remote sensing

Review

Bibliometric Analysis of the Permafrost Research: Developments, Impacts, and Trends

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Abstract: Permafrost is a significant part of the cryosphere, which has gained increasing attention from scientists, policy-makers, and the general public due to global warming, environmental degradation, water shortages, and intense human activities. Although many permafrost research review articles have been published, these studies were predominantly limited to either one subject or one field, while systematic studies about permafrost based on bibliometric analysis methods remain limited. We aim to fill this gap by conducting a bibliometric analysis of 13,697 articles in the field of permafrost research from 1942 to 2021, collected from the Web of Science core collection database. The results indicate that permafrost research is a typically multi-author, multi-country, and multi-institution cooperative field, involved in many research fields. The cumulative number of publications has presented an exponential increase over the past 80 years, with an average annual growth rate of 10.40%. Since 2000, China has seen a rapid growth in the number of publications per year, surpassing the USA in 2016 and leading in the years since then. In addition, the authors from China have great contributions in publications, and there is good room for permafrost development in the future according to the authors' M-index ranking. After the analysis of authors' keywords, we found that, compared to the conventional methods, machine learning and interferometric synthetic aperture radar (InSAR) are new technological approaches introduced in recent years, and the Qinghai–Tibet Plateau has become a popular study area. The results presented here can help related researchers, scholars, and students in the field to better understand the past developments, current status, and future trends of permafrost research. Furthermore, this paper presents and expands the general process of the bibliometric method used in permafrost studies, which can provide researchers with new inspirations and improve discipline research approach.

Keywords: bibliometrics; permafrost; cryosphere; bibliometric analysis; knowledge map; web of science

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1. Introduction

Frozen ground or frozen soils refer to rock or soil containing ice at or below the temperature of 0 °C [1–4]. Rock layers with temperatures at or below 0 °C for at least two consecutive years are called permafrost [2–8], one of the most significant components of the cryosphere [3]. The global area of permafrost (excluding permafrost beneath the ice caps) is 1.32–1.80 × 10^7 km^2, mainly in the Northern Hemisphere [2,3]. Specifically, this includes more than half of the land area of Russia (65%), almost half of the land area of Canada (49%), 22% of China, and 85% of Alaska in the U.S. [2,4]. The glacier-free areas of Antarctica and Greenland are both permafrost zones [3]. In addition, permafrost is also found in the high-altitude mountains of South America, Central Asia, and Europe, as well as on the summit of Kilimanjaro in Africa, in Hawaii, and at the Earth's equator [2–4,9,10]. Thus, permafrost is a widespread phenomenon in the natural landscape.

In recent years, with global warming, scientists, government policy-makers, and the general public have become more and more concerned about climate change. The cryosphere is the most sensitive part of the climate system (including another four parts, i.e., the atmosphere, hydrosphere, biosphere, and lithosphere), and changes in it have implications for global and regional climate, ecology, and human well-being [3]. As one of the key components of the cryosphere, permafrost is sensitive to climate change, acting as both an indicator and amplifier of climate change [11–13]. An Intergovernmental Panel on Climate Change (IPCC) assessment report has stated that, since the 1980s, the temperatures of permafrost have increased by 2 °C; the active layer thickness in east Siberia has increased by 25 cm since 2005; the southern boundary of permafrost in the Northern Hemisphere has shifted northwards, and the thickness of seasonal permafrost has decreased by 32 cm since the 1930s [3,7,14]. The freeze–thaw process in permafrost affects soil moisture content, vegetation, and ecosystems; freeze-swelling and thawing can damage ground infrastructure; when the climate warms, the melting of permafrost may release large amounts of greenhouse gases such as carbon dioxide and methane, contributing to global warming [2–4,14]. Micro-organisms long latent in permafrost may also recover from dormancy due to permafrost degradation, increasing public health and safety risks, such as epidemics or heavy metal contamination [15–18]. It is because of this social importance of permafrost and its changes that research on permafrost has become increasingly prevalent, which is now in the foreground of geosciences research [19,20].

