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Review

New insights on climate change and adaptation research in Brazil: a bibliometric and bibliographic review

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Abstract
We present a thorough analysis of the scientific production in climate change and adaptation in Brazil. We conducted a bibliometric and bibliographic review to reveal and discuss how climate change research has been carried out. We compared a broader climate change research dataset with a more specific climate adaptation research dataset, to understand the main differences and convergence points, and how science conducted from a mitigation and adaptation perspective demonstrates potential to confront the climate change challenges and drivers in Brazil. Four main clusters of investigation within climate change were detected: (1) impacts on forest and plant development, (2) land use and ecology, (3) adaptation/governance, and (4) climate/atmospheric studies. Only about 5% of the total studies on climate change address adaptation, for which three main clusters of research were identified: (1) adaptation actions and policies; (2) urban environment, vulnerability, and health and (3) food and coastal impacts. Although there are strong research trends in climate change for the Amazon Forest, there was less evidence of studies concerning climate adaptation for this and other Brazilian biomes, smaller cities, rural and traditional communities, and poorer regions. Our results shed a light on the more commonly chosen research topics, their strongest points and potential gaps and trends. This can contribute to the scientific communication and implementation of climate actions in Brazil, and a better understanding of the climate science knowledge from the perspective of a middle-income country.

Keywords Climate change · Climate adaptation · Brazil · Literature review · Climate change communication · Climate impacts · Climate governance · Keyword clustering · Scientific production

1 Introduction

In July 2023, unprecedented heat waves spread across the Northern Hemisphere, making it the hottest month ever in record. In July 2022, extreme precipitation events in Brazil's Northeast region led to impacts such as thousands of displacements—mainly low-income populations, which are more vulnerable to the impacts of climate change. In the same year, a late winter heatwave struck Brazil, with positive anomalies of 1.4–4.3 ºC— mainly caused by human-induced climate change [1]. According to the World Health Organization (WHO), climate change has been recognized as "the century's defining issue" for public health [2].

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While mitigation actions are paramount to stop greenhouse gases (GHG) emissions and their build-up in the atmosphere, the increased intensity and frequency of extreme events brings urgency to climate adaptation actions, which allow societies to thrive under more extreme conditions [3]. Even though low-income populations correspond to lower per capita GHG emissions, they present a higher degree of climatic and environmental vulnerability (living in low quality houses, located in risk or contaminated areas, lacking access to sanitation, health, etc.) [4–6]. Therefore, adaptation actions present unique opportunities to decrease both social and environmental inequalities.

Forecasted climate change impacts in South America for the end of this century include, for example, potential warming between 1° to 6 °C. Varying degrees of warming are predicted across its regions, depending on different scenarios. The higher temperature increases are forecasted for tropical areas such as the Amazon and the Brazilian southeast [7]. According to IPCC's SSP 5–8.5 scenario, in sub-region NSA (North South America), which includes the Amazon Forest, the intensity and frequency of extreme precipitation and pluvial floods are projected to increase at 2 °C of global warming level and above (medium confidence); meanwhile, there is high confidence for an increase in the number of dry days and drought. Other expected impacts include more frequent extreme precipitation events, species extinctions, replacement of tropical forest by savannas, increased water stress, impacts on food production, sea level rise, coastal erosion and impacts on land and coastal ecosystems. The most intense impacts will be felt in the tropical regions of the continent, home of biological hotspot and biomes with great biodiversity, freshwater stocks, and other important ecosystem services, such as the Amazon. Since 90% of the Brazilian territory lies in the intertropical zone and lacks access to sanitation, poor housing conditions and widespread poverty, Brazil shows a high degree of socio-environmental vulnerability to climate change [8].

It is vital to produce research robust enough to address such challenges. Scientific knowledge should guide public policies in the implementation of mitigation and adaptation actions. Several studies evaluated the production of knowledge about climate change. For example, Benevolenza and DeRigne [9] evaluated 12 years of literature to understand the impacts of extreme events on vulnerable populations in the US. Fawzy et al. [10] used a systematic review to analyse a great variety of mitigation actions, recommending biogenic-based carbon sequestration techniques. Moore et al. [11] showed the importance of understanding the perspective of developing countries, and to focus both on mitigation and adaptation simultaneously. Other works reinforced the importance of evaluating and tracking adaptation actions in developing countries, due to their greater vulnerability, the scarcity of scientific knowledge, as well as organisational, political, discursive and communication constraints [12–14].

Economic and political crises have been affecting Brazil in the last few years, leading to increased socio-environmental vulnerability. The previous federal administration (2018–2022) was infamous for neglecting environmental policies, leading to dramatic increases in deforestation, GHG emissions, and systemic impacts caused by the transformation of rainforests into savannah-type biomes used for pasture (such as decrease in soil moisture, loss of biodiversity, etc.) [15]. Studies characterizing the Brazilian scientific production on climate change (particularly those involved in climate adaptation) are scarce and can provide opportunities to portray its characteristics, the main topics and potential research gaps, the potential to solve related problems in Brazil, and point ways forward.

In this study, we present an analysis of the scientific production in climate change and adaptation in Brazil. Besides evaluating climate change research, we also analysed a subset of data composed exclusively of climate adaptation documents. We compared this more specific dataset to the broader climate change dataset to understand their main differences (for example, if climate adaptation has received the same attention as mitigation) and how science conducted from both perspectives demonstrates the potential to confront the different climate change challenges and drivers in Brazil. Our results shed light on the most popular research topics, their strongest points, trends and potential gaps. This can contribute to better scientific communication and implementation of climate change and adaptation actions in Brazil and a better understanding of the climate science knowledge from the perspective of a middle-income country.

2 Materials and methods

We used combined quantitative and qualitative approaches to report and discuss the scientific research on climate change and adaptation produced in Brazil,[1] inspired by previous literature review works [9–12]. Our process was similar to the SALSA framework (Search, Appraise, Synthesis, Analysis) [16, 17]: we firstly conducted searches in the scientific repositories, then screened the results to make sure no grey literature would be included and to check how the documents fitted into our climate adaptation definition. At this step we extracted and organized the data into spreadsheets

[1] The works are not limited to analysis of the Brazilian territory, as there are partnerships with different countries.

