Focus Article

A bibliometric analysis of climate engineering research

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The past five years have seen a dramatic increase in the number of media and scientific publications on the topic of climate engineering, or geoengineering, and some scientists are increasingly calling for more research on climate engineering as a possible supplement to climate change mitigation and adaptation strategies. In this context, understanding the current state of climate engineering research can help inform policy discussions and guide future research directions. Bibliometric analysis—the quantitative analysis of publications—is particularly applicable to fields with large bodies of literature that are difficult to summarize by traditional review methods. The multidisciplinary nature of the published literature on climate engineering makes it an ideal candidate for bibliometric analysis. Publications on climate engineering are found to be relatively recent (more than half of all articles during 1988–2011 were published since 2008), include a higher than average percentage of nonresearch articles (30% compared with 8–15% in related scientific disciplines), and be predominately produced by countries located in the Northern Hemisphere and speaking English. The majority of this literature focuses on land-based methods of carbon sequestration, ocean iron fertilization, and solar radiation management and is produced with little collaboration among research groups. This study provides a summary of existing publications on climate engineering, a perspective on the scientific underpinnings of the global dialogue on climate engineering, and a baseline for quantitatively monitoring the development of climate engineering research in the future.

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INTRODUCTION

Scientific interest in climate engineering, also referred to as geoengineering, has soared in recent years. Position statements and reports on climate engineering have been issued by scientific societies, e.g., Refs 1–3, conferences and articles in scientific journals on climate engineering have proliferated,[4–6] and a few scientists and individuals are advocating additional research, and in some cases implementation,[7,8] of various proposals.

In this context, it is constructive to examine the current state of scientific research on climate engineering. Such an analysis would be useful to inform policy discussions surrounding climate engineering experiments, to suggest future research directions on this topic, and to provide a baseline for similar analyses designed to monitor future developments in this research. Here, we examine the most tangible products of climate engineering research—scientific publications—using bibliometric analysis techniques. Although scientific publications are only a part of the scientific research process, they are a useful and representative proxy for scientific research that can be analyzed to provide insight into the nature and evolution of that research, e.g., Refs 9–13. In addition, bibliometric analysis is particularly well suited for analyzing topics like

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climate engineering with large bodies of research literature (more than 500 publications) and spanning different scientific disciplines, which make them difficult to review by traditional means. Although reviews of the climate engineering literature have been conducted,[3,14–16] bibliometric techniques can offer a different perspective on this literature.

Defining climate engineering is a difficult task. As early as 2000, Keith[14] noted the ambiguity of the concept and proposed a definition and taxonomy of climate engineering that has informed much of the subsequent discussion on the topic. Distinguishing between climate engineering and climate change mitigation can be especially challenging, as techniques such as carbon capture and storage, biochar, and afforestation have been considered by some to be climate engineering,[17–19] and by others to be mitigation. In addition, some have used the terms 'geoengineering' and 'climate engineering' to refer solely to solar radiation management (SRM) techniques.[20,21] Heyward,[22] noting this ambiguity and the substantial differences between climate engineering methods, advocates disaggregating geoengineering as a concept and discussing SRM and CO_2 removal techniques independently.

For the purposes of this analysis, we define climate engineering as deliberate, large-scale manipulation of the earth system with the intention of mitigating the effects of climate change. We include techniques—such as soil carbon sequestration and large-scale application of biochar to soils—that some classify as mitigation, rather than climate engineering. We exclude carbon capture and storage because its intervention is typically at the point of emission and so does not involve the large-scale manipulation of the earth system. However, we include methods of capturing CO_2 from the atmosphere. Although the literature on biochar is fairly extensive, we only include articles that mention the use of biochar as a global climate change mitigation strategy and exclude articles primarily concerned with local effects. Similarly, we only include articles on afforestation or reforestation that consider such techniques at scales large enough to affect the global climate system.

