Environmental Science and Policy 152 (2024) 103663

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

Thirty years of climate change research: A fine-grained analysis of geographical specialization

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ARTICLE INFO

Keywords:
Climate change
Geographic specialization
Developing countries
Natural language processing
Bibliometrics

ABSTRACT

Bibliometric overviews of climate change research typically focus on the main topical trends and few countries with the largest share of the scientific production. These are important limitations: most of the world's population live in countries that are heavily affected by climate change but have a relatively small scientific production, so that their topics of interest might be neglected. This contribution aims to address both limitations by investigating variations across countries in climate change research specialization. We employ a combination of state-of-the-art language modelling techniques to gain a fine-grained representation of the research topics on climate change, considering abstracts of 193,471 publications from 1990 to 2020. The analysis reveals the existence of five major country blocks, with distinct research specializations. Countries' research specialization is driven by the specific challenges posed by climate change, such as extreme precipitation and floods and food, as well as the level of resources at disposal, so that research into the phenomenon of climate change and its global solutions is more important in affluent western countries. Less affluent countries – which host several billion people – develop distinct research focuses on local problems' causes and mitigation strategies, but typically have limited resources to address these challenges. Hence, leading scientific countries should possibly contribute even more to addressing such issues.

1. Introduction

Climate change is one of the fundamental challenges of our times. Human activities have impacted – and are still impacting – local and global climate dynamics, causing a rise in temperatures, altering weather events patterns and disrupting biodiversity (IPCC, 2023). This globally salient set of phenomena has been drawing the attention of the scientific community for decades, giving birth to a very active and interdisciplinary area of research, experiencing a strong growth (Haunschild et al., 2016). Making sense of a continuously growing scientific literature is extremely difficult. The problem is compounded by the sheer volume of publications on the subject and the challenges to organize, search, and analyse them. Literature reviews are very labour intensive, and they are not easily scalable to the level of broad scientific fields. As a consequence, bibliometric overviews and science mapping exercises often provide a general picture of big scientific areas at the expense of a coarser granularity. It has to be noticed, though, that between these two extremes is possible to find an integration in cases in which the desired level of description is still manageable by small groups of researchers (e.g. Fang et al., 2023).

Climate change research has been investigated several times with bibliometric techniques, ever since its outset, during the '90s (e.g., Schwechheimer and Winterhager, 1999). The most well documented finding is the rapid and substantial growth in the number of publications, together with a trend of increased co-authorship, international collaboration and interdisciplinarity (Stanhill, 2001; Grieneisen and Zhang, 2011; Haunschild et al., 2016). There are few general overviews of climate change research, while topic-specific analyses are commonly used to assess the state of the art of specific research areas. Some recent examples include overviews of research on the relation between climate change and infectious diseases (Li et al., 2020), and on carbon sinks (Huang et al., 2020).

These studies – see Section 2.1 – share a limitation common to much of the bibliometric overviews in general, namely, a focus on a macro level description of the research trends. Limiting the analysis to the identification of main topical trends hampers the level of detail of

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https://doi.org/10.1016/j.envsci.2023.103663
Received 27 April 2023; Received in revised form 11 December 2023; Accepted 19 December 2023
Available online 28 December 2023

bibliometric studies and hides the variety of research topics. In addition, many of these studies either ignore the geographical dimension or focus solely on the leading countries in terms of gross scientific production. Essentially, they focus only on major scientific players, and implicitly assume that these are representative of the global distribution of scientific topics. This approach is particularly problematic for climate change research because most of the world population is concentrated in developing countries, which experience the most severe consequences of climate change but have a very low scientific production per capita. For example, 1.4 billion people live in India and the Indian sub-continent is among the areas of the world most threatened by climate change (ND-GAIN vulnerability index 2020), yet its entire scientific production on climate change is one third of the United Kingdom's, despite a 20 times larger population. In turn, the combination of using macro level trends and focusing only on countries with high absolute scientific production underrepresents or hides research topics that are specific to countries highly impacted by climate change and home to a large share of the global population.

The aim of our contribution is therefore twofold. First, to provide a fine-grained overview of climate change research, highlighting the wide variety of research topics. Second, to explore how climate change research varies across countries, in terms of its relative importance and specific topics' importance, and what factors seemingly affect countries' focus on different topics. We do so by analysing a dataset of 193,471 scientific publications on climate change spanning 30 years (see Data and Methods). We address the first limitation by leveraging recently developed natural language processing techniques to gain a fine level of granularity. Regarding the second limitation, we start comparing the number of climate change related publications to the total scientific production by country to highlight efforts in this research area in a simple way; we then delve deeper into 472 research topics and reveal their unequal geographical distribution. A further limitation, that pertains to our study as to most of the studies that make use of textual data, is the exclusive focus on the literature written in English.

In the following section, we summarize the features and limitations of bibliometric overviews on climate change. We also discuss the factors that may affect the choice of research topics, and hence countries' specialization. We then proceed to describe the data and methods, where we also explain the added value of a new approach combining different techniques for bibliometric studies in unveiling fine-grained research topics. In section four, we present the empirical analysis, which includes the identification and description of five country blocks based on their research specialization, as well as the discussion of their drivers of specialization. In the final section, we discuss the main findings and implications of the article.

2. Literature review and theoretical framework

2.1. Climate change research

Since 1970s, climate change has become a relevant topic that attracted considerable attention of scholars in the decades ahead. The field has grown at a fast pace, with climate change papers doubling every 5–6 years (Haunschild et al., 2016). This major interest and the huge societal and political implications have consequently led to the development of review papers aimed at assessing the state of climate change research. Bibliometric analyses have played a major role in this regard, providing both a description of the overall productivity of the field over time, and an exploration of more specific aspects related to climate change science.

The most comprehensive bibliometric analyses exploring climate change research have been developed in the last decade. Grieneisen and Zhang (2011) leveraged an in-depth selection of key words related to the climate change research and investigated a pool of 110,139 publications in the period 1997–2009. The authors stressed the fast-growing publication rate of the field in the first 2000 s and presented the occurrence of climate change papers in relation to both the ten largest categories of Web of Science and the 253 subject categories. Also, they identified the most prolific institutions globally. Li et al. (2011) examined 41,457 climate change publications based on the online version of Science Citation Index Expanded between 1992 and 2009. The authors discussed the research patterns of major western countries and the most productive institutions. Further, they identified, through a keyword analysis, the most prominent areas of climate change research in the 21st century. Li and Zhao (2015) collected 113,468 publications (1993 to 2012) on environmental assessment (EA), i.e., a broader area of research including climate change, and described productivity patterns across several dimensions, including the evaluation of research performance of the most productive countries, major subject categories, and most representative journals in the field. Relying on 15,000 publications (1999–2010), Pasgaard and Strange (2013) investigated the gap between rich and poor countries in the supply of climate change knowledge and showed a significant unbalance between resource-rich and poor contexts and the presence of divergent climate change concerns. Rich countries focused more on mitigation issues (CO_2 emission reduction), while in less developed countries, research was more concerned about climate change adaptation and impacts. Haunschild et al. (2016) considered 222,060 articles and reviews (1980–2014, Web of Science), and highlighted the strong growth across macro fields (e.g., natural sciences, medicine, engineering) and seven climate sub-systems (e.g., atmosphere, oceanic water); further, they provided descriptive statistics on aggregate publication outputs for 32 countries. Callaghan et al. (2020) identified 140 topics on climate change research, using a broad sample of over 400,000 climate change related publications (until 2018), and hence investigated the over and under representation of research topics in the IPCC reports' reference list. More recently, Fu and Waltman (2022) conducted a descriptive analysis on 120,000 articles (2011–2018) and implemented a term mapping and burst detection analysis (limited to a sub-set of 25,000 articles) to provide an overall picture of climate change research and insights about its evolution. The analysis was centred on five clusters of research topics (physical sciences, paleoclimatology, climate change ecology, climate policy) and focused on the eight most productive countries.