To date, although there have been many review articles focused on permafrost research, these studies were mainly limited to a certain theme, a certain field, or a certain region, and there are relatively few systematic reviews on permafrost research. In detail, Hugh French reviewed the literatures issued in the interval from 2002 to 2007, focusing on the previous existence of permafrost (past permafrost) that was generated during the cold geological periods of the Pleistocene in the northern mid-latitude and alpine-cold regions [21]. The results suggested that the knowledge of past permafrost primarily resulted from a further understanding of both present permafrost and relict permafrost, coupled with the continued application of increasingly sophisticated modelling and Quaternary dating techniques [21]. Abramov et al. have reviewed the current understanding regarding the time–temperature history records and age characteristics of permafrost, correlation with the available microbiological, and related metagenomic dataset and information [22]. Furthermore, the impact of global warming on permafrost micro-organisms and the changes in their functional roles have been reviewed by Jansson and Tas [23]. There have been some reviews considering permafrost hydrogeology [24–30], all of which were mainly concerned with the degeneration of permafrost resulting from climate change [14–16,18,31–33]. Studies have described the research advances in permafrost modelling in detail [11,34–38].

Bibliometric methods are useful for scientific literature analyses based on bibliographic data from online data sets [39,40]. A bibliometric analysis conducted on the basis of such data allows for a scientific study and a comprehensive view of the area of scientific investigation [39] and has been widely used in many disciplines and research areas [39,41], such as remote sensing [42–46], big data and cloud computing [47,48], ecological environment [40,49–54], habitat environment and health [51,55,56], crops [57], tsunamis [58], earthquakes [59], and so on. Bibliometrics has been defined as "the application of mathematical and statistical methods to articles, books, and other media of knowledge semination" [40,45], as first proposed by Pritchard in 1969 [60]. Bibliometrics provides powerful tools for analyzing the development of scientific research, based on quantifying information collected from online scientific citation databases related to specific research topics and objects, including information on the number of authors, documents, types of publications, and the distribution of research institutions in the field [46]. In addition, bibliometrics can identify the important studies related to a research object; provide keywords, institutional or national linkages, and distribution characteristics via an intuitive knowledge map; explore the past development and evolution; quantify the current status; and identify the future trends and hotspots of a research topic [40,41]. The notable advantage of literature reviews based on bibliometrics approaches, compared to those derived from traditional paper-reading methods, is the clustering and quantitative analysis of the references, thus allowing the researcher to mine more potential information [46,61,62]. In general, the more references contained in a literature collection for bibliometric analysis, the better and deeper an understanding of the study field we can obtain [40,46,62]. Table 1 lists previous review studies on permafrost that have used bibliometric or related research methods. Although similar and homologous analysis approaches [60–64] have been adopted, the exact research themes and time frame of these studies differed significantly. Specifically, the research was limited to one study element, one field, or one region, and review papers that provide a systematic and comprehensive bibliometrics analysis on the permafrost literature over the entire time period are relatively scarce.

Table 1. List of the previous bibliometric studies related to permafrost.

References	Methodology	Field
Jeffery et al., 2016. [65]	Meta-analysis	Methane emissions
Vonk et al., 2015. [66]	Meta-analysis	Organic carbon
Masyagina and Menyailo, 2020. [67]	Meta-analysis	Carbon dioxide and methane fluxes
Palmtag and Kuhry. [68]	Meta-analysis	Soil organic carbon
Ren et al., 2020. [69]	Meta-analysis	Soil C release
Bordignon, 2020. [20]	Lexicometric analysis	Permafrost
Sjöberg et al., 2020. [70]	Bibliometric	Permafrost
Qin et al., 2021. [71]	Bibliometric	Distributed hydrological models—visual
Li et al., 2019. [72]	Bibliometric	Frozen soil (permafrost)
Jiang et al., 2022. [73]	Bibliometric	Permafrost micro-organisms
Gu et al., 2021. [74]	Bibliometric	Arctic environment
This paper	Bibliometric and scientometrics	Permafrost

Based on the aforementioned descriptions, we collected the literature related to permafrost from the online Web of Science (WoS) Core Collection databases, in order to summarize and analyze the related developments, impacts, and trends by applying the traditional literature-reading method and bibliometric analysis. This paper aims to provide researchers with a good reference and understanding of permafrost research, with respect to the historical progress, current status, and future directions and study hotspots.

To attained the research purpose, we introduced the following three questions [20]:

Q1. What is the worldwide past development, current status, and future trend of issued scientific publications of permafrost?

Q2. What core and worthy information can be uncovered from this prophase development, present influence, and tomorrow's trend?

Q3. How will permafrost research develop in the future and what is the development direction and hotspots?