To our knowledge, bibliometric analysis has not been used previously to analyze research on climate engineering. However, it has been applied to related topics. Li et al.,[23] Schwechheimer and Winterhager,[24] and Stanhill[25] all used bibliometric techniques to analyze the structure and growth of climate change research. Bjurstrom and Polk[26,27] used bibliometric analysis to examine the interdisciplinarity of the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report, whereas Vasileiadou et al.[28] used it to analyze the effects of the IPCC reports on scientific research. Anderegg et al.[29] used bibliometric analysis to demonstrate the credibility of climate change research. Bibliometric analyses of atmospheric simulation[30] and aerosol research[31] have also been conducted. Janssen et al.[32] analyzed the structure and trends of research on global environmental change. Jappe[33] investigated the internationality of research in earth and environmental sciences. Kajikawa et al.[34] analyzed articles in sustainability science and identified 15 major research directions. Via analysis of the coauthor network of articles on sustainability science, Bettencourt and Kaur[35] were able to conclude that this field had recently coalesced into a coherent scientific discipline. Schoolman et al.[36] found that research in sustainability science was more interdisciplinary than other scientific disciplines, but fell short of the ideal recommended in its literature. Using these bibliometric studies as models, this study aims to answer similar questions regarding the current nature of climate engineering research.

METHODOLOGY

Bibliometric analyses are typically conducted using one of three standard databases: Web of Knowledge, Scopus, and Google Scholar. This analysis is based on Web of Science, Science Citation Index Expanded (WoS), a database within the Web of Knowledge group of databases covering the natural sciences with archives, in our subscription, dating from 1984. We did not employ Google Scholar because of concerns about the reliability of its metadata, e.g., Refs 37 and 38, or Scopus because it was not available to us.

Data Collection

Data used in this analysis (conducted in 2012) are derived from article metadata in WoS for 1984–2011. Articles on climate engineering were identified in two phases. In the first phase, we queried WoS using the following search string:

TS = (geoengineer* OR geo-engineer* OR 'climate engineer*' OR 'solar radiation management' OR (albedo NEAR/3 enhance*) OR (ocean* NEAR/3 fertiliz*)) OR (TS = (carbon OR CO(2) OR CO2 OR 'climate change' OR 'global warm*') AND TS = ((atmosph* OR air) NEAR/5 capture)) OR TS = ((enhance* OR artificial*) AND 'weathering' AND ((carbon OR CO(2) OR CO2) AND sequest*)) OR TS = (biochar* AND ('climate change' OR 'global warm*')) OR (TS = (soil NEAR/3 carbon NEAR/3 sequest*) AND TS = ('climate change' OR 'global warm*')).

It instructs WoS to perform a topic search ('TS' in the string) using wildcards (denoted with asterisks) and the proximity operator NEAR for articles that use words or phrases relevant to climate engineering in their titles, keywords, and abstracts. We then manually verified the search results for accuracy and to remove articles not topically relevant to climate engineering. An extensive search string was necessary because not all articles meeting our definition of climate engineering used the terms 'climate engineering' or 'geoengineering' in their titles, abstracts, and/or keywords. Climate engineering methods were selected for this string based on those identified in previous literature reviews, e.g., Refs 3, 14, 15, and 18.

In the second phase, we identified additional articles through citation tracking. We examined the reference lists and WoS-defined 'related records' of review articles identified in the first phase. We also examined the articles citing the most highly cited articles we had identified. We added topically relevant articles identified through these methods to our final list. Articles published in 2012 were excluded from both phases to focus the analysis on full calendar years.

Once the list of articles was complete, we parsed them into eight topic areas—air capture of CO_2, artificial (or enhanced) weathering, biochar, general (articles discussing multiple methods), land-based methods (soil carbon sequestration and large-scale land-use changes such as afforestation), ocean fertilization, SRM, and other methods—based on manual inspection. The final list of articles analyzed is available online[a] in the form of a substantial bibliography of journal articles on climate engineering. While it is likely that our search process missed a few topically relevant articles, we feel it is unlikely that their omission or inclusion would significantly change our results.

Data Analysis

We then queried WoS to return only the articles in our final list and analyzed them all to identify their publication year, article type, and country of origin. We edited the country names to match those used by the Yahoo! Geocoder, assigned latitude and longitude values to each country using the Yahoo! Geocoder, and geographically mapped country publication rates using the Science of Science (Sci2) Tool,[39] a scientometric analysis software package. We then collected the metadata and citation data from these articles and used the Sci2 Tool to create a bibliographic coupling network[40] and a coauthor network[41] from these articles. Such networks draw on the insights of network science[42,43] to analyze and create visual representations of the research on climate engineering as a 'knowledge domain'.[44] In network science terminology, the individual members of a network are called 'nodes' (or sometimes 'vertices') and the relationships between members are called 'edges'.