Parallel to these comprehensive reviews, several bibliometric assessments have been performed to examine specific aspects of climate change research. These span from studies interested in reviewing the current state of climate science in relation to certain domains, like adaptation, vulnerability, resilience, and specific areas, like geo-engineering and tourism (e.g., Janssen et al., 2006, Belter and Seidel, 2013, Wang et al., 2014, Aleixandre-Benavent et al., 2017, Wang et al., 2018, Rana, 2020), the analysis of collaborative research patterns in the field (Jappe, 2007; Sangam and Savitha, 2019; Engels and Ruschenburg, 2008), the understanding of climate change controversies (e.g., Jankó et al., 2014, 2017), the detailed investigation of single target journals' performance like *Climate Change* and *The Bulletin of the American Meteorological Society* (e.g., Stanhill, 2001, Hellsten and Leydesdorff, 2016), to the examination of the impact of IPCC reports on climate change research (e.g., Vasileiadou et al., 2011). These studies were based on specific focus and mostly descriptive approaches.

In general, few studies provided an extensive evaluation of the climate change research whereas many more contributions explored detailed subjects. In both cases, these bibliometric assessments were often limited in their geographical scope and focused on the performance of few top prolific countries (generally located in the western part of the world), and mostly related to a restricted set of topics or subject areas.

2.2. Factors affecting countries' specialization in climate change research

Climate change research is a vast interdisciplinary area of study stretching from theoretical problems and modelling aiming to understand the reasons and possible evolution of the phenomenon, to the exploration of the ecological, economic, socio-political impact of climate change, as well as political and technological solutions. Therefore, several factors are likely to matter in affecting which research topics are more salient in each country.

In most cases, the decision about what to research is ultimately in the hands of individual scientists or research groups. Sociologists and economists of science have explored the drivers of researchers' behaviour - including decisions on what to research - and revealed the importance of several types of motivations, namely: *intrinsic* motivations, such as intellectual curiosity and pleasure of solving puzzles (Merton, 1974), *extrinsic* motivations – like recognition from colleagues for being the first to make a scientific discovery (Merton, 1974) or obtaining funds and progressing in career (Stephan, 1996) – and *pro-social* motivations, i.e. to have a positive impact through the research work (Iorio et al., 2017; Sormani and Uude, 2022). Scientists are embedded into countries that differ along economic, social, political, cultural, and geographical traits, that may affect such motivations, the interest in specific questions and arguments, and hence the preference for certain research topics. Variations between countries may also depend on the existence of regional and national disciplinary communities. The discipline is the most important source of values, sense of belonging, and scientific goals for a scientist (Clark, 1983; Whitley, 2000). Disciplines, however, vary considerably in their intellectual and social organization, the degree of internal cohesion and hierarchical control, and therefore on the influence on what their members research and how (Whitley, 2000). For example, *Theoretical Physics* displays a high level of cohesion that enables an international elite to influence the goals and procedures used by most researchers around the globe, whereas *Management* is an a-paradigmatic, fragmented discipline, where several schools coexist and address diverse problems and with diverse approaches (Whitley, 2000). In turn, national disciplinary communities are partly independent from an international community, and can develop specific interests, traditions, or schools. The impact of each one of these potential sources of variation arguably depends on the specific research problem and topic.

Research problems may be largely disconnected from the surrounding context, while others are affected by the specific context. The specific traits of a country are of little importance for abstract conceptual problems that do not vary depending on the specific context, such as research in *Mathematics*. Variations between countries may still exist, in similar fields, due to the existence of specific schools or traditions, leading to partly different specializations. Research in *Astrophysics* or *Nuclear Physics* also investigates phenomena and natural laws that are not affected by the context in which the research is conducted. However, research in these fields requires extremely large investments in scientific instruments such as telescopes and particle accelerators, and it is concentrated in countries with large available resources. In a similar vein, we can expect that topics in climate change research that require large investments, for example on simulation and computational tools, will be comparatively more important in affluent countries.

Climate change is a global phenomenon, but its impact varies considerably from context to context, as well as the solutions to mitigate such impact. These variations can affect specialization in two regards. First, countries' specialization will likely reflect their respective challenges and search for targeted solutions. Environmental factors, namely how climate change manifests in a specific area, arguably directly and indirectly affects which topics will be more relevant and researched. Recent studies suggest, for example, that experiences of climate change disasters raised citizens' environmental concerns and affected their choices, such as increasing voting for green parties (Hoffmann et al., 2022). Another example showed that extreme events and perceived risk affect the development of local adaptation measures (Braunschweiger and Ingold, 2023). In a similar vein, experiencing the effects of climate change on themselves and their local community can directly affect scientists' choices. Influence can also be indirect, through governments earmarking research funds for the specific challenges that a country is facing. Second, research on abstract and theoretical problems, regarding political aspects of climate change, about its global causes and political solutions, is also expected to be comparatively more relevant in countries at the research frontier, with large financial resources and more influence on world politics. Scientists in less affluent countries, on their side, are likely pressed to focus on urgent practical challenges.

Finally, researchers are embedded in networks of collaborations and interactions that provide new ideas and puzzles, stimulate a researcher's curiosity and perceptions about which are the most important scientific questions and knowledge gaps. Hence, we can expect that countries that collaborate intensely may display a similar specialization, also in spite of different contextual conditions and resources. The creation of network ties – including scientific collaborations – are driven by several networking mechanisms. By affecting the probability of scientists to communicate and collaborate, these mechanisms may also affect whether two countries display a similar research specialization. For example, people tend to connect with people perceived to be like themselves (McPherson et al., 2001), and such *homophily* mechanism favours collaboration between scholars holding similar traits, like their culture, language, or ethnicity (Freeman and Huang, 2014). The probability of two nodes being connected is also greater if both are connected to one or more common nodes (Newman, 2001); such *transitivity* mechanism is common in scholarly collaboration (Franceschet, 2011; Newman, 2001; Schilling and Phelps, 2007) and creates a path-dependency effect (Zhang et al., 2018a, 2018b). *Homophily* and *transitivity* mechanisms lead to the expectation that scientists that share similar traits, like culture and language, will collaborate frequently, influence each other, and in turn display a similar research specialization. Accordingly, countries like Australia and United Kingdom, which are very far away and face very different climatic conditions and challenges, may still collaborate intensely because of their common language and cultural background, and hence display a similar profile.

3. Data and methods

We retrieved scientific publications on climate change from Scopus database, using the search terms "climate change" and "global warming." The search was run in October 2021. Scientific production before 1990 is sparse (around 400 publications from 1911 to 1989) while Scopus coverage gets worse going back in time; we hence considered the period from 1990 until 2020. We kept articles, conference papers, reviews, book chapters and books,[1] and removed all the entries without an abstract written in English. The final sample includes 193,471 publications.

We restricted the choice of language for two main reasons: first of all, to ensure uniform data coverage – i.e., by using only one source we do not have to deal with over or under representation of local languages or specific disciplines due to the use of specialized databases –, second the Large Language Model we employ to embed the texts is trained on an English corpus. On the one hand, this limitation is conservative regarding the aim of the article to show a wider variety of topics across countries that are typically disregarded: i.e., by hypothetically including non-English literature our point could only be strengthened. On the other hand, regarding the country level specializations, our work is representative of specialization in the internationally oriented research in English. Further work would be needed to highlight the specialization of research in local languages (and/or not indexed in Scopus), e.g., research directly dealing with local decision makers in non-English speaking countries.

The empirical analysis is organized in fourth sections. In first and second sections, we analyse the evolution of climate change research production over time and its relative importance by country. In the third section we explore geographic specialization and in the fourth, the

[1] We excluded, e.g., editorials, notes, letters.

drivers of such specialization.

To explore geographic specialization, we adopted the following text analysis procedure. First, we composed the corpus to be analysed by concatenating the textual data available, i.e., title and abstract. The next step was to embed the documents in a vector space by using a state-of-the-art pretrained language model, namely Sentence-BERT (Reimers and Gurevych, 2019). This kind of model is particularly useful when the aim is to group similar documents, and significantly outperforms methods based on simple bag-of-words assumptions. Since the resulting space is still very high-dimensional, we used a nonlinear dimensionality reduction algorithm – UMAP (McInnes et al., 2018) – in order to have a representation amenable to be managed by a density-based clustering algorithm – i.e., HDBSCAN (Campello et al., 2013; McInnes et al., 2017) – but still retaining the local relationships between nearest neighbours. The dimensionality reduction step involves stochasticity; hence, we repeated the reduction-clustering phase several times to ensure a higher stability of the results. As core of the final clusters, we used the sets of documents co-occurring in every iteration of the procedure. We then extended the classification to other documents through a diffusion process which included them in the closest cluster. After a manual inspection to ensure semantic coherence, we obtained the most distinguishing words by cluster – through a simple TF-IDF weighting of words and bigrams – to support the interpretation of the content. Overall, this pipeline is similar to the approach used by the BERTopic algorithm (Grootendorst, 2022).

Through this process we obtained 870 clusters of documents representing research topics. In the subsequent analysis we then only kept the 472 clusters consisting of at least 100 publications – which covers 85% of the original sample. Then, we focused on the 54 countries with at least 500 publications on climate change. We built a matrix of the *relative* weight of each topic in each country – measured by the fraction of publications included in the target topic over the total from the target country. To assess the over/under-representation of topics across countries we then standardized the matrix topic-wise so that each entry represents the distance from the global mean in relative weight of the target topic in the target country, measured in standard deviations (i.e., z-score). Finally, we used Ward's clustering to identify five Country Blocks (CBs) with a similar research focus – i.e., groups of countries in which the same topics are over/under-represented. To describe the Country Blocks' distinctive specialization, we manually analysed the 30 topics with the highest average z-score for each of them.

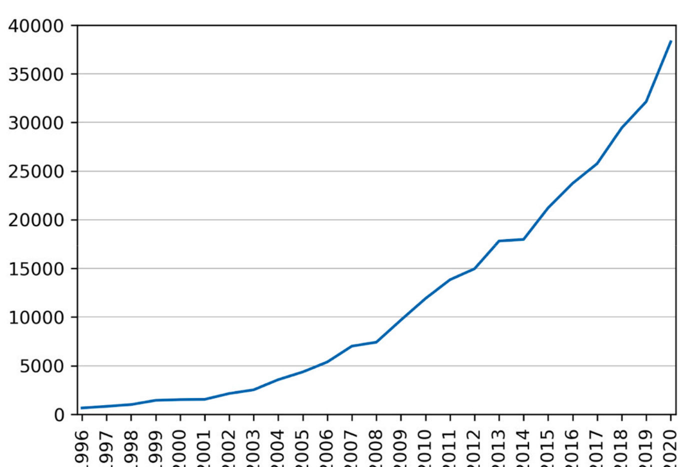

Fig. 1. Absolute number of climate change related publications by year.

4. Results

4.1. Climate change research production over time

Fig. 1 presents the yearly total number of scientific publications on climate change from 1996 until 2020 and shows that the number of scientific articles on climate change increased exponentially. Fig. 2 displays the share of scientific publications on climate change on the total scientific production and reveals that the share of scientific publications on this theme has increased from 1.1 per thousand in the year 2000 to almost ten per thousand publications in 2020, or 1% of the global scientific production.[2]

The distribution of this massive literature is not uniform across countries. As expected, at an absolute scale, the main countries are the major players of the global scientific production. The top ten countries – i.e., United States, China, United Kingdom, Germany, Australia, Canada, France, Spain, Italy, India – are involved in 62.5% of the publications. The scientific production has increasingly decentralized over time: the top ten countries went from producing over 70% of the new literature on climate change in the '90 s to less than 60% in 2020. The dominant role of western countries, and especially the US, has been rounded off (Fig. 3).

4.2. Importance of climate change research

The percentage of publications focused on climate change on total publications (1996–2020) varies remarkably across the 54 countries considered for in-depth analysis, between 0.2% to almost 3% (see Figure A in the Appendix).

Fig. 4 shows that there is not a clear geographical pattern. Countries strongly focused on climate change research, such as Nepal (2.95%),

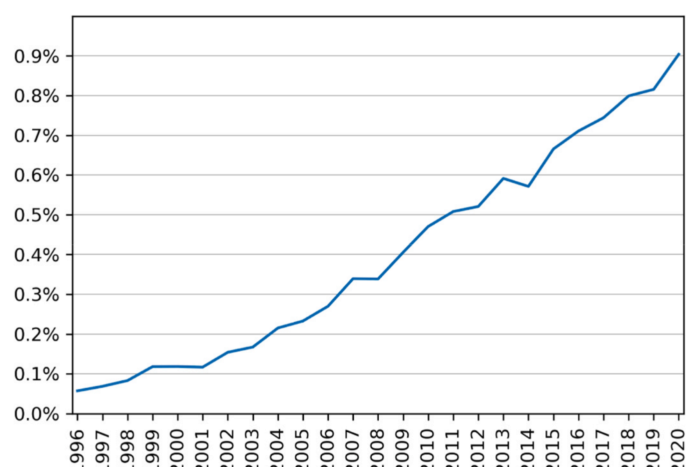

Fig. 2. Estimated percentage of climate change related publications over the global scientific production.

Kenia (2.45%), Ethiopia (1.88%), Norway (1.39%), Bangladesh (1.35%), Australia (1.07%), belong to different geographical and political areas, as much as those very little focused, like Russia (0.22%), Japan (0.24%), Israel (0.24%).

Fig. 5 presents the ND-GAIN vulnerability index for the selected countries, namely the propensity to be negatively impacted by climate

[2] As an estimate of the global scientific production, we considered the sum of the Citable Documents by country (source: scimago-scopus). Those include articles, reviews, and conference papers. The time frame is limited since this information is available only from 1996.

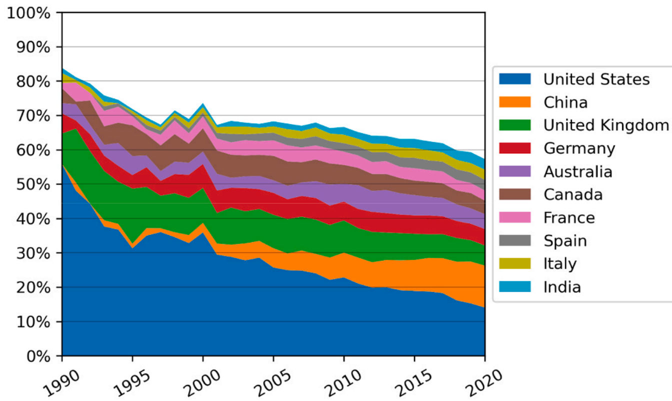

Fig. 3. Percentage of the global scientific production by each of the top 10 countries for absolute production of climate change related publications by year.

hazards (Chen et al., 2015)3 – from low vulnerability (dark blue) to high vulnerability (dark red) – and juxtaposes the relative importance of climate change research (Y-axis), with the absolute (left) and per million inhabitants (right) number of scientific publications on climate change (X-axis).

The figures show that there is not a clear relationship between country's vulnerability and the relative importance of climate change research: some of the most vulnerable countries are strongly focused on climate change research, while others are not.

The figures also shows that countries that are more vulnerable to climate change hazards (red dots) tend to be less productive in absolute term (left picture) and even more in proportion to their population (right picture) compared to countries less vulnerable (blue dots). Such negative relationship is not due to a lower interest on climate change (Y-axis) but on the fact that the most vulnerable countries tend to be less wealthy, invest less in research, and therefore produce less publications in general. This corroborates the idea that focusing only on research from countries with high absolute scientific production hides topics that are most important for countries highly impacted by climate change.

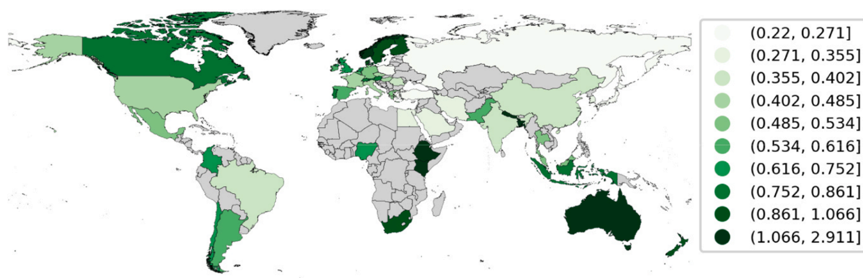

Fig. 4. Fraction of climate change related publication per country (1996–2020). Note: colour by decile.

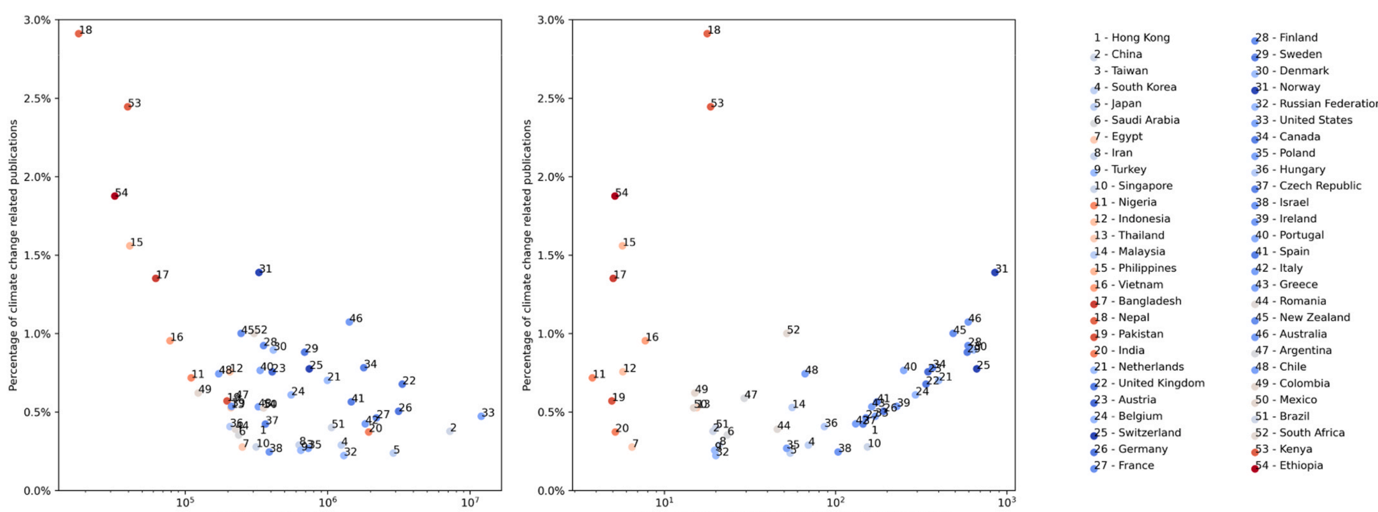

Fig. 5. Total (left side) and per capita (right side) publications on climate change (X-axis) vis-a-vis percentage of climate change related publication (Y-axis) and climate change vulnerability: from low (dark blue) to high (dark red).

[3] The ND-GAIN vulnerability index assesses the countries propensity to be negatively impacted by climate hazards by considering six life-supporting sectors: food, water, health, ecosystem services, human habitat, and infrastructure. Each sector is represented by six indicators that represent three components: the exposure of the sector to climate-related or climate-exacerbated hazards; the sensitivity of that sector to the impacts of the hazard and the adaptive capacity of the sector to cope or adapt to these impacts (Chen et al., 2015)

4.3. Geographical specialization

Fig. 6 reports the full matrix of standardized relative weight of the 472 research topics across the 54 considered countries, together with the dendrograms depicting the hierarchical relations of similarity among countries' specialization. The red colour stands for over-represented topics, while the blue one for the under-represented ones; white spaces represent topics that are absent from a given country. For more details on the definition of the matrix see the Section "Data and Methods".

To make a manageable description of the research focus by geographic area, we aggregated the countries into five Country Blocks (CBs) according to their similarity in terms of over/under-representation of the research topics (see Data and Methods). This grouping relies on a fine-grained level of description, and – more importantly – allows us to delve deeper into each block.

Fig. 7 presents the countries coloured by their Country Block.[4]

In the following, we describe each Country Block's distinctive specialization in climate change research.

Country Block 1 includes five east-Asian countries, with a total population of 1.6 billion people,[5] and represents 16% of the global publications on climate change (on average, 19 per million inhabitant).[6] Two main focuses characterize research on climate change in this block. The first includes topics related to: i) weather events, namely extreme precipitations, cyclones, monsoon, hurricanes, and extreme heat, also with a focus on specific areas like Yangtze and Yellow rivers, and Tibetan plateau, as well as ii) the causes of extreme events, like Sea Surface Temperature (SST) anomalies, and iii) their specific consequences, like landslides, floods, and flash droughts. The second area of focus is research about carbon emissions in the perspective of reducing them by increasing energy efficiency, through low carbon technologies, renewable sources, energy taxes, and reducing the carbon impact of the supply chain.

This specialization pattern reflects distinctive challenges posed by climate change on this geographical area. East Asia, together with India and Southeast Asia, is a region that combines extreme precipitations – related to monsoons and typhoons – with high density population (Zhang et al., 2018a,2018b), hence resulting in the extremely high flood hazard and flood risk, with the displacement of millions of people (Carozza and Boudreault, 2021).

Increasing energy efficiency is also a recognized objective and challenge for the largest country in this group: China, which is not only the largest emitter of CO_2 globally but has consistently displayed one of the highest ratios of CO_2 emissions per wealth produced. While China is by far the largest producer of renewable energy in the world,[7] and reduced the CO_2 per wealth ratio from 1.95 Kg of CO_2 per US Dollar of GDP in PPP (Purchasing Power Parity) in 1990 to 0.46 in 2019 (−73%), nevertheless, it still displays the 8th highest ratio in the world out of 228 countries.[8]

Country Block 2 includes countries in Southeast Asia, Indian Subcontinent, the Middle East, Egypt, and Nigeria – for a total population of 2.7 billion inhabitants, and 8% of the global publications on climate change (on average, 6 per million inhabitant). The most prominent area of research in CB2 revolves around food, with a central role played by topics related to the farming of rice, maize, and wheat, but also including fishing, aquaculture, and water management. It is also possible to observe a wide range of different approaches to the issue, from the study of rural households and small farmers adaptation strategies to the selection of resilient and productive species of crops. Renewable energies – mainly photovoltaic, solar, heat pumps and wind turbines – also appear frequently, followed by topics related to biogas and biofuel. Two additional areas of interest are disaster management – with research about floods and monsoons – and public health – with a focus on the diffusion of malaria and heat stress related diseases.

Also in this case, specialization patterns reflect distinctive challenges – but also opportunities – of countries in this block. Countries in this block are particularly vulnerable to hazards that climate change poses on their food production and supply. For example, the ND-global adaptation index measures *food vulnerability* with a composite indicator that considers, among others: projected change of cereal yields, food import dependency, agriculture capacity – and countries in this block have the highest average score (0.51) compared to the other blocks (1: 0,30, 3: 0,24; 4: 0,30; 5: 0,42). Interest about floods, monsoons, malaria and heat stress related diseases are also highly relevant for countries in this area. Research focus on solar energy and photovoltaics is also clearly driven by opportunities since this area of the planet displays very high levels of irradiation.

Country Block 3 includes countries in the Northern part of the Northern hemisphere – namely most of the western countries and Russia – for a total population of 805 million inhabitants, and 53% of the global publications on climate change (on average, 128 per million inhabitant). Two research areas play a prominent role. The first one is related to climate policy – featuring research on e.g., the Paris agreement, carbon tax implementation, climate governance and climate change narratives. The second area comprehends basic research on the phenomenon of climate change itself and topics like the albedo effect, the level of oceanic heat uptake, the carbon cycle and the AMOC (Atlantic meridional overturning circulation). Other focus areas include regional biology – especially of arctic species – and studies on the state of ice and snow coverage.

The research focus of this area is related to the role played in shaping policies and responses to climate change, both through the influence on global governance and through a leading role in research.

Country Block 4 includes South and East European countries, with a total population of 219 million inhabitants, and 11% of the global publications on climate change (on average, 97 per million inhabitant). The topics of specialization are rather heterogenous. It's single largest and most relevant topic of specialization is related to urban car traffic, electric vehicles, and sustainable transportation in general. Other prominent topics of specialization include disaster management – with studies on heat waves, extreme precipitations, and floods – soil degradation and erosion of the coastline. Among applied topics we also find research on renewable energy policies, water management and viticulture. Basic research, on the other hand, includes many topics from biology, with a focus on the sea fauna.

In this case the focus on vehicles and traffic might be related to the prevalence of road transportation both in private mobility and in freight shipping. Vehicles – especially commercial and industrial ones – also tend to be older, on average, in south and east Europe.[9] Another factor, partially related to the first one, is the low air quality – in particular with respect of PM10 pollutants – of several areas of eastern and southern Europe, especially Poland and northern Italy.[10] The focus on the erosion of the coastline, on the other hand, is probably explained by the advancement of the process in the Mediterranean area that dramatically

[4] The full list of countries included in each block is reported in the appendix.

[5] All the population data are from the World Bank, year of reference 2020. Available at: https://data.worldbank.org/indicator/SP.POP.TOTL

[6] The percentage of global publications on climate change in which each Country Block is involved is computed considering our sample of publications to be representative of the global scientific production on climate change.

[7] Source: Statista. Available at: https://www.statista.com/statistics/267233/renewable-energy-capacity-worldwide-by-country/

[8] CO_2 emissions (kg per PPP $ of GDP). Wolrd Bank data. Available at: https://data.worldbank.org/indicator/EN.ATM.CO2E.PP.GD

[9] ACEA Vehicles in Use report (2022), see also: https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/

[10] European Environment Agency data: https://www.eea.europa.eu/data-and-maps/dashboards/air-quality-statistics

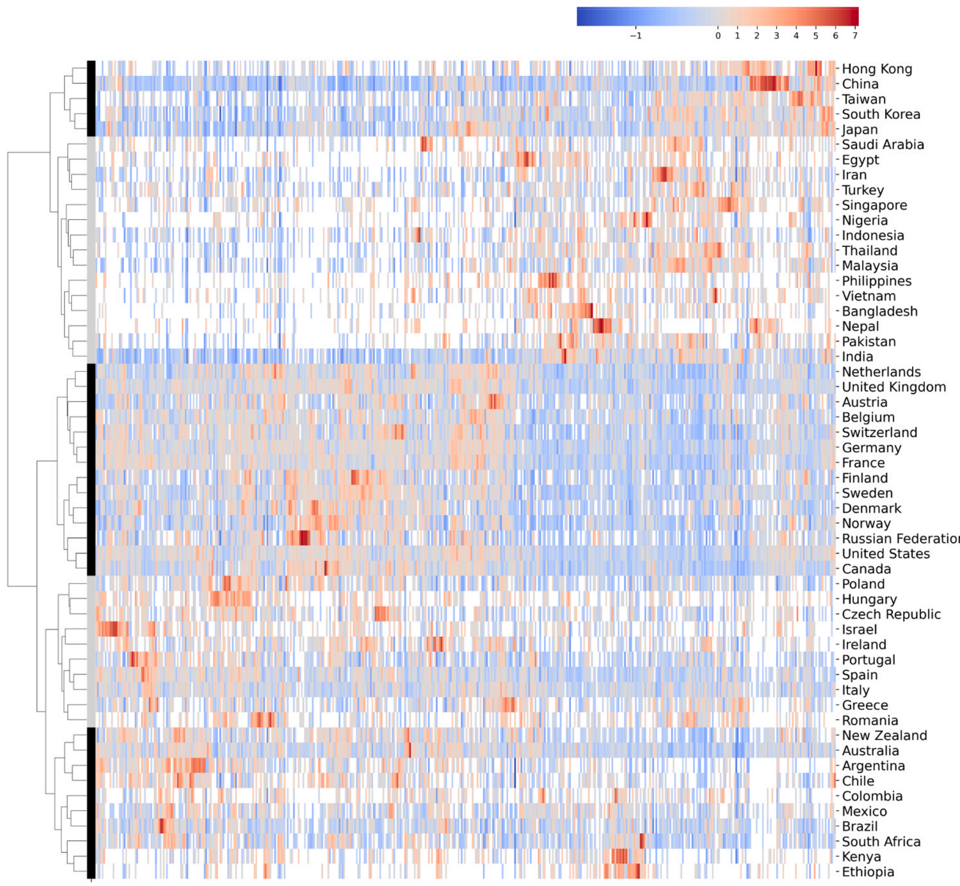

Fig. 6. Standardized weight of topic by country matrix. Note: White spaces indicate topics that are fully absent from a given country.

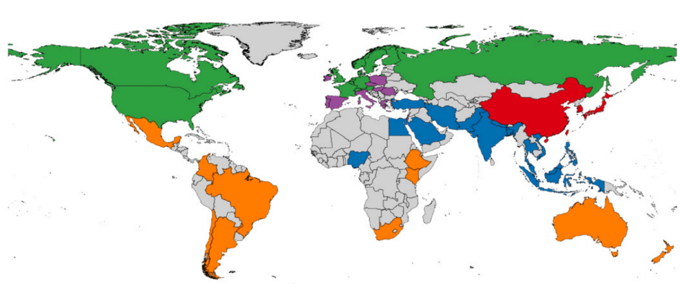

Fig. 7. Countries coloured by block. Countries belonging to the same block have similar specialization profiles over research topics.

affects countries with extensive coastlines like Italy and Greece.[11]

Country Block 5 includes countries in the southern hemisphere, with a total population of 713 million inhabitants, and 13% of the global publications on climate change (on average, 35 publications per million inhabitant). Like for CB2, a major specialization is in food-related research topics: from studies on food security to research on livestock or maize and coffee cultivation. Another important area of research is the impact of climate change on public health, particularly on the diffusion of malaria and the emergence of zoonotic diseases. A third area regards local adaptation policies, the enactment of protected areas to preserve biodiversity and the study of forestry management. More region-specific topics revolve around the Amazon Forest and the presence of indigenous communities.

The focus on food is arguably due, like in the case of CB2, to the high-level food vulnerability (see above). The rest of the areas of specialization are instead clearly related to the geography of the countries in this block. The presence of some of the areas with the highest biodiversity in the world[12] – like the Amazon Forest – increases the efforts in preserving the wildlife. At the same time, tropical regions with a high wildlife biodiversity display a high risk for the emergence of new zoonotic diseases (Allen et al., 2017).

4.4. Forces affecting countries' specialization

In Section 2.1 we discussed and anticipated some factors that may affect countries' specialization. In a first place, it is important to note that there is indeed a high degree of differentiation and specialization, leading to five main country blocks. The extent of variation between countries' specialization is evident from Fig. 8, which reports the cosine similarity among the countries' specialization profile (i.e., the cosine similarity among the rows of the matrix represented in Fig. 6).[13]

We expected that the specific environmental challenges faced by countries, directly and indirectly drive an interest into specific topics exploring the nature, causes and possible solution for those challenges, and that countries facing similar challenges will display a similar research specialization. The results corroborate this perspective: country

[11] European Environment Agency data: https://www.eea.europa.eu/data-and-maps/figures/coastal-erosion-patterns-in-europe-1

[12] National Biodiversity Index, available at: https://www.cbd.int/gbo1/annex.shtml

[13] The cosine similarity is a measure of similarity among vectors. Vectors pointing in the same direction (i.e. countries with the same specialization profile) have similarity = 1, orthogonal vectors have 0, while vectors pointing in opposite direction have − 1. In Fig. 8 the scale of color is bounded at 0 to ease the visualization.

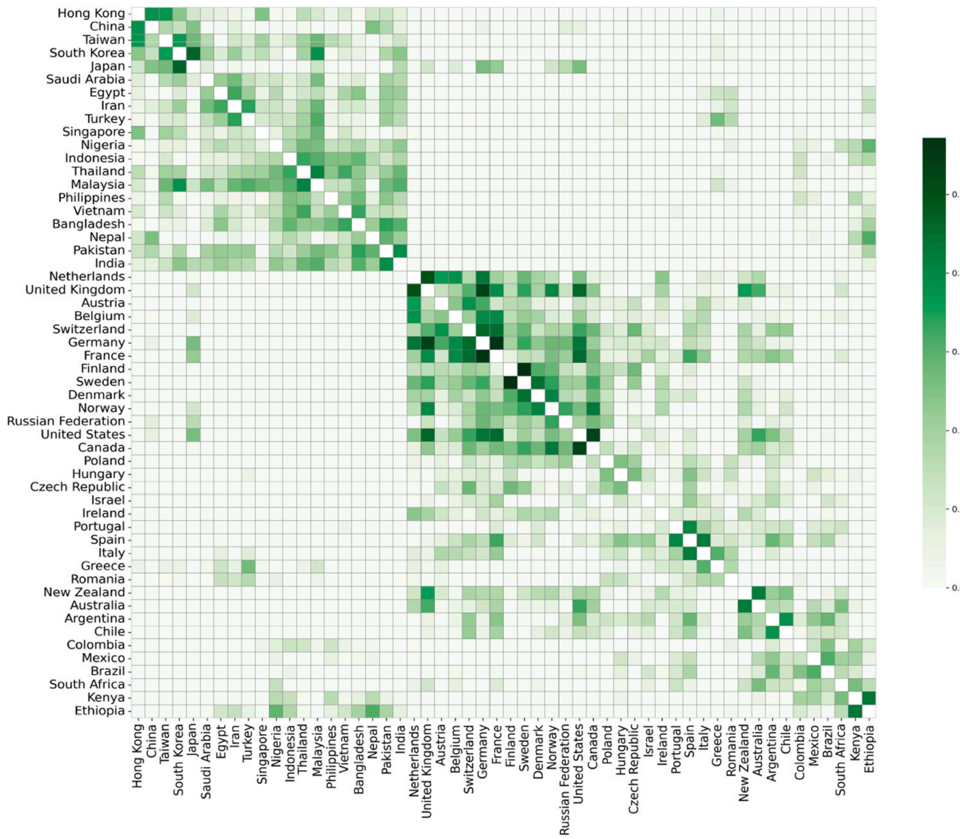

Fig. 8. Cosine similarity of the countries' research profile.

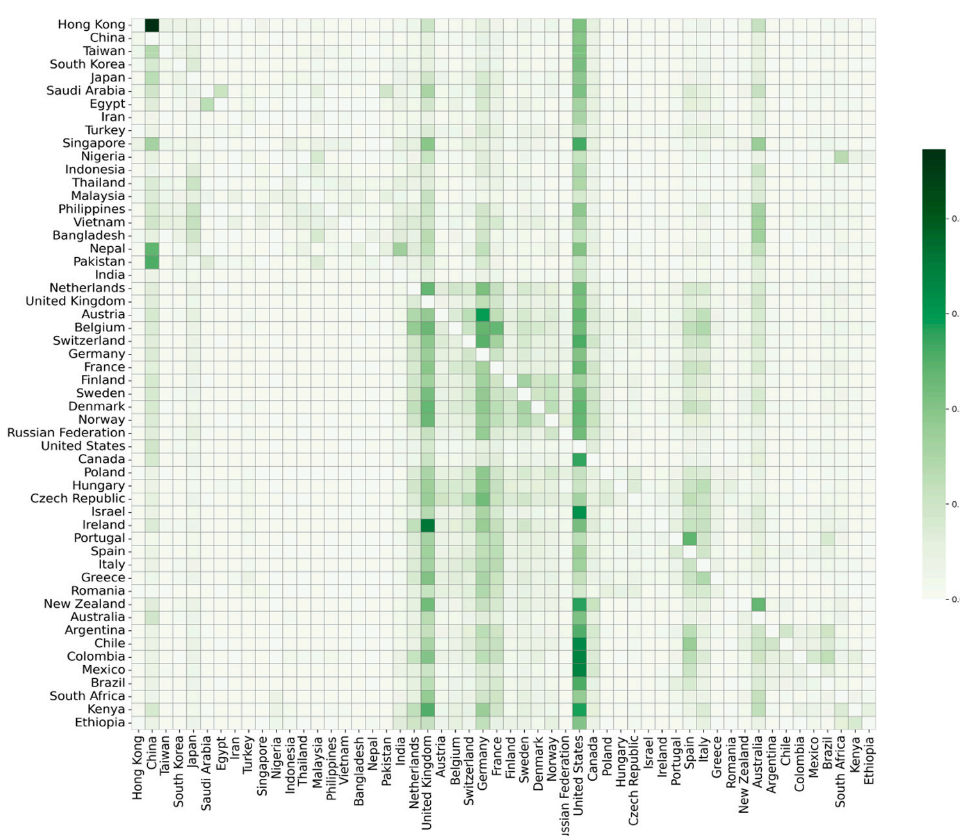

Fig. 9. Fraction of scientific collaboration among countries (row normalized).

blocks' common drivers of specialization are often their shared challenges, such as extreme precipitation and floods (CB1), food (CB2 and CB5), sustainable transportation (CB4).

At the same time, we also observe, as expected, that the research focus is affected by the level of available resources. Less affluent CBs focus on applied topic, local problems' causes and mitigation strategies, whereas basic research into the phenomenon of climate change and its global solutions, such as policies and international negotiations, is comparatively more important in affluent western countries (CB3).

Finally, since collaboration affects topics' selection and a common interest drive collaboration, then countries with a strong level of collaboration should display a similar specialization. This is not confirmed. Fig. 9 presents the co-publication matrix between the countries in our sample and shows that for most countries' the most common co-publication partners are the same, namely the United States (12.3% of all collaborative publications), the United Kingdom (8.8%) and Germany (7.2%). However, this does not lead to a similar specialization to those countries. Rather, it emerges a quite different picture from the topic specialization pattern (Fig. 6) and the topic cosine similarity (Fig. 8). Hence, collaboration does not have a decisive impact on topic specialization, nor vice versa.

5. Discussion

This article developed a bibliometric overview of climate change research to address two main limitations of existing analyses of this kind in an integrated fashion. First, existing overviews are limited to the identification of main topical trends, hiding the large variety of research topics. In addition, they either ignore the geographical dimension or focus only on major scientific players, implicitly assuming that these are representative of the global distribution of scientific topics. These are important limitations of bibliometric overviews, especially for climate change research, since most of the world's population live in countries that are heavily affected by climate change but have a relatively small scientific production, so that their topics of interest might be neglected.

Therefore, the article aimed to provide a fine-grained overview of climate change research, as well as to explore how climate change research specialization varies across countries and what factors seemingly drives specialization. It did so, by employing a combination of state-of-the-art language modelling techniques to analyse the abstracts of 193,471 publications produced from 1990 to 2020.

Before discussing the empirical results, some choices and limitations should be addressed. First, the restriction of the sample to 54 countries and 472 research topics is based on two thresholds that – despite being adopted to ensure the inclusion of cases with a reasonable number of observations – are somehow arbitrary. Another limit to be considered is the restriction of the sample to publications in English indexed on Scopus; despite this choice, we were able to observe a wide variety of research topics, and our main claims about the variety of topics and country variations would not be weakened in the event of an even higher variety resulting from the inclusion of publications from other sources or in other languages. Future works could expand on our results by exploring country-level specialization in local languages.

The empirical analysis revealed that scientific production on climate change has increased drastically over time – in the last two decades from one per thousand to almost one percent of the total scientific production – and became less concentrated in the most productive countries. Countries that are more vulnerable to climate change hazards tend to be less productive of climate change research – both in absolute and per capita terms – not due to a lower interest on climate change, but because they typically produce less publications in general. The relative importance of climate change research varies remarkably across countries, from 0.2% to over 3% of their research output, but there is not a clear geographical pattern nor a clear relationship with their vulnerability to climate change.

The analysis identified 472 research topics and found remarkable differences in the countries' research foci. Five blocks of countries with a similar specialization emerged. Country blocks' common drivers of specialization are often their shared challenges, such as extreme precipitation and floods (CB1- East Asia), food (CB2 - Southeast Asia, Indian Subcontinent, the Middle East, Egypt, and Nigeria - and CB5 - Southern hemisphere), sustainable transportation (CB4 - South and East European countries). The research focus is also affected by the level of available resources: less affluent CBs focus on applied topic, local problems' causes and mitigation strategies, whereas basic research into the phenomenon of climate change and its global solutions, such as policies and international negotiations, is comparatively more important in affluent western countries (CB3 – Northern part of the Northern hemisphere). This finding is in line with the evidence provided by Pasgaard and Strange (2013) on a narrower corpus of publications.

It is also interesting to note that, while most countries in our sample collaborate strongly with leading scientific countries like the US, UK, and Germany, nevertheless this is not associated to a similar specialization. This is an important finding for studies of science and for science policy. Namely, strong scientific collaborations between central and peripheral countries do not necessarily drive what topics are studied in the latter, and peripheral countries can develop a distinct research focus. At the same time, these countries typically have limited resources to address these challenges and host several billion people. Hence, a further research policy implication is that leading scientific countries should possibly contribute even more to addressing such issues.

A related aspect highlighted by this study is that the uneven geographical spread of the topics represents a risk for bibliometric overviews that only consider the countries with the greatest scientific output and/or the main topical trends. These might systematically underestimate the importance of research areas concentrated in less productive countries and overlook the diverse and original research focus of many developing countries (see also Pasgaard and Strange, 2013). This issue is particularly problematic in the case of climate change research, given the necessity to develop global strategies that consider also the challenges faced by countries with relatively low scientific output. For example, previous research has shown that developing countries are underrepresented among IPCC reviewers (Palutikof et al., 2023). A broader and more detailed approach to bibliometric overviews can help in highlighting these issues and restoring the balance.

Finally, this study represents an example of the benefits that recently developed techniques in natural language processing – still not widely adopted in scientometric research – might bring to the mapping of the scientific literature, especially in the case of big and fast-growing fields like climate change research.

6. Conclusions

In this article, we provide evidence of a progressive decentralization of climate change research from leading countries to developing ones. This process takes place along a diversification of the research specialization at the country level, with developing countries focusing more on applied topics and prominent ones on basic research and global policies. Awareness of these developments is crucial for the public discourse on climate change research in order not to underplay the role of developing countries and the topics they prioritize.

Future developments of this work might provide information on the temporal evolution of the specializations identified in this study, unveil the growth dynamic of research topics in relation to climatic challenges, investigate the role of specific institutions in developing country-level research foci and analyse the representation of countries and research topics in the narrative of policy documents.

CRediT authorship contribution statement

Debernardi Carlo: Conceptualization, Formal analysis, Software, Writing – original draft, Writing – review & editing. **Seeber Marco:**

Conceptualization, Supervision, Writing – original draft, Writing – review & editing. **Cattaneo Mattia:** Investigation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The authors wish to thank Flaminio Squazzoni for the insightful suggestions, as well as the participants of the Science Policies and Scientific Collaboration session of the ESHS 2022 Conference for their feedback.

Appendix

Table A
Detailed information on the countries in the sample.

Country	Country Block	ND-GAIN Vulnerability 2020	Population in 2020	Percentage of country publications on climate change	Climate change publications	Climate change publications per million people
Hong Kong	1		7481,000	0.36	1215	162.14
China	1	0.40	1411,100,000	0.38	27,225	19.28
Taiwan	1		23,821,464	0.27	1924	80.77
South Korea	1	0.38	51,836,239	0.29	3604	69.45
Japan	1	0.38	126,261,000	0.24	6905	54.36
Saudi Arabia	2	0.41	35,997,107	0.35	841	23.36
Egypt	2	0.44	107,465,134	0.28	699	6.49
Iran	2	0.39	87,290,193	0.29	1830	20.96
Turkey	2	0.35	84,135,428	0.26	1661	19.72
Singapore	2	0.39	5685,807	0.28	874	153.72
Nigeria	2	0.50	208,327,405	0.72	794	3.81
Indonesia	2	0.45	271,857,970	0.76	1561	5.73
Thailand	2	0.44	71,475,664	0.53	1112	15.50
Malaysia	2	0.38	33,199,993	0.53	1855	55.84
Philippines	2	0.46	112,190,977	1.56	641	5.70
Vietnam	2	0.48	96,648,685	0.95	749	7.75
Bangladesh	2	0.54	167,420,951	1.35	843	5.04
Nepal	2	0.52	29,348,627	2.91	523	17.82
Pakistan	2	0.53	227,196,741	0.57	1124	4.95
India	2	0.51	1396,387,127	0.37	7250	5.18
Netherlands	3	0.35	17,441,500	0.70	7051	401.11
United Kingdom	3	0.30	67,081,000	0.68	22,838	337.71
Austria	3	0.28	8916,864	0.76	3103	346.87
Belgium	3	0.35	11,538,604	0.61	3392	293.10
Switzerland	3	0.26	8638,167	0.77	5794	667.97
Germany	3	0.29	83,160,871	0.50	15,938	190.99
France	3	0.31	67,571,107	0.46	10,223	150.61
Finland	3	0.31	5529,543	0.92	3301	594.08
Sweden	3	0.30	10,353,442	0.88	6104	587.82
Denmark	3	0.35	5831,404	0.89	3742	639.81
Norway	3	0.26	5379,475	1.39	4606	853.43
Russian Federation	3	0.35	144,073,139	0.22	2898	20.02
United States	3	0.33	331,501,080	0.47	57,054	170.62
Canada	3	0.30	38,037,204	0.78	14,121	369.11
Poland	4	0.33	37,899,070	0.27	1972	51.85
Hungary	4	0.37	9750,149	0.41	843	86.15
Czech Republic	4	0.30	10,697,858	0.42	1556	144.80
Israel	4	0.32	9215,100	0.24	960	103.63
Ireland	4	0.32	4985,382	0.54	1138	228.07
Portugal	4	0.33	10,297,081	0.76	2577	250.07
Spain	4	0.30	47,365,655	0.56	8290	174.83
Italy	4	0.32	59,438,851	0.42	7813	131.24
Greece	4	0.33	10,698,599	0.53	1747	162.92
Romania	4	0.41	19,265,250	0.39	881	45.73
New Zealand	5	0.31	5090,200	1.00	2492	486.62
Australia	5	0.32	25,655,289	1.07	15,343	595.67
Argentina	5	0.41	45,376,763	0.59	1335	29.33
Chile	5	0.32	19,300,315	0.74	1284	66.42
Colombia	5	0.42	50,930,662	0.62	769	15.10
Mexico	5	0.42	125,998,302	0.53	1874	14.87
Brazil	5	0.40	213,196,304	0.40	4276	20.03
South Africa	5	0.42	58,801,927	1.00	3063	51.99
Kenya	5	0.53	51,985,780	2.45	972	18.66
Ethiopia	5	0.56	117,190,911	1.88	604	5.15

Sources:
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