EW represents a promising solution with potentially positive spillovers spanning through all the aforementioned dimensions. As of today, however, and perhaps due to a smaller sample size ($n < 100$) we cannot detect a robust effect. Our results are robust to several checks, including the use of (i) different control groups (i.e. climate-related), (ii) alternative model specifications (OLS with log counts as dependent variable), as well as (iii) different data sources (see section Regressions SI for details).

Mentions in scientific journals (i.e. forward citations) are well established as a partial but effective proxy for spillovers in science [52, 53]. In contrast, to date, the use of mentions in policy documents to quantify spillovers in the policy domain is less well understood [32]. Hence, as an additional exercise, we try to disentangle positive and negative mentions in policy documents, estimating their sentiment [54]. Our results suggest that, on average, policy documents citing CDR-related research show a positive attitude, with a higher sentiment ratio for documents citing BECCS (see section Policy sentiment analysis SI). Public perception is crucial to understand the trajectories of development and deployment of climate technologies, especially for CDR and geoengineering, and generally favors methods perceived as more natural [55–57]. Further investigating how local and global actors (e.g. local governments and international organizations) discuss different technologies and whether their vision is aligned with the public view will be a challenging yet necessary endeavor for both researchers and policymakers.

In summary, our analyses suggest that advances in CDR-related research have a stronger ability to stimulate further scientific developments than comparable advances in other research fields—even than comparable advances in climate change research unrelated to CDR. Nevertheless, to date, most CDR-related research hardly leaves the ‘ivory tower’ to make its way into technological innovations; we find evidence for such a transition only for DAC and Biochar. In addition, impacts in the policy and media dimensions seem relatively disconnected from those in science and technology. For instance, research in BECCS exhibits the strongest link to policy documents, though its spillovers to science and technology are small and not significant. To some extent, standard CCS methods may be technologically close to BECCS in practical applications. However, our focus is to uncover the potential use of BECCS’ scientific advances in patents. Therefore, we only focus on ‘pure’ BECCS articles rather than looking at the CCS literature and its already well-established technological application [18].

In general, DAC and BC generate synergic spillovers to both technical and public dimensions. On the contrary, BECCS and Biochar generate isolated, but yet significant, spillovers to either science (Biochar) or policy (BECCS). These findings have also implications for climate and innovation policies that aim to identify and foster solutions that connect technical advances with social and public impact.

3.4. The geography of CDR research

Prior studies have shown that innovation is disproportionately concentrated around hubs located close to where they are needed or where there are relevant scientific and technological capabilities [58–60]. To investigate the geographical distribution in negative emissions research, we geolocalize CDR articles using author affiliation data from WoS (see section 2.1). Geo-localization allows us to investigate the heterogeneity of scientific production and measure the relative specializations of different countries (see sections 2.3 and Geography SI for details).

As mentioned before, figure 1(B) depicts the total number of CDR articles, highlighting that the US and China maintain their role as the primary research hubs worldwide. We now switch to considering CDR solutions separately.

First, to investigate specialization, we compute Relative Scientific Advantages (RSA) for each country and CDR solution. While European countries and the USA specialize in engineering-based solutions requiring industrial facilities (specifically BECCS and DAC), China focuses on more conventional solutions (specifically AR, SCS) and Biochar, though its specialization levels are generally low. Switzerland displays the highest degree of specialization in DAC across the globe, while Indonesia—one of the largest reserves of coastal forests—is almost entirely specialized in BC (see figure 5(A)). This evidence of high country-level specialization may have relevant implications for the future of CDR deployment. Since technologies require knowledge to be operated, and such knowledge is typically cumulative and tacit [16, 17], carbon removal strategies should coherently match local capabilities with the technical requirements of CDR solutions, as to increase the likelihood of rapid diffusion. For instance, countries with high renewable and nuclear energy penetration may want to develop knowledge in DAC. Conversely, countries subject to drought or water scarcity may avoid solutions such as BECCS [61].

Next, we use citations from patents and policy documents to measure the relative influence that countries play in the diffusion of knowledge to the technological or policy sphere. In more detail, for each country, we define a measure of policy and technological coverage as the share of CDR articles that get cited by patents or policy documents over the total number of articles related to a given CDR solution in the same country. When doing so, a first-order observation is that most countries produce science that is

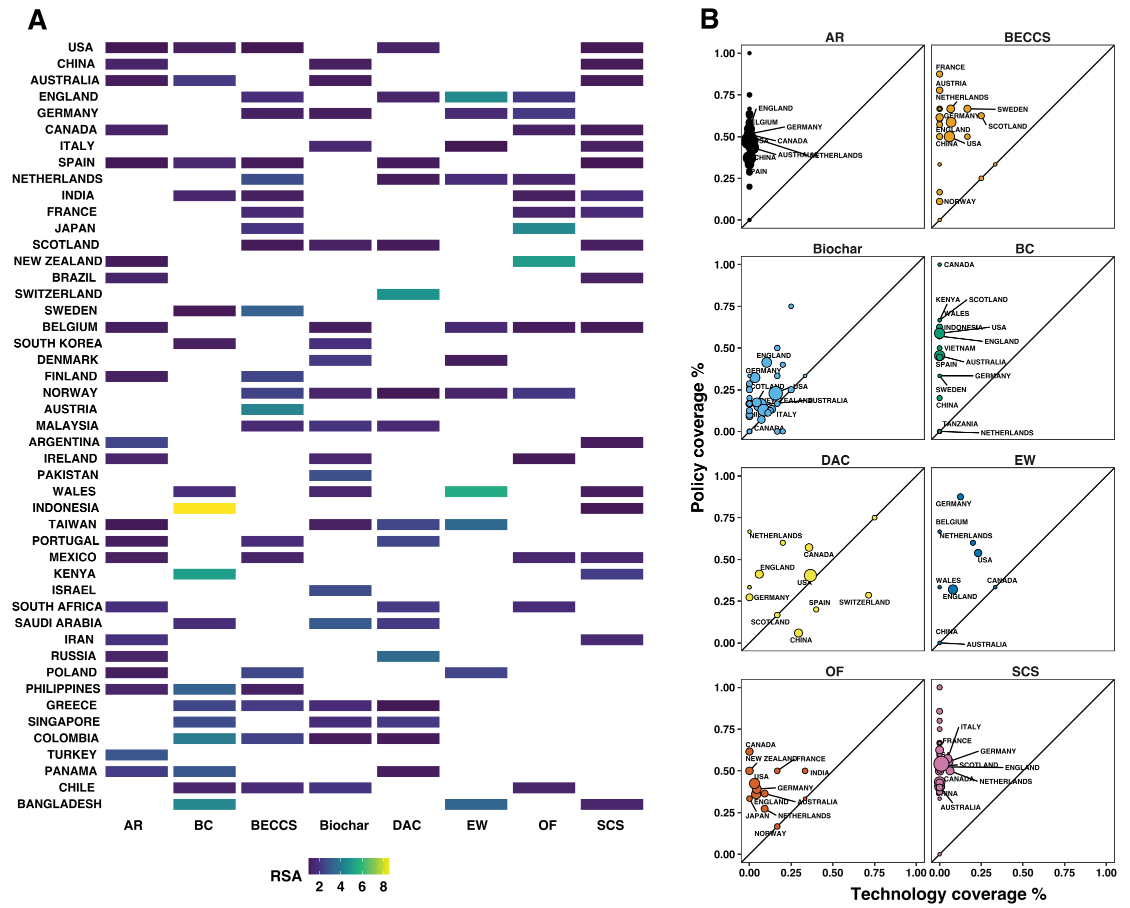

Figure 5. Countries' scientific specialization, technology and policy coverage. (A) Revealed Scientific Advantage of selected countries (CDR articles > 10). White cells indicate values below 1. (B) Share of articles cited by patents and policy documents by country and CDR. Countries with less than 3 articles in any given CDR are omitted.

somehow influential for the policy debate (i.e. mentions in policy documents). As points in figure 5(B) tend to concentrate in the upper-left area, a larger share of CDR articles get cited by policy reports rather than patents. On the technological side, as far as DAC is concerned, we can notice that some countries (such as Switzerland) can act as technological hubs in linking scientific research to innovation. Interestingly, the company that first brought to market a commercial DAC solution was founded as a spin-off of the ETH in Zurich. This example highlights the importance of basic scientific research in developing technologically viable climate solutions and the role of geographical proximity between science and technology (see figures S19 and S20 for city-level descriptive analyses). Indeed, discovery, technological innovation, and entrepreneurship benefit from co-location, which facilitates collaboration and knowledge sharing [62, 63]. However, some locations with a high potential to accelerate advances in CDR remain relatively overlooked in policy documents (e.g. China). We further investigate the potential mismatch in public interest by ranking countries in all four dimensions (figure S23). Overall, we find evidence of missing alignment: countries that lead the way in scientific production lag behind in other dimensions. These results suggest that some countries already relatively successful in scientific commercialization might benefit from a more active role in policy, while others that are relatively more influential in the policy debate might redirect some effort to the commercialization potential of scientific discoveries (e.g. USA). However, let us emphasize that exceptions exist, and we find some consistency for DAC and EW: Switzerland, Canada and the USA rank consistently well (top 5) for DAC, while England, Germany, the Netherlands and the USA for EW. China is relatively consistent (top 10) across all dimensions in Biochar.

4. Discussion and conclusions

Climate change will require a combination of novel scientific research, practical technological innovations, targeted policy and public support[14]. We provide a quantitative comparison of CDR solutions from the perspective of the public use of science, focusing on the first wave of CDR developments. We

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[14] See, for example, calls for attention by the EU Commission and the UK government.

consider multiple impact dimensions, investigating spillovers of CDR research onto science itself, technology, policy, and the media. Scientific advances in CDR capture public interest, generating larger spillovers than similar scientific results in different fields as well as within the climate-related literature

However, they are quite removed from practical innovation and the marketplace, especially when considering conventional solutions. As of today, DAC appears to be the most promising solution in terms of actual technological spillovers. In contrast, BECCS—which is the most popular solution in the integrated assessment literature and significantly covered in policy documents—does not display robust impacts on technology. Since patenting precedes cost reduction in climate technologies [64], our results suggest that BECCS deployment might be more difficult than previously thought and that DAC should be consistently included in mitigation scenarios. Among solutions based on a biological capture process, Biochar exhibits sizable and positive science-to-science and, although to a lesser extent, science-to-technology spillovers. Yet, this solution is not prominent in policy documents and media. Finally, we find that CDR research and collaborations cluster geographically, generating different areas of specialization and different hubs for each solution. It is unclear, though, whether the emerging geographical landscape of CDR is coherent with that of broader mitigation pathways.

The analyses presented here have, of course, a number of limitations. The first type of limitations concerns the quantification of impacts. We retrieve relevant articles characterizing the first wave of CDR research with a query strategy based on specific keywords and patterns, but this may be suboptimal due to the fast-changing and interdisciplinary nature of CDR research [65]. Advanced Machine Learning approaches (e.g. Large Language Models) may improve article identification and the definition of disciplinary spans. We perform article matching to produce effective control groups, iterate model fits on multiple control groups to gauge result stability, and employ a variety of control covariates, model specifications, and other robustness checks—but we cannot, and do not, claim to be able to identify causal mechanisms. Finally, scientific and technological trajectories in the early stages of -development are intrinsically challenging for standard statistical predictions, as relatively small advances might lead to sudden and sizable leaps forward. For instance, a specific breakthrough may precipitate the patenting and accelerate the impact on the technological development of an existing CDR solution, or an entirely novel and universally superior solution may emerge and change the whole dynamics of impacts and spillovers. Our analysis is not a technology forecast exercise but rather a first exploration of the public use of CDR scientific advances in several and often overlooked dimensions.

From a policy perspective, our findings provide two insights. First, when evaluating the applicability of a diversified portfolio of CDR technologies, their knowledge bases and spillovers should be considered carefully; our analyses provide little evidence of synergies among them. Second, given the limited impacts of CDR in the technology domain (at least for what concerns the first wave of advances), the urgency of their diffusion at scale would benefit from both conventional and unconventional innovation policies [66–69]. In addition, the evidence of strong positive knowledge spillovers could support a mission-oriented approach towards CDR, but it is necessary to consider the heterogeneity that characterizes different carbon removal solutions [70].

Our future research will aim at studying (i) novel waves of CDR advancements, (ii) the science-technology nexus of conventional and novel CDR patents, (iii) policy coordination to support CDR across science, technology, policy, and media.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

In detail, SciSciNet raw data are publicly available at the following link: https://doi.org/10.6084/m9.figshare.c.6076908.v1. Reliance on Science raw data are publicly available at the following link: https://zenodo.org/records/11461587. Those interested in raw data from Altmetric and Web of Science should contact Digital Science and Clarivate, respectively. An R project with shareable data files and code to replicate the main results is available at the following link: https://github.com/CoMoS-SA/Public_use_CDR_2024.

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Author contributions

All authors conceived and designed the study. GT performed all analyses. All authors wrote the manuscript.

Conflict of interest

The authors declare no competing interests.

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