We created the bibliographic coupling network to examine the topical structure of climate engineering research. In a bibliographic coupling network, nodes represent articles and edges represent shared references. If article A and article B both cite article C, then an edge is created between A and B; the strength, or weight, of the edge is equal to the number of articles cited by both A and B. Because articles on similar topics draw on the same body of previous work, articles in a bibliographic coupling network tend to self-organize into the major research topics covered by those articles. Bibliographic coupling was selected for this analysis because of its accuracy in identifying research structure[45] and its ability to match both very recent and uncited articles, which co-citation,[46] an alternative bibliometric mapping method, cannot.[47]

We also created a coauthor network to investigate the level of collaboration in this field. In a coauthor network, nodes represent authors and edges represent articles on which two authors have collaborated; edge strength is equal to the number of coauthored articles the two have published. Author names were not 'cleaned' prior to creating this network, resulting in possible misidentification or multiple identification of authors, but such errors are not likely to significantly affect the overall structure of the network.[41]

We then created visualizations of both networks using Gephi,[48] a network visualization software package. We analyzed these networks using the community detection algorithm of Blondel et al.[49] with resolution by Lambiotte et al.[50] to more clearly show the components of each network. In the bibliographic coupling network, these components represent research topics and in the coauthor network these components represent research groups.

RESULTS

We identified and analyzed a total of 750 articles on climate engineering published between 1988 and 2011, with none identified during 1984–1987. The main subject disciplines, or WoS-defined categories, of these articles are Environmental Sciences (196 articles), Meteorology and Atmospheric Sciences (127), Multidisciplinary Sciences (118), Oceanography (112), and Ecology (75). These articles were published in over 200 different journals, but most frequently in these five journals: *Climatic Change* (50), *Deep-Sea Research Part II* (49), *Science* (32), *Nature*

(30), and *Geophysical Research Letters* (22). This lack of concentration of climate engineering articles in particular journals underscores the appropriateness of bibliometric analysis to review this literature.

Publication Trend

Publication counts of all climate engineering articles for the years 1988–2011, shown in Figure 1(a) in comparison with counts of all publications included in WoS, reveal an order of magnitude increase, with 115 articles appearing in 2011. Mercer et al.[51] also noted this increase and linked it to the 2006 publication of an influential essay on SRM by Crutzen.[52] Whatever the cause, the result of this increase is that approximately 56% of all articles on climate engineering were published since 2008. However, publication counts per method, shown in Figure 1(b), reveal substantial differences in the publication of articles among methods. Articles on land-based methods and ocean fertilization account for the majority of the growth of this literature from 2000 to 2008. Peaks in the publication of articles on ocean fertilization seem to reflect the series of mesoscale iron enrichment experiments conducted from 1988 to 2008.[53,54] Publications on land-based methods, air capture, biochar, and SRM account for much of the growth during 2008–2011, with an exceptionally large increase in the publication of articles on SRM from 2006 to 2009. General discussions of climate engineering spike during 2008–2010 but then fall dramatically in 2011.

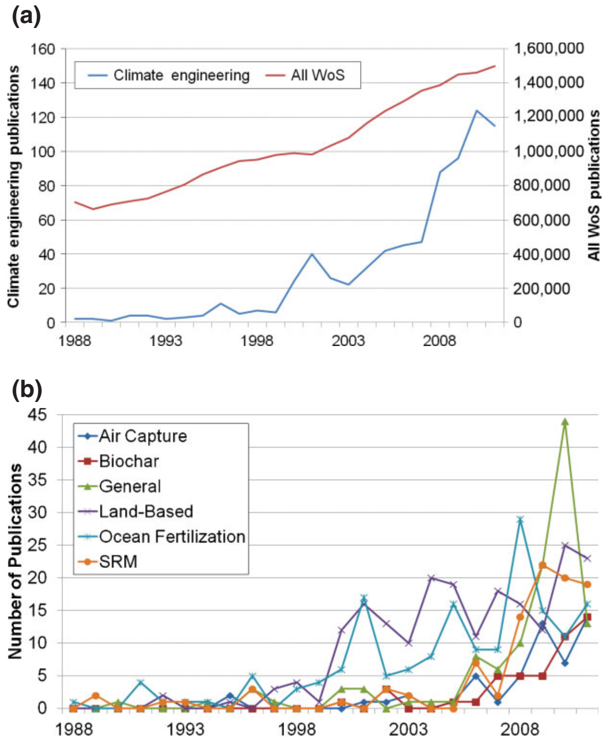

FIGURE 1 | Number of articles published on climate engineering per year for all methods (a) and for each method (b).