The specific contents and steps of this study are as follows:

(1) We process bibliometric information of 13,679 papers on the topic of permafrost, collected and filtered from the WoS Core Collection databases;

(2) We convert the format of and quantitatively analyze the refined papers, based on the R language, the bibliometrix R-package (https://www.bibliometrix.org/home/, accessed on 20 December 2022), and the interactive biblioshiny web interface app

(https://www.bibliometrix.org/home/index.php/layout/biblioshiny, accessed on 20 December 2022);

(3) We extract the research area information of processed documents; create science overlay maps based on the global map of science, which were collected and produced from the aggregated journal citation data in 2015 [75,76]; and quantitatively analyze their characteristics and trends;

(4) We identify the core countries, central institutions, leading authors, predominant journals, and guiding documents in permafrost research, according to the total citations, publications, h-index, and co-citation network;

(5) We clarify historical and current research hotspots and estimate future focuses and directions based on a keyword analysis.

The remainder of this paper is organized as follows: Section 2 introduces the literature collection and related methodologies used in this paper. Section 3 presents the results, including bibliometric information extracted from the document data set; research category classification and analysis; the current influence rankings by country, institution, author, source, and publication; and historical and future development trends. In Section 4, we discuss the results obtained in Section 3, as well as the advantages and limitations of this article. Finally, we provide our conclusions in Section 5.

2. Literature Collection and Methods

2.1. Data Collection and Search Strategy

WoS is a multidisciplinary literature database that includes three major citation databases—the science citation index (SCI) database, the social sciences citation index (SSCI) database, and the arts and humanities citation index (AandHCI) database—two fact-based databases of chemical information—current chemical reactions (CCR) database and the Index Chemicus (IC) database—three extra and significant databases—the science citation index, expanded (SCIE) database, and the conference proceedings citation indices for the science (CPCI-S) database and the social sciences and humanities (CPCI-SSH) database [45,46]. It utilizes the Institute for Scientific Information (ISI) Web of Knowledge as the retrieval platform. The WoS core collection is the world's leading citation database (part of ISI WoS). It contains records of publications from the highest impact journals all over the world, including open-access journal papers, conference proceedings, abstracts, and books. Coverage of some information of titles dates back to the early 1900s (although coverage will depend on a particular institution's subscription depth) [77,78].

For this paper, we set the topic keyword as "permafrost" and the search database as the "WoS core collection", which comprises five citation databases: SCIE (1900–present), CPCI-S (1991–present), CPCI-SSH (1991–present), CCR (1991–present), and IC (1993–present). As the default WoS search is case-insensitive, only the topic search term "permafrost" was needed to retrieve the relevant results, and a total of 14,677 relevant papers were retrieved (accessed on 30 September 2022). The deadline for this study was 30 December 2021, as the literature for 2022 was not fully collected, and all records were exported to plain-text format files with the record content "full record and cited references" [40]. This was further refined by setting the literature publishing cut-off date (2021) in the bibliometric analysis software, and a total of 13,697 publications were obtained for the bibliometric analysis.

2.2. Bibliometric Analysis

The tools used in this paper include the R language platform (version 4.2.1) [79], the bibliometrix R-package [80–82] (version 4.0.2), the biblioshiny web app [40], and the VOSviewer software (version 1.6.18) [83], all of which are free and open-source. The bibliometrix R-package is dependent on the R language tool and can be used to analyze literature through code commands or a web visualization interface (biblioshiny) app. VOSviewer is a Java-based powerful software for constructing and visualizing bibliometrics oriented to document data and can be used to construct and visualize co-occurrence networks, overlay visualizations, and density visualizations of the important terms extracted from a body of scientific literature [84,85].

The literature bibliometric analysis consisted of five main steps (Figure 1). First, the study-design part consisted of identifying the study topic; posing research questions; and clarifying the search strategy, formula or expression and database scope for document collection, which is needed to export data with a complete and effective format record. Then, the exported data sets, including full records and cited references, were converted into bibliometrix R-Data format [40], such that bibliometrix could recognize and conduct the data loading and conversion step, which is mainly carried out using the bibliometrix R-package or the web-based interactive biblioshiny platform. The third data analysis step is the further processing of the data already converted in the previous step, including a qualitative description of the overall literature data sets and a quantitative analysis process, which includes normalization, document × attribute matrix creation, data reduction (e.g., principal component analysis, PCA; multi-dimensional scaling, MDS; correspondence analysis, CA; multiple correspondence analysis (MCA); clustering; and so on), and network matrix creation (e.g., bibliographic coupling, co-citation, collaboration, co-occurrence, historiographic analysis, and so on) [82]. The result visualization step was conducted using R (tidyverse and ggplot2 packages), biblioshiny, VOSviewer, OriginLab, Excel, and others. The visualization methods included network maps, histograms, statistical tables, and so on. After the above four steps were conducted, the bibliometric analysis was completed, combining relevant literature, summaries, and interpretations in the final step, and relevant characteristics and conclusions could be drawn regarding permafrost research, such as historical development, current status, future trends, and so on. The results and interpretations of the literature analysis are detailed in Section 3.