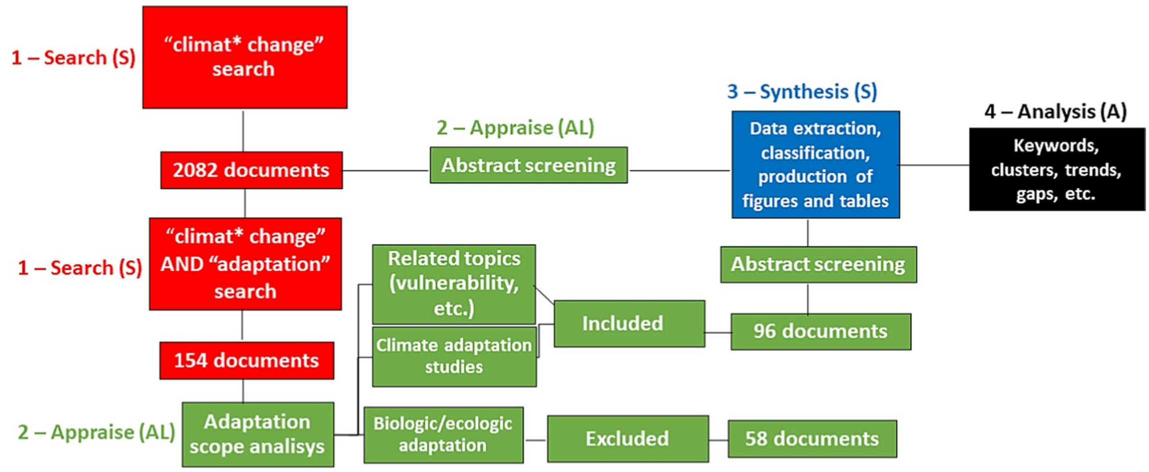


Fig. 1 Methodology flowchart showing the different steps taken using the SALSA framework: 1: Search (S), 2: Appraise (AL), 3: Synthesis (S), 4: Analysis (A). Sources: The authors

and produced graphs and tables. Finally, we analysed the results by using different indicators, such as the most used keywords, and discuss the topics identified in the previous steps. We explain these processes in detail in the following Sects. 2.1 and 2.2, which are summarized in Fig. 1.

2.1 Data collection

We used a broader dataset, representing all climate change research, and a smaller database, representing only climate adaptation research, both retrieved from Web of Science and Scielo Citation Index. For obtaining the larger climate change database, the strings "climat* change" were used, while for the more specific climate adaptation dataset, the string ""climat* change" AND "adaptation"" was used. The broader climate change dataset was then comprised of 2082 studies, while the more specific climate adaptation dataset, of 96 studies. We used the search criteria 'Topic', which includes strings found in the keywords, title, and abstract. Since all these fields were searched using "climat* change", any terms such as 'climate change', 'climatic change' or similar others in the title, abstract or keywords would be included by our search. We conducted this work in 2022 and did not specify a time frame for our search, so the documents retrieved ranged from 1991 to 2021.

This project was carried out as part of an interdisciplinary program of strategies for the dissemination of scientific knowledge, financially supported by the Pro-Rectory of Research of the University of São Paulo (USP), a large and relevant public university in Brazil. Thus, we applied an institutional distinction in our search, using only works from this university. While we are aware that this choice has its limitations, it is important to state that the USP concentrates about 30% of the research conducted in the entire country. Therefore, it can be used as a reasonable proxy for the most popular and innovative research due to its leading position. Besides that, we also present data of co-authorships with institutions from different regions of Brazil. For example, our analysis revealed that 28% of the documents from institutions with 10 or more repetitions in our database were from Brazil, demonstrating the strong presence of national institutions from different regions in our database. Supplementary Information 2 shows the most frequent institutions (excluding the USP), demonstrating the key role of federal institutions in climate change research in Brazil.

2.2 Data organization and analysis

Most of the documents (94,5%) consisted of different types of peer-reviewed articles—research, review, etc. while the remainder were book chapters, editorials, and conference papers. In this step we made sure that no thesis, reports, or other grey literature material were included. They were organized in spreadsheets and evaluated using VOS Viewer, for the co-occurrence of keywords and country of origin of co-authorships. Co-occurrence of keywords indicates the frequency of the combined use of keywords. By counting how many times the keywords appear together; such networks can form clusters of themes that are consistently studied together. The analysis by co-authorship of countries reveals the most common partnerships between different countries in the research field and their respective clusters.

Cluster analysis using VOS Viewer and similar tools have been widely used for literature review research [18–20]. VOS Viewer clusters are calculated a distance-based approach through a similarity matrix (more details can be found in Van Eck and Waltman [21]). To determine clusters in this work, we used keywords with a minimum of 50 repetitions for the climate change database, and a minimum of 20 repetitions in the climate adaptation database (as it was smaller), resulting in fewer clusters and a more straightforward and robust analysis [19]. We tested with fewer repetitions (30 and 40), and the results yielded similar clusters to the graphs using 50 repetitions. Therefore, we concluded that the clustering process is robust and indicates a strong research trend (the clustering with 30 and 40 repetitions can be found in Supplementary Information).

In this work, we also evaluated the temporal evolution of keywords and clusters. Initially, we considered dividing the papers in equal periods of time, but this approach was questionable, as the temporal evolution is very unbalanced, with much more papers published in the latter years. For example, from 1991 to 2007 (about half the period of the database), there were only 87 papers, from a grand total of 2082. Since the clustering depends on the number of papers, periods with uneven number of papers would be too difficult to analyse. Therefore, we chose to elaborate graphs comparing periods with similar scientific production in terms of the number of papers. This resulted in the periods of 1991–2017 and 2018–2021 for the climate change database, and 2007–2019 and 2020–2021 for climate adaptation. This also enabled us to capture the more recent trends more exclusively.

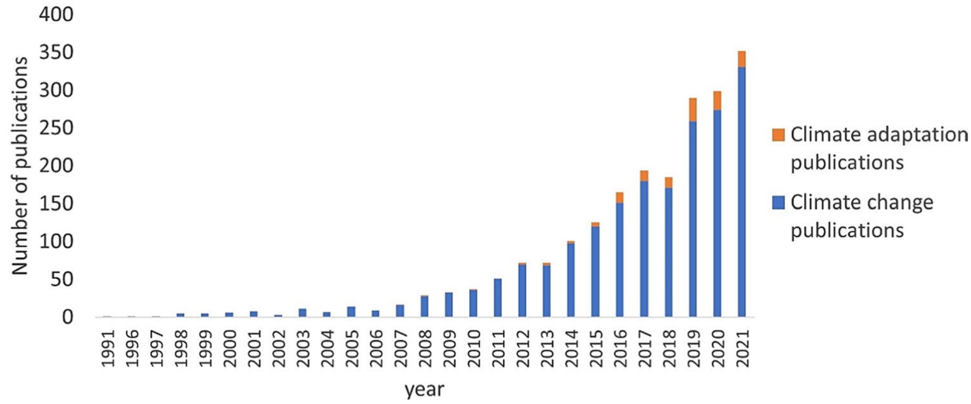
While this type of analysis indicates theoretical/methodological affinities between different areas, some words can have different meanings in different contexts, such as "adaptation". In this work, the adopted definition of "adaptation" is linked to the implementation of actions towards making human and natural systems more resilient or resistant to climate change, adapting our infrastructures, cities, livelihoods, and economic activities to more unstable climate patterns, in which not only average temperatures are higher, but also extreme events are more frequent [3, 12, 22]. Therefore, we are looking at climate adaptation from a societal perspective. We didn't necessarily consider only those actions aimed at human settlements or activities, but from the point of view that the action was deliberately taken by human society to adapt. This is different from natural adaptation mechanisms, in which organisms adapt to changing/specific environmental conditions as a result of biological/ecological processes, the focus of research of natural sciences fields. Although we recognize the importance of understanding these complex mechanisms, particularly in a changing climate, it was not the aim of our research, as we intend to understand the production of knowledge on how society responds to climatic impacts.

Therefore, based on previous systematic reviews which also approached climate adaptation [3, 12], we classified the climate adaptation papers according to their relevance to this definition, excluding the studies related to biological adaptation. To classify the papers (from 1—most relevant to 4—not relevant), we used, in this order: the keywords, the study title, the results sections of the study, and journal of publication. Therefore, papers with relevance rated 1–3 comprised our climate adaptation database, while papers of relevance 4 were excluded for the climate adaptation analysis (Table 3).

Other indicators obtained were the temporal evolution of publications, the list of ten most used keywords and frequency per of studies per Brazilian region. There are five regions in Brazil: Northeast, North, Centre-West, Southeast and South. Historically, the Southeast and South regions are richer and more developed, and more recently, the Centre-West region has experimented some development as well. This represents a sharp contrast compared to the North and Northeast regions which still present higher levels of illiteracy, lack of access to sanitation, etc. For instance, the Human Development Indexes for the Northeast and the North regions are 0.66 (medium development), while for the Southeast, South and Centre-West, it's 0.76 (high development) [23]. Since universities tend to focus on their regional/local level, it is assumed that the region of origin of institutions would provide an indication of which regions are actually being studied. So, it is important to understand if climate change research is being carried out in a way to help mitigate national inequities or focusing on the more vulnerable regions instead of the more developed regions. A few national-scale research institutes were flagged as "Not Applicable" for this analysis.

Another procedure was the building of a thesaurus file, in order to aggregate keywords such as "South-America" and "South America" and to remove words such as "study" that are too general. This step was performed before the other procedures and the thesaurus file can be found in Supplementary Material 1. The methodology, which follows closely the SALSA framework, is summarized in the flowchart shown in Fig. 1.

Fig. 2 Temporal Evolution of the number of publications, concerning "climat* change" (blue) and ""climat* change" AND "adaptation"" (orange). Sources: Web of Science and Scielo Citation Index



3 Results and discussion

Figure 2 shows the temporal evolution of publications in the topic of climate change (blue) and climate adaptation (orange). There were less than 50 publications per year until 2011. There was a steady increase from 2013 to 2017, reaching nearly 200 publications per year. From 2018 to 2019, the number of papers almost doubled, peaking at 350 in 2021. For adaptation, the first publication was in 2007, but only a very small percentage of studies specifically concerned with climate adaptation were published throughout the years, corresponding to approximately 5% of the total studies on climate change. There were, however, expressive increases from 2013 (6 papers) to 2014 (14) and from 2018 (14 papers) to 2019 (31). While these increases follow the trend in all climate change publications, it shows that the interest in climate adaptation, although late, remains steady.

In 2019, record-breaking deforestation and fires took place in the Amazon Forest and brought more international attention to climate issues in Brazil. This could be connected to the increase in the number of publications from this year onwards. In fact, recent studies demonstrate the dynamics of deforestation-related fires and how the Amazon region is switching from a sink to a source of carbon to the atmosphere, which constitutes an enormous challenge [15, 24, 25].

3.1 Climate change

3.1.1 Keywords analysis—climate change

Table 1 shows the top ten keywords and their number of occurrences for "climat* change".

"Impacts", "Brazil" and temperature" are the top three keywords, with 159, 146 and 128 occurrences, respectively. This indicates an expressive concern on climate change impacts on Brazil, particularly with temperature increase. This paints a broader picture, from which other more focused topics will branch from. For example, "Impacts" encompasses a wide array of contexts; there can be impacts on health, ecosystems, infrastructure, food production, precipitation regimes, and urban/social impacts, such as financial losses and displacements [8]. So, while this keyword is very general, it represents attempts to address the main challenges of climate change in the Brazilian territory. Other keywords show concern with ecological issues, such as "biodiversity", "forest", and "amazon" [26]. The other most popular keywords seem to be concerned with atmospheric science studies, such as "precipitation", "variability", "carbon dioxide" and "climate"—however, "precipitation" and "climate" can also easily be linked to "impacts" or other topics.

To better clarify the relationship between keywords and identify the main research areas, we present the clustering of keywords for Climate Change in Fig. 3. We were able to identify four main clusters of investigation within climate change: (1) impacts on forest and plant development (green in Fig. 3), (2) land use and ecology (red in Fig. 3), (3) adaptation/governance (purple in Fig. 3), and (4) climate/atmospheric studies (blue in Fig. 3). The size of the circle is associated to the number of repetitions of each keyword individually; line thickness indicates how often they appear together, forming clusters of the same colours.