Article Type

To determine the fraction of these articles reporting original research results, as opposed to essays and discussions, we examined climate engineering articles by their article type (research article, review, editorial, etc.), using the article types assigned automatically by WoS. We then compared the distribution of article types in climate engineering to those in other related disciplines. Percentages were obtained by querying WoS for all publications in these disciplines during 1988–2011 and analyzing them by article type. These percentages are shown in Figure 2.

Approximately 30% of all articles on climate engineering are nonresearch articles (i.e., reviews, editorials, letters, news items, and other types), much higher than in related disciplines (8–15%). It is closer to the percentage of nonresearch articles in the Multidisciplinary Sciences category (40%), which is dominated by journals such as *Nature*, *Science*, and *PNAS* that devote a larger fraction of their pages to nonresearch articles than most other journals. This might indicate a relative lack of original research on the topic, or it might be an indication of the emerging or controversial nature of this research, or both.

Internationality

As deliberate manipulation of the earth system has global implications, we also investigated the internationality of climate engineering research by analyzing the production of articles on climate engineering per country. Articles with authors from multiple countries were counted as full publications for each country, rather than fractionally. Article production by country is mapped in Figure 3 and listed in Table 1.

In agreement with previous analyses of climate and climate change research, e.g., Refs 23, 28, and 31, we find that the production of articles on climate engineering is dominated by Western and industrialized countries. However, there seem to be two biases in the geospatial distribution of these articles. The majority of these publications were produced by countries in the Northern Hemisphere, with only Australia and New Zealand in the Southern Hemisphere having produced a substantial number of articles on the topic. There also seems to be a bias toward English-speaking countries, as four of the five

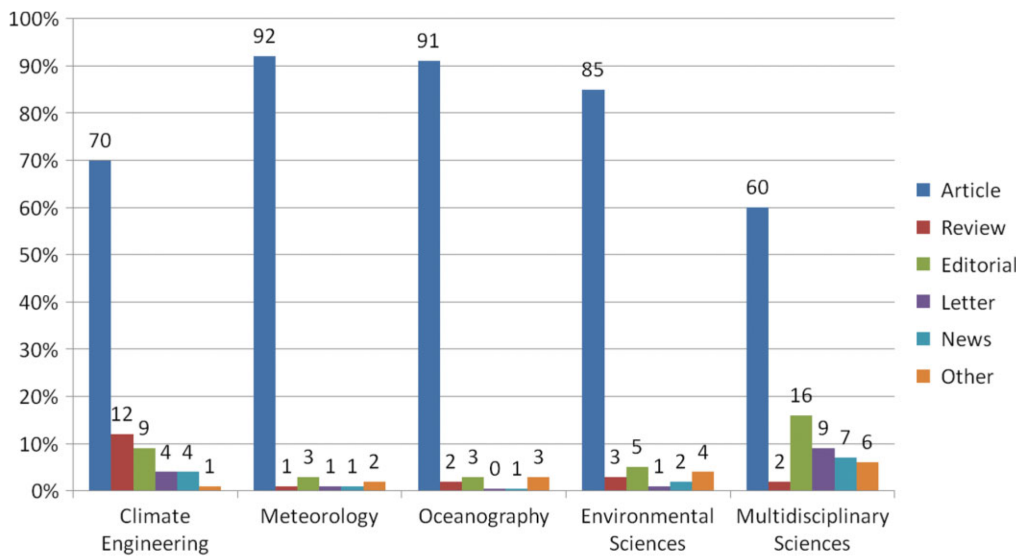

FIGURE 2 | Approximate percentage of articles per WoS-defined article type on climate engineering and in related scientific disciplines (1988–2011).