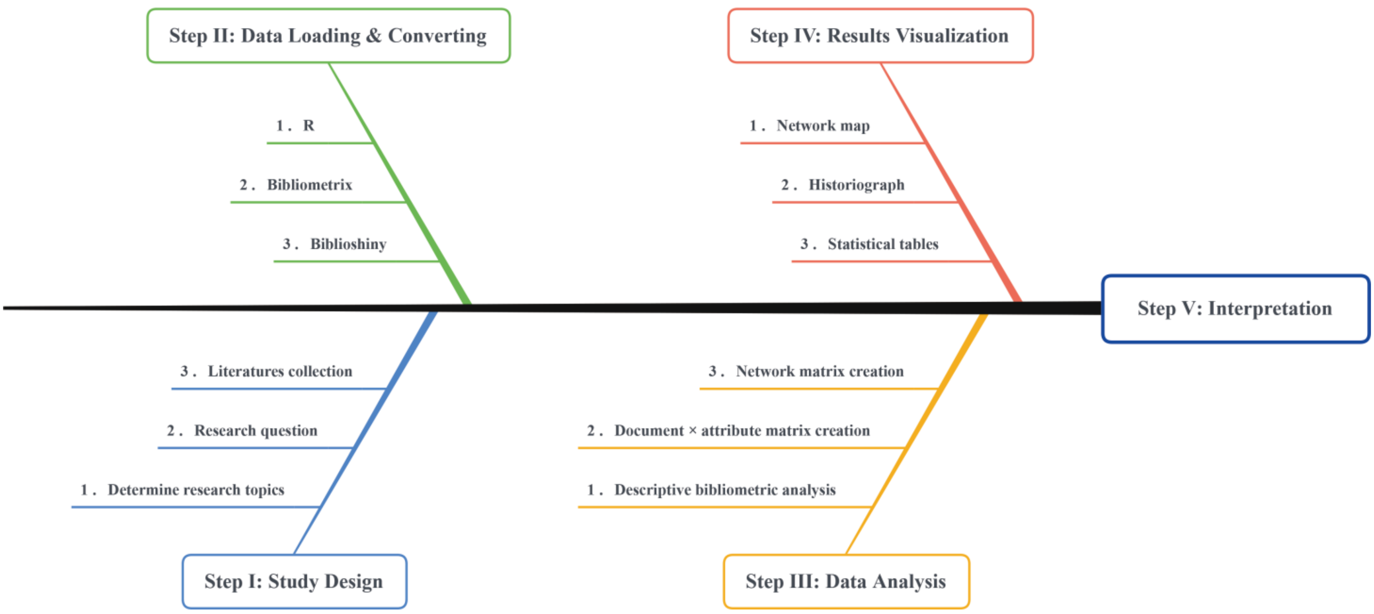

Figure 1. Schematic diagram and main steps of bibliometric analysis method, adapted with permission from publications [39,40,81,82]. Copyright 2017, Aria and Cuccurullo; copyright 2019, Firdaus et al.; copyright 2020, Secinaro et al.; and copyright 2022, Xu et al.

3. Results

3.1. Overall Bibliometric Descriptive Analysis

Figure 2 shows the 13,697 scientific publications related to permafrost research published from 1942 to 2021, which is useful to understand the basic and overall characteristics. The earliest record of permafrost research available in the WoS core collection database was the weekly reports of the sessions of the Academy of Science (Comptes rendus hebdomadaires des seances de l'academie des sciences 215, Jul–Dec 1942) of Demangeot in

1942 [86], entitled "The discovery of a permafrost in relation to a reticulated soil in Oisans", published in French. Unfortunately, the authors were not able to locate and read this document, and the record of its inclusion only contains the title, author, journal, document type, and publishing date, with all other relevant information being difficult to trace. However, it is the first record of permafrost research and, thus, is of great significance.