Cluster 1 (green in Fig. 3) is more focused on plant and vegetation from a perspective of the plant sciences, addressing biophysical processes ("photosynthesis", "growth") in a more specialized manner than cluster 2. Such an example

Table 1 Top ten keywords in "climat*change" publications and number of times used

Keyword[a]	Occurrences
Impacts	159
Brazil	146
Temperature	128
Biodiversity	108
Precipitation	106
Amazon	104
Climate	99
Forest	93
Variability	91
Carbon dioxide	89

Sources: Web of Science and Scielo Citation Index

[a]We omitted the keyword "climate change"

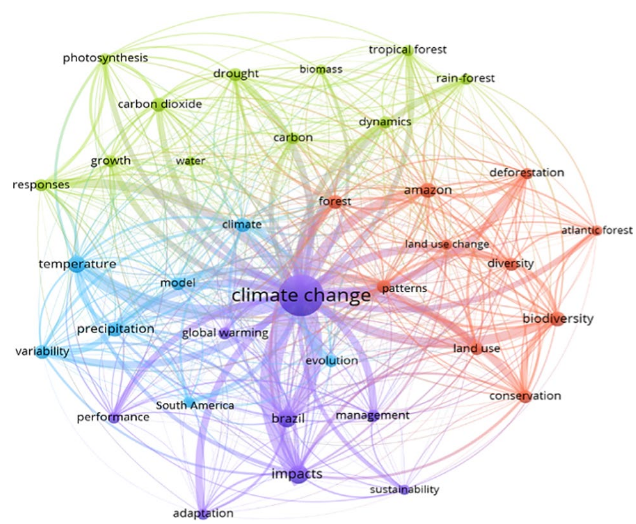


Fig. 3 Clustering of the co-occurrence of keywords with 50 repetitions or more for "climat* change". Sources: Web of Science and Scielo Citation Index

can be found in an analysis of the impacts on the productivity of plant species under scenarios of climate change [27, 28]. Cluster 2 (orange/red in Fig. 3) shows keywords more connected to ecology and geography ("land use"), thus bringing a more systemic/interdisciplinary view of biodiversity and landscape, such as coupling economic assessments with crop production and pollination services [29]. Either way, the research fields represented by clusters 1 and 2 are both important and, in fact, complementary. Keywords such as "amazon" and "forest" are part of both fields and located at the edge between these clusters. "Land use" is part of cluster 2, but much closer to cluster 3 (purple in Fig. 3). This can be explained by "land use" being also a popular topic in urban studies, since cluster 3 seems more related to the human dimensions of climate change, ("adaptation", "management") [30]. As mentioned in Sect. 2.2, we also tested clustering with fewer repetitions (30 and 40, which can be found in Supplementary Information), but the results yielded similar clusters. So, this potentially indicates robust research trends.

The main keyword "climate change" is part of cluster 3—this implies that the keywords in this cluster are used more often with climate change than the keywords in the other clusters. Cluster 3 seems related to the social, political, and institutional aspects of climate change (with keywords such as 'management' and 'sustainability'). It is reasonable to suppose that the environmental problems related to climate change faced by Brazilian society in the past few years (such as human-induced fires in forests) might have propelled a greater number of studies aimed at better understanding these aspects. Also, there are good examples of climate governance in other spheres of government, such as municipal climate plans, which are aligned with this scientific production [31–33]. Finally, cluster 4 (blue in Fig. 3) is related to climatic and atmospheric studies that seeks to understand the Earth sciences aspects of climate change [34]. These studies are vital for building the climate science knowledge, as they form the basis upon which all the other more impact-oriented studies are developed. Using tools such as atmospheric modelling (e. g., WRF, RegCM,

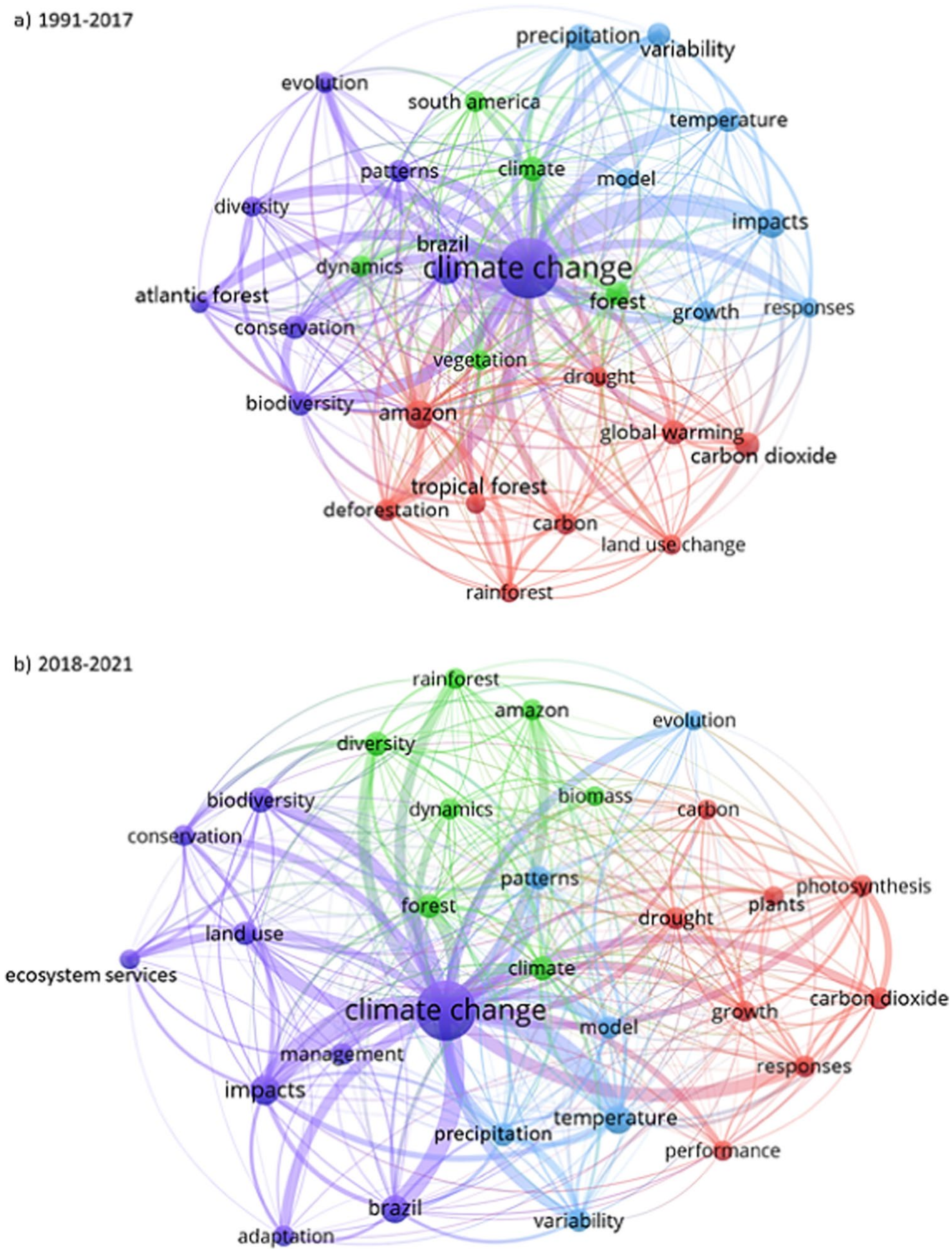


Fig. 4 Temporal evolution of the clustering for the co-occurrence of keywords for "climat* change", **a)** 1991–2017 (top—at least 25 repetitions) and **b)** 2018–2021 (bottom—at least 30 repetitions). Sources: Web of Science and Scielo Citation Index

among others), these studies strive to make climate science as robust as possible ("model", "variability") for the understanding of climate change and are usually performed for larger spatial scales than other clusters ("South America").

Figure 4 shows the temporal evolution of the keywords and clusters related to climate change database. The blue cluster showed a slight change, with "growth" and "responses" being replaced by "patterns" and "evolution". This suggests that the atmospheric sciences studies became more concerned with the temporal evolution of climate components (such as atmospheric variables or systems). The green cluster, concerned with ecological studies, initially showed a more continental scale focus ("South America") while later, such studies were more focused on the Amazon region and its connection to climate ("amazon", "rainforest"). Most of the ecological keywords such as "biomass" and "rainforest", initially present in other clusters, moved to the green cluster in the later years. This could indicate an increasing and interdisciplinary focus on the Amazon region in climate change research [15, 26, 29]. "Global warming" was excluded from the graph in recent years, as it got replaced by "climate change" both in academic research and mainstream media, since it represents a more complete and accurate description of the phenomenon. The keywords "drought", "carbon" and "carbon dioxide" kept on—demonstrating a steady focus on the carbon balance and drought episodes - which can affect nearly

Table 2 Clustering according to the country of origin of co-authorships, considering "climat* change"

Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Argentina	Austria	Australia	Belgium	Brazil
Bolivia	Czech Republic	Canada	India	USA
Chile	Denmark	England	Israel	
Colombia	Estonia	Ireland	New Zealand	
Costa Rica	Finland	Japan	South Africa	
Ecuador	France	China	Turkey	
Ghana	Germany	Philippines		
Kenya	Greece	South Korea		
Malaysia	Italy	Taiwan		
Mexico	Norway	Thailand		
Netherlands	Poland	Vietnam		
Panama	Portugal			
Peru	Romania			
Scotland	Russia			
Singapore	Spain			
Uruguay	Sweden			
Venezuela	Switzerland			
Wales				

Sources: Web of Science and Scielo Citation Index

all regions of Brazil. Recent studies were more focused on plant sciences ("photosynthesis", "plants"), demonstrating an important trend [27]. Finally, the purple cluster has become more attuned to interdisciplinary studies with the addition of "impacts", "adaptation" "land use" and "ecosystem services", which is quite relevant for successful climate adaptation strategies [24–29, 35]. The change in the top 10 keywords is available in Supplementary Information.

3.1.2 Origin of authorships—"climat* change"

The region of origin of authors is presented in Table 2 (international) and Fig. 5 (national). In Table 2, clusters were identified in VOS Viewer according to the most common international partnerships.

Although there are slight variations, cluster 1 is generally related to Latin American countries and cluster 2 is dominated by European countries. Asian countries prevail in cluster 3, cluster 4 has mixed "outliers" without a prevailing region, and cluster 5 is composed only of Brazil and USA.

Cluster 1 is the largest cluster, which demonstrates the relevant presence of many Latin American authorships, investigating issues related to conditions experimented in Latin America. However, Brazil's strongest association is with the USA. Cluster 2 is entirely made up of European countries and is the second largest cluster. It is interesting to note that countries were grouped by continent, so, we conclude that Brazilian research on climate change presents a high level of regionalization. Closer regions may experience similar impacts and therefore similar challenges when confronting climate change [7, 11, 22].

Figure 5 shows the regional distribution of authorships among Brazilian regions, which is important to understand the regional differences in Brazil (as explained in Sect. 2.2). Research on climate change is dominated by institutions from the Southeast and Northeast regions, which are the most populous regions in Brazil. While concerns in the Southeast are usually related to the increase in extreme precipitation events (due to the large urban population and its vulnerability), the Northeast is the driest region in Brazil, for which desertification has already been identified as an impact [36]. These regions concentrate more than 60% of the authorships in Brazil, but there are, in fact, institutions from all Brazilian regions. It demonstrates research partnerships and collaborations across the country. In fact, our analysis revealed that the top ten institutions with the most partnerships in this database were Brazilian (particularly federal institutions, which can be found in Supplementary information). Apart from the Amazon Forest, which has been a constant focus of research, there is a need to improve the representativeness of the less densely populated regions in Brazil.

Table 3 Classification of papers according to relevance for the climate adaptation scope used in this study

Relevance to climate adaptation	Description	N. of papers	Percentage (%)
1	Investigates a past, present or future issue in climate change adaptation within the scope of this study	57	37%
2	Focus on topics closely related to climate adaptation such as impacts, vulnerability or infrastructure	24	16%
3	There is a potential link to the adopted scope of climate adaptation	15	10%
4	Biological/genetic adaptation or other non-related topics	58	37%

Sources: Web of Science and Scielo Citation Index

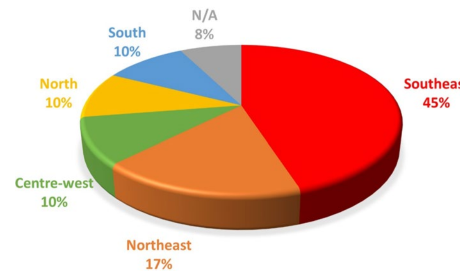


Fig. 5 Distribution of papers for "climat* change" per Brazilian region. SE: Southeast, NE: Northeast, CO: Centre-west, N: North, S: South, N/A: Non-Applicable. Sources: Web of Science and Scielo Citation Index

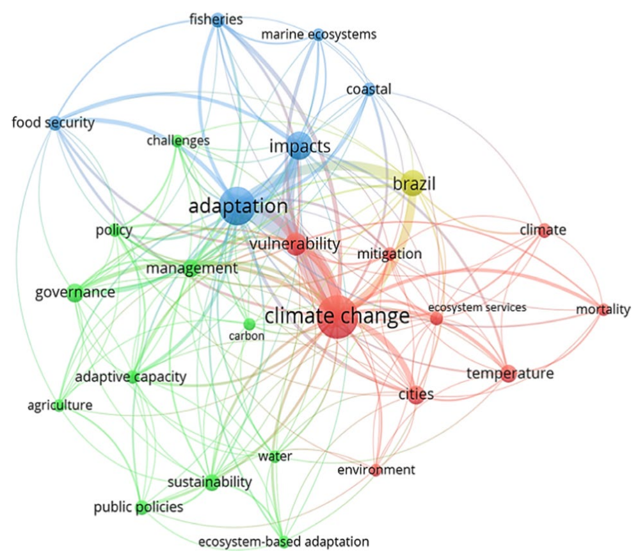


Fig. 6 Clustering of the co-occurrence of keywords with 4 repetitions or more for ""climat change" AND "adaptation"". Sources: Web of Science and Scielo Citation Index

3.2 Climate adaptation

As explained in Sect. 2.2 and shown in Table 3, we classified the climate adaptation studies in four categories of relevance according to the adopted definition of adaptation (Table 3) [3, 12]. Category 1 represents studies directly focused on climate adaptation actions, policies and case studies. In category 2, we grouped studies closely related to adaptation, such as vulnerability and infrastructure analyses. Category 3 was assigned for studies in which there is a potential link to our definition of climate adaptation, and category 4 for those clearly focused on biological adaptation.

Nearly a third of the papers (37%) were classified as category 4, and so, not included (Figs. 5, 6, 7, Tables 4 and 5). However, the same percentage of papers (37%) were classified as the highest relevance (category 1). A smaller percentage of studies were classified in the relevance 2 (16%), which are studies closely related to climate adaptation and an even smaller percentage of studies (10%) were not clear in their link to our definition of climate adaptation, but still hold

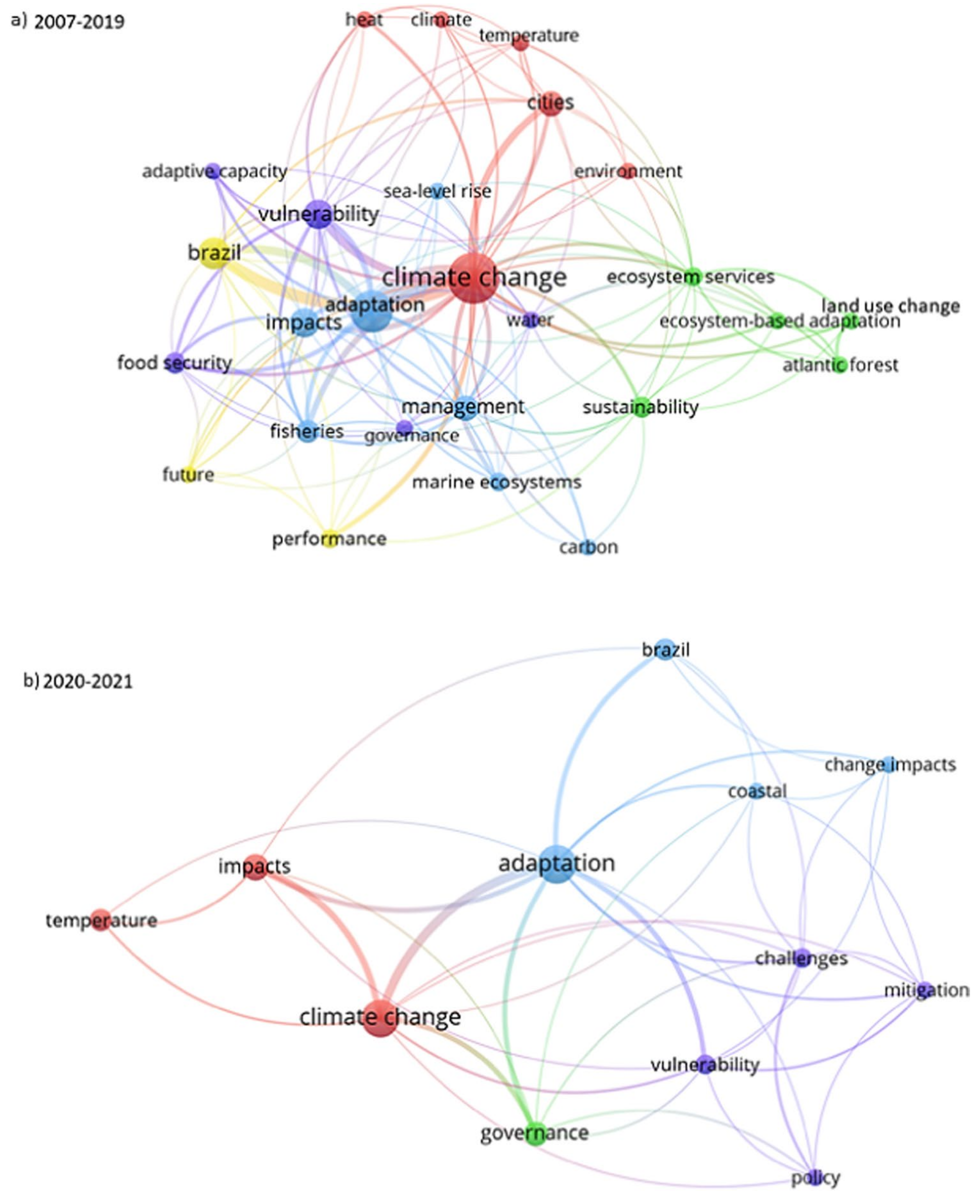


Fig. 7 Temporal evolution of the clustering for the co-occurrence of keywords with 3 repetitions or more for ""climat* change" AND "adaptation"", **a** 2007–2019 (top) and **b** 2020–2021 (bottom)

Table 4 Top ten keywords in ""climat* change" AND "adaptation"" publications and number of times used:

Keyword	Occurrences
Impacts	20
Brazil	18
Vulnerability	14
Cities	9
Governance	9
Management	8
Temperature	8
Sustainability	7
Climate	6
Fisheries	6

Sources: Web of Science and Scielo Citation Index

Table 5 Clustering according to the country of origin of co-authorships, considering ""climat* change" AND adaptation""

Cluster 1	Cluster 2	Cluster 3
Canada	Australia	Argentina
China	Brazil	France
Ireland	England	Germany
Italy	India	Mexico
Japan	Netherlands	
Spain	South Africa	
Sweden	USA	
Switzerland		

Sources: Web of Science and Scielo Citation Index

some potential (relevance 3). Given the smaller amount of adaptation papers retrieved compared to the broader climate change literature, we decided to keep relevance 3 studies in our analysis.

3.2.1 Keywords analysis—""climat* change" and "adaptation""

The same procedures (top ten keywords, cluster analysis, temporal evolution, and origin of authorships) were used to characterize scientific production on climate adaptation. Table 4 indicates that the same two keywords from the climate change analysis (Sect. 3.1.1)—"impacts" and "Brazil"—were also the most popular in climate adaptation. However, the remaining keywords show a much closer resemblance to what was found in cluster 3 from the cluster analysis of the climate string documents (purple cluster in Fig. 3). Thus, the most frequent keywords for climate adaptation are related to sustainability, management, and policy-related studies, such as "cities", "governance" and "sustainability". "Vulnerability" stands out as the 3rd most used keyword, which is clearly associated with the relevance 2 studies from Table 3.

Figure 6 shows the identified clusters for climate adaptation and the most frequently used keywords within them. Three main clusters were identified: (1) adaptation actions and policies; (2) urban environment, vulnerability and health and (3) food and coastal impacts (the keyword "Brazil" stood out from all clusters, as discussed below). Cluster 1, the largest (red in Fig. 6), is related to adaptation actions and policies, namely, strategies to improve climate adaptation and enhance societal and environmental resilience and quality of life. Management topics within this cluster can be identified by the keywords "policy", "management", "sustainability" and "challenges", by the proposition of policies, or their evaluation [31–33]. Some of the most popular strategies or focus areas for climate adaptation can be identified by the keywords "ecosystem-based adaptation", "water", "adaptative capacity" and "agriculture" [37]. This can be related to the relevance 1 studies from Table 3. Cluster 2 (red in Fig. 6), however, is more aligned with the urban environment, vulnerability, and health, thus, more aligned with relevance 2 studies in Table 3. The health concerns are evident from the keywords "mortality" and "vulnerability", while "cities" demonstrates a focus on urban environments. The keyword "climate change" is part of this cluster, showing that, in our database for climate adaptation, the overarching topic of climate change is more strongly related to the impacts and vulnerabilities than the institutional approach revealed in cluster 1 (red in Fig. 6).

The keywords "mitigation" and "ecosystem services" show that cluster 2 studies include strategies characterized by co-benefits (both for adaptation and mitigation, for instance) in the attenuation of climatic impacts, for example, via green infrastructure, urban greenery, etc. [37]. Cluster 3 (blue in Fig. 6) is smaller and focused on coastal impacts, possibly due to the threats posed by sea level rise, ocean acidification and impacts on marine ecosystems [38]. There is an evident concern with food production on coastal environments ("food security", "fisheries" [35]). This cluster also shows the keywords "impacts" and "adaptation", which demonstrate that even though there is a wide umbrella of scientific production concerning climate adaptation, there is a relevant trend in Brazil linked with coastal impacts. It is vital to study them, as more than 25% of Brazil's population lives on the coast, with many important cities of economic relevance, and the fact that coastal and ocean impacts are already taking place [22].

Still, there was less evidence of scientific production concerning climate adaptation for environments such as smaller cities, rural communities, and the Brazilian biomes (apart from the coast), including indigenous populations, which demonstrates a possible research gap in this area. It is also worth noting that "adaptation" was also a central keyword, strongly tied to all clusters (noticeable by its central position and line thickness to keywords of all clusters). The keyword "Brazil" (yellow in Fig. 6) was not part of any of the clusters in particular, but strongly connected with the main keywords "adaptation" and "climate change". This suggests that all clusters produce literature relevant to Brazil.

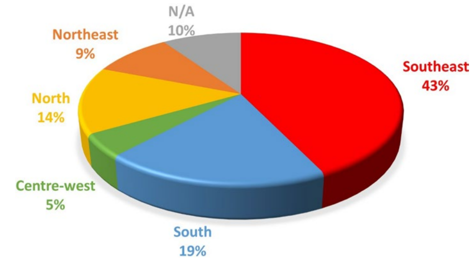


Fig. 8 Distribution of papers for ""climat* change" AND "adaptation"" per Brazilian regions. SE: Southeast, NE: Northeast, CO: Centre-west, N: North, S: South, N/A: Non-Applicable. Sources: Web of Science and Scielo Citation Index

The temporal evolution of keywords for climate adaptation is shown in Fig. 7. A few aspects can be highlighted, such as a steady tendency to study climatic adaptation for coastal locations in Brazil, such as in the work of Popova and collaborators [38]. The blue cluster in both periods suggests that initially the focus was on understanding the nature of impacts ("fisheries" and "marine ecosystems" in 2007–2019), and later, on understanding the change and evolution of impacts ("change impacts" in 2020–2021). The evolution of keywords in the purple cluster suggests a recent trend in the institutional aspects of climate adaptation, with the addition of keywords such as "policy" and "challenges", and interestingly enough, "mitigation", showing that there might be a recent trend in aligning mitigation and adaptation actions, which is a promising path forward [33]. "Water" and "food security" were not as present in the most recent studies (2020–2021), but "vulnerability" remained throughout the entire period, which is extremely important for adaptation planning across the Brazilian territory [39]. "Governance" as a separate keyword in the latter years indicates that not only this topic remained relevant through time, but also evenly distributed through all climate adaptation clusters in 2020–2021. This could reflect that the successful implementation of climate adaptation policies is heavily influenced by the interchange between different sectors of society [30, 39].

3.2.2 Origin of authorships—""climat* change" AND "adaptation""

Table 5 shows the distribution of authorships at the international level, and Fig. 8, at the national level, for climate adaptation. In the international scale, Brazil's scientific partnerships in climate adaptation is dominated by developed countries. There seems to be no pattern of regional division, as it was observed for the broader climate change literature (Table 2). The only Asian countries are in Cluster 1—Japan and China—and the remaining countries in this cluster are European. Cluster 3 has the only two Latin American countries apart from Brazil (Argentina and Mexico)—together with France and Germany. Cluster 2 is composed of different countries from different continents. Overall, the profile is rather different than the broader climate change literature, with a much smaller range of countries, no regional division and dominated by developed countries, and an absence of many Latin American and Asian countries present in the climate change research.

Concerning the national scale, our analysis indicates that 10 out of the 14 institutions with the largest number of co-authorships in climate adaptation are Brazilian, which indicates a scientific production representative of national-scale research. However, nearly two thirds (62%) are dominated by the Southeast and South regions, which are the most developed regions in Brazil. The rest presents low percentages (North 14%, Northeast, 9% and Centre-West, 5%). Climate adaptation is a relatively newer concept compared to the broader climate change field in Brazil (Figs. 2 and 4), therefore, it is expected that the richest regions will lead the scientific production in a new trend. However, it is important that institutions from more rural and less developed regions in Brazil adopt climate adaptation as a priority for research, considering that they are home to Brazil's endangered biomes, such as the Amazon Forest, the Caatinga (semi-arid zone) and the Cerrado (Brazilian savannah), as well as indigenous and other vulnerable population groups [39].

There are a few limitations to consider when interpreting the results of this work. Firstly, the institutional distinction: this project was part of a larger project evaluating the dissemination of scientific knowledge of a specific university, though, by the considerable cross-country academic collaborations, it can provide a trustable proxy for the most recent research trends in Brazil. Another point to consider is related to the keywords and indexation processes. A few articles relevant to climate change and climate adaptation may have not been captured if they did not use 'climat* change' in their indexing fields (title, abstract or keywords), particularly if coming from more specialized research fields (which usually do not employ interdisciplinary approaches or keywords). These gaps may be filled by future research outlines.

4 Conclusions and final remarks

We performed a bibliometric and bibliographic review of climate change and climate adaptation research performed in Brazil. Four main clusters of investigation within climate change were detected: (1) impacts on forest and plant development, (2) land use and ecology, (3) adaptation/governance, and (4) climate/atmospheric studies. The cluster analysis highlighted the importance of the human dimensions of climate change. This suggests that, although there is robust scientific research about the socioenvironmental and climate-related problems faced by Brazil (human-induced fires, vulnerability, extreme precipitation events, etc.), there is still a lack of effective actions from the Brazilian authorities. In fact, this complicated context might have propelled scientific production on climate change, as observed in the increase in studies after 2019, a year with record-breaking fires in the Amazon Forest (Fig. 2).

The co-authorship analysis by country showed a high degree of regionalization and important partnerships with many Latin American, European and Asian countries, and a relevant collaboration between Brazil and the USA. The Brazilian region of origin of co-authorships revealed a predominance of research developed at the most densely populated regions, such as the coast and the larger cities. This is clearly relevant due to the million inhabitants of these regions, however, apart from the Amazon Forest, there seem to be fewer studies on climate change for the less densely populated regions and communities.

Climate adaptation studies comprised only about 5% of the total studies. This indicates a need to increase interest in this topic, as climate adaptation actions can also help to mitigate social and environmental inequalities. Three main clusters were identified: (1) evaluation or proposition of climate adaptation actions and policies; (2) urban environment, vulnerability and health and (3) food and coastal impacts. Governance and vulnerability seemed to be themes of constant interest through the entire period, and recent trends indicates a rising concern in the institutional aspects of climate adaptation. As adaptation tend to be more local in scope, we hope that such studies can form a basis for relevant, science-informed municipal climatic plans and actions which also encompass adaptation.

The cluster and keywords analysis for climate adaptation revealed less evidence of scientific production concerning climate adaptation for small and medium-sized cities, rural communities and the various Brazilian biomes, including indigenous populations, which demonstrates a possible research gap in this area. This was reinforced by the co-authorships analysis, which showed the predominant role of co-authors from the richest regions of the country and the urgent need to engage with research institutions from the less developed regions of Brazil. The international partnerships revealed that Brazil's scientific collaborations in climate adaptation are dominated by developed countries, which could be a vector for funding and development. This is particularly relevant at the present moment, when Brazil is going through a promising political transition, bringing international attention to the country as a global player in the geopolitical and environmental arena, with the hosting the 2025 edition of the Conference of the Parties (COP). Hopefully, national climate science development will keep up and play an ever-increasingly important role in facing the country's challenges and drivers of climate change.

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Data availability The datasets generated during and/or analysed during the current study are available in the CAPES Periódicos repository, under the "Web of Science" and "Scielo Citation Index" databases: https://www-periodicos-capes-gov-br.ezl.periodicos.capes.gov.br/index.php/acervo/lista-a-z-bases.html. We uploaded the basic spreadsheet in figshare: https://doi.org/10.6084/m9.figshare.25325788.v1.

Code availability Authors declare the use of VOS Viewer software https://www.vosviewer.com/.

Declarations

Competing interests The authors declare no competing interests.

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