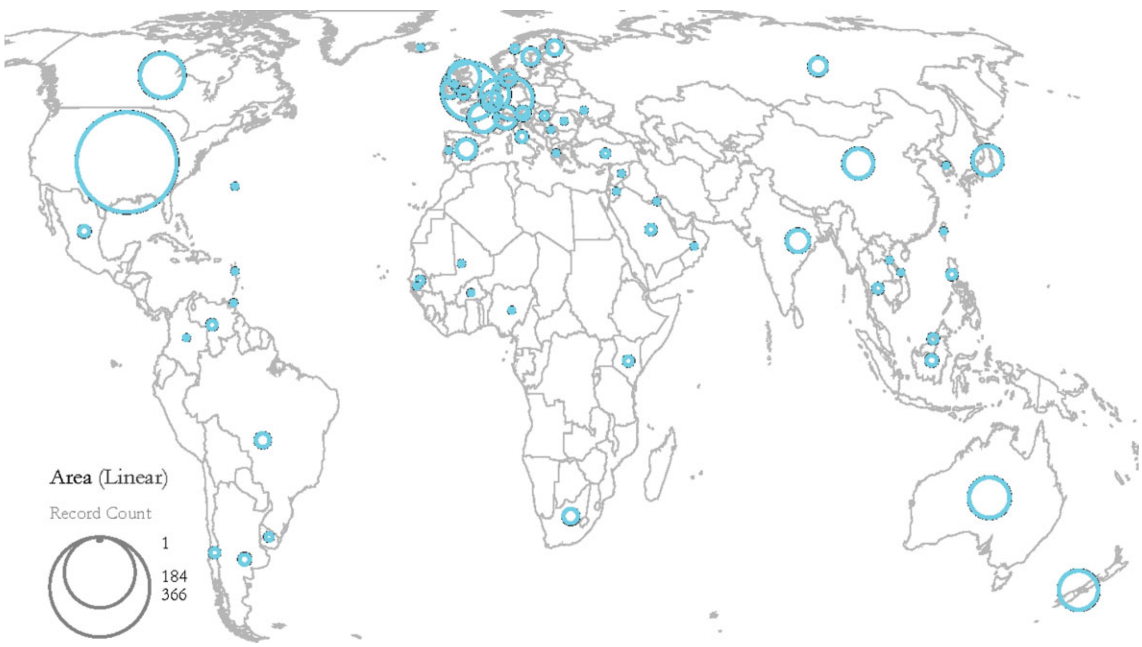

FIGURE 3 | Number of climate engineering articles published per country (1988–2011).

most frequently publishing countries speak English as a primary language. These biases are surprising given the high degree of international collaboration in the earth and environmental sciences found by Jappe.[33]

To investigate whether English-language bias in climate engineering research resulted from the known English-language bias of WoS,[55] we compared the percentage of articles produced by the most prolific countries in climate engineering research to the percentage of articles produced by these same counties in related disciplines in WoS. Country percentages were obtained by querying WoS for all records in each discipline for the years 1988–2011 and analyzing them by country. Figures for each country indicate the percentage of articles in each discipline with at least one author from that country. This comparison is presented in Figure 4.

These figures seem to confirm that English-speaking countries are overrepresented in climate engineering research beyond the internal bias of WoS.

TABLE 1 | Number of Climate Engineering Publications Per Country for Countries That Produced Two or More Publications During 1988–2011

Country	Number of Publications
USA	366
England	119
Canada	72
Germany	63
Australia	60
New Zealand	56
Scotland	36
Japan	32
China	32
Netherlands	31
France	30
India	18
Switzerland	18
Spain	14
Belgium	13
Russia	11
Ireland	10
Sweden	10
Denmark	9
Finland	8
South Africa	8
Brazil	7
Austria	6
Argentina	4
Indonesia	4
Italy	4
Mexico	4
Wales	4
Chile	3
Kenya	3
Malaysia	3
Philippines	3
Saudi Arabia	3
Thailand	3
Venezuela	3
Hungary	2
Norway	2
Senegal	2
Turkey	2
Uruguay	2

An additional 23 countries that produced one publication each during 1988–2011 are not listed here.

Each of the English-speaking countries published a higher percentage of articles on climate engineering than they did in related disciplines, whereas non-English-speaking countries published a comparable percentage of articles in each field.

These biases toward Northern Hemisphere and English-speaking countries in climate engineering research raise potential geopolitical and ethical issues. Climate engineering approaches, if implemented, would have global impacts, which should necessitate global dialogue, research, and consent prior to implementation.[56] Our analysis suggests that, at present, scientific research on climate engineering is not globally distributed, which may undermine the quality or inclusiveness of such dialogue.

Topical Structure

Our initial bibliographic coupling network consists of 662 articles and 33,912 edges. This initial network excludes 88 of the original 750 articles in our set because these excluded articles do not share at least one cited reference with any other article in our set. To concentrate this network on the strongest topical links between articles, and to increase the clarity of the resulting visualization, we removed edges with a weight of less than three and deleted isolated nodes. The resulting network consists of 593 articles (79% of the original 750 articles identified) and 10,933 edges. The comparatively low percentage of articles in this final network is likely owing to the high percentage of news items, letters, and editorials—article types that typically do not include many cited references—in the original publication set. This seems to be a reasonable explanation for this percentage, because 18% of the articles in the original set were classified as being these types. In the visualization of this network, Figure 5, circles represent nodes and lines represent edges.

Publications on climate engineering seem to cluster into five main topics: land-based methods of sequestering carbon in soils, the application of biochar to soils, capture of CO_2 from the atmosphere, SRM and other methods, and ocean fertilization. Although other methods of engineering the climate—artificial weathering, enhanced upwelling/downwelling, and so on—were represented in the original publication set, these methods lack a sufficient number of commonly cited publications to emerge as separate clusters. Instead, the algorithm groups them with publications on SRM and with general discussions of climate engineering, suggesting that these publications tend to cite the same body of literature.

Previous reviews of climate engineering research, e.g., Refs 3 and 15, have divided this research into two fields: removal of CO_2 from the atmosphere

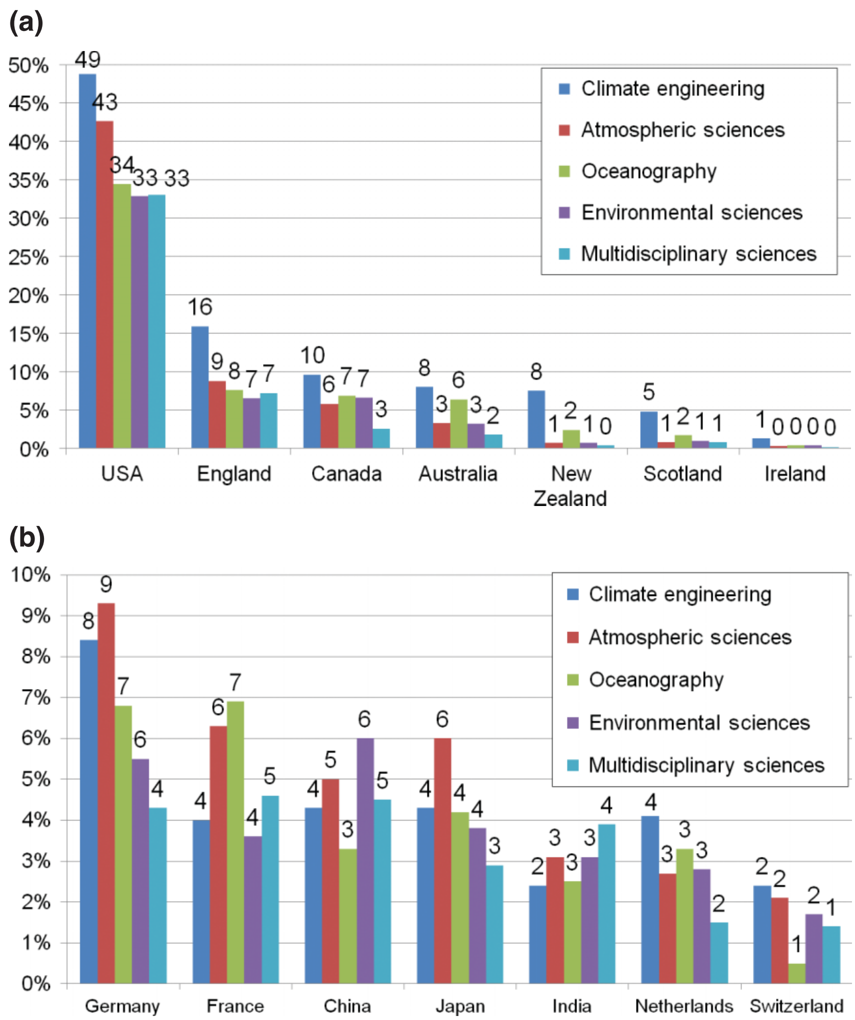

FIGURE 4 | Approximate percentage of articles with at least one author from each country in climate engineering and related disciplines (1988–2011) by English-speaking countries (a) and non-English-speaking countries (b). Because of collaborative articles between countries, the sums of these percentages exceed 100%.

and enhancement of Earth's reflectivity. Our analysis suggests that the vast majority of climate engineering publications focus on CO_2 removal, because four of the five major topics identified and nearly three-quarters of the publications (437 of 593 or 74%) in this network are on CO_2 removal. By contrast, 154 publications (approximately 26%) are on SRM and other methods. Within these fields, the largest number of publications deal with land-based methods (187 of 593 or 32%), followed by ocean fertilization (167 or 28%), SRM and other methods (154 or 26%), air capture (45 or 8%), and biochar (38 or 6%).

Collaboration Structure

Our initial coauthor network consists of 1904 authors, 13,222 edges, and 273 components, 105 of which are isolated authors. The largest connected component of this network was extracted for further analysis. The largest connected component of a network is the largest set of nodes that are all connected to each other, however distantly, by edges; this component is called a giant component if it contains over 50% of the nodes in the network. The largest connected component of our coauthor network was a giant component and consists of 1034 authors and 11,621 edges. This network is visualized in Figure 6.

This giant component represents only 54% of the authors in the publication set. Findings from previous coauthor network analyses, e.g., Refs 41, 57, and 58, suggest that this percentage is typically closer to 80%. The connectivity of the network is also fairly sparse, with few edges connecting research groups within and between methods. The network has an

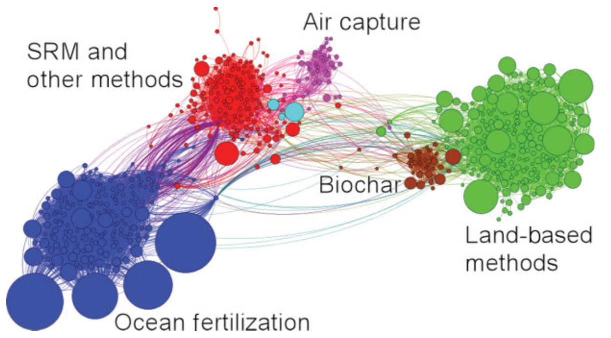

FIGURE 5 | Bibliographic coupling network of climate engineering articles. Node diameters are proportional to article citation counts (range: 0–956). Node colors depict the results of a community detection algorithm and indicate the topic of articles in each cluster. Clusters are labeled based on manual inspection of the articles in each cluster. 'SRM' denotes solar radiation management; teal nodes located between the red and pink clusters are articles on the effects of afforestation on Earth's albedo. Edges are sized based on bibliographic coupling strength (range: 3–65) and colored based on the color of the nodes they connect.

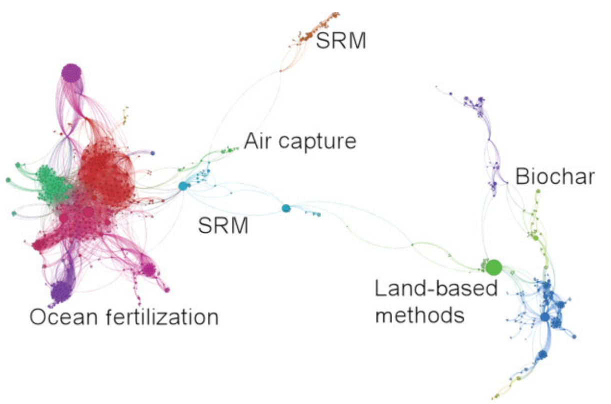

FIGURE 6 | Coauthor network of climate engineering articles. Nodes are sized based on article productivity (range: 1–39). Node colors are based on the results of a community detection algorithm and indicate research groups. Edges are sized based on the number of collaborative articles between authors (range: 1–9) and colored based on the color of the nodes they connect. Labels indicate the research area of authors in each cluster; 'SRM' denotes solar radiation management.

overall density of 0.022, where a value of 1 indicates a fully connected network with edges connecting all the nodes in the network. These findings suggest that climate engineering publications tend to be authored by relatively independent research communities that rarely collaborate on formal publications.

However, Figure 6 depicts substantial differences in the collaboration structure of different methods. Authors in the ocean fertilization clusters are densely interconnected, with several central authors collaborating with multiple research groups, whereas authors in the soil science clusters display a more distributed structure. Authors in the SRM and air capture clusters seem to organize into relatively autonomous research groups with little collaboration connecting them to each other or to other methods of climate engineering.

These differences in topology could reflect differences in collaboration practices among disciplines, with collaboration being more common in oceanography than in the soil sciences, for example. They could also be indications that land-based methods and SRM are collections of distinct, but related methods that feature little collaboration between methods. These differences may also be indications of the relative history of publication on each method. As publications on SRM and air capture tend to be more recent than those on the other three methods, SRM and air capture may simply not have had enough time to develop the degree of connectivity displayed by ocean fertilization and land-based methods.

Both the coauthor network and the bibliographic coupling network display similar overall structures. In both networks, the majority of the nodes are concentrated in ocean fertilization and the soil sciences. These clusters are located on opposite ends of the two networks and connected by a smaller number of nodes in SRM and other approaches. Both networks also seem to divide along disciplinary lines, with oceanography on one end, connected to atmospheric sciences in the middle, which is in turn connected to the soil sciences on the other end. This structure also seems to be a logical reflection of the connectivity of the earth system. The central position of the atmospheric sciences in these networks may reflect the fact that the atmosphere interacts with both soil and ocean processes, whereas soil and ocean processes can be considered relatively independent of each other. These similarities suggest that our characterization of the intellectual structure of climate engineering research is fairly robust.

CONCLUSION

Through our analysis of 750 climate engineering articles published from 1988 to 2011, we find that articles on climate engineering differ from those in related fields in several ways. Climate engineering articles tend to be recently published and include a larger than average percentage of discussions and reviews. Production of climate engineering articles seems biased toward countries located in the Northern Hemisphere and that speak English as a primary language. Articles on climate engineering focus on three methods—ocean fertilization, SRM, and land-based methods—with the majority of these publications focusing on ocean fertilization and land-based methods. With the exception of articles on ocean fertilization, these articles tend to be produced by relatively autonomous research groups that rarely collaborate with each other either within or across methods.

These findings are constrained by our definition of 'climate engineering'. Although we have attempted to adopt a definition that is consistent with previous literature reviews on the topic, it is important to note that this definition is not universally accepted. Adopting other definitions of climate engineering—those that exclude soil carbon sequestration and/or ocean fertilization, include all of the literature on afforestation and biochar, restrict climate engineering to SRM alone, and so on—could substantially affect our findings concerning the article type, country, language, and topical focus of the climate engineering literature. Future research examining the literature on each approach individually could determine the extent of such effects.

Determining how well our analysis of climate engineering articles reflects the actual state of research on climate engineering, as we define it, is beyond the capabilities of bibliometric analysis. Although bibliometric analysis is an established method of analyzing scientific research, its focus on publications is an oversimplification of the complexities of that research. In addition, while bibliometric analysis is useful for identifying trends in published articles, it cannot, by itself, offer explanations as to why these trends occur. Additional, more qualitative, research would be necessary to understand the underlying causes of the trends we have identified here. Such research might also determine whether our characterization of the literature on climate engineering is an accurate representation of climate engineering research as a whole.

Nevertheless, this study may serve as a baseline for monitoring future developments in climate engineering research. As climate engineering can be considered a relatively young and developing field of research, our findings represent a 'snapshot' of the field at an early stage in its development. Repeating this analysis in the future would offer insight into how this field, and possibly scientific research in general, evolves over time. If climate engineering research continues to grow in size and complexity, then bibliometric methods will become increasingly useful in characterizing what may become a critically important area of climate research.

NOTE

[a] http://www.lib.noaa.gov/researchtools/subjectguides/climate_engineering.html

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