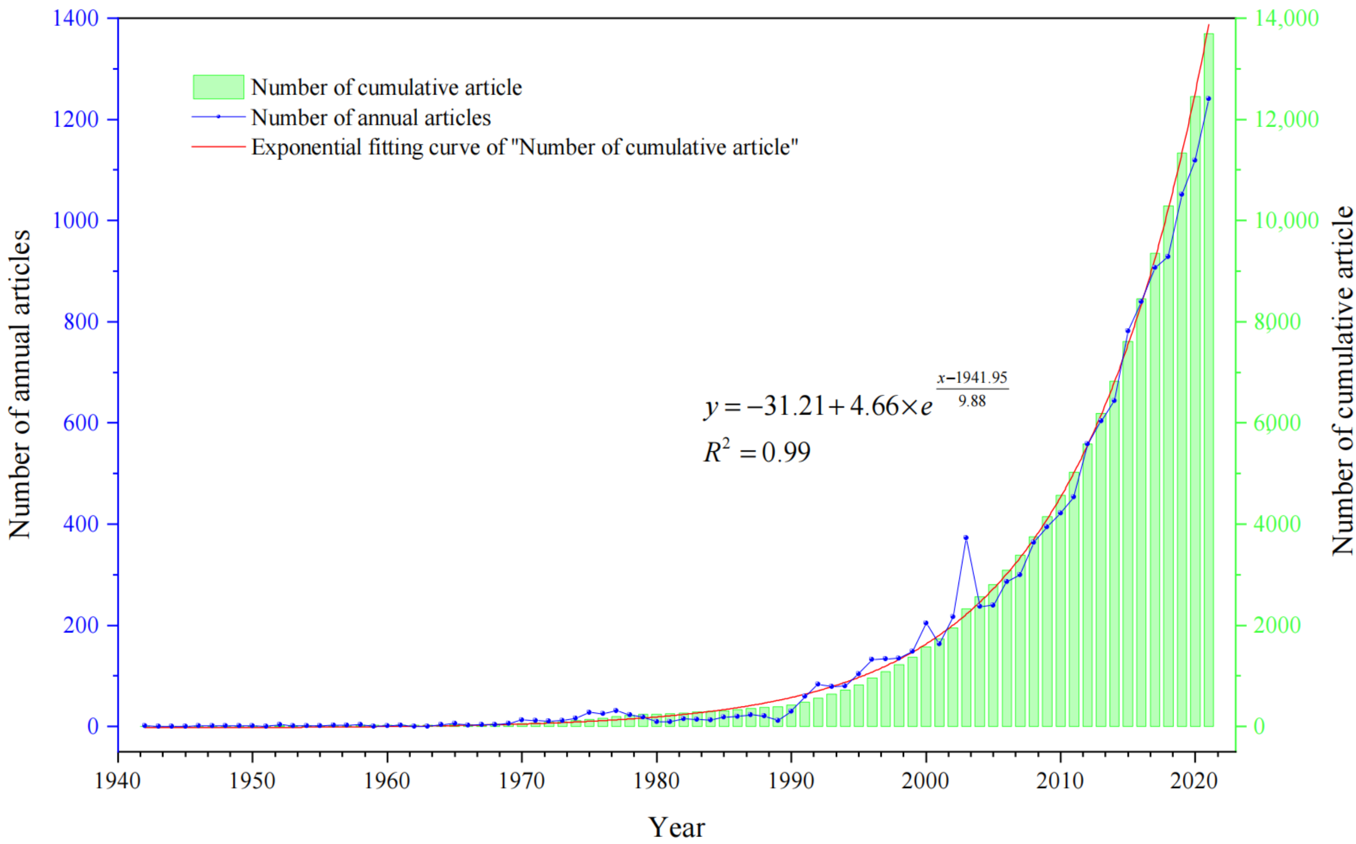

Figure 2. Number of articles issued per year (blue curve with dot) and cumulative number of articles issued (green histogram) from 1942 to 2021. Red curve presents the exponential fitting based on cumulative publications.

Further analyzing Figure 2, we found that no relevant literature was recorded in the next three years (from 1943 to 1945). In addition, no literature related to permafrost research was included in 1951, 1962, and 1963. Up to 1969, the cumulative number of publications was only 48, with an annual maximum of six and a general publication rate of one per year. Between 1970 and 1989, the number of publications exceeded ten in all years (except for 1980 and 1981, both of which had nine articles). There was a small increase in the number of publications during the four years from 1975 to 1978, with 28, 25, 31, and 23 articles, respectively. By 1989, the cumulative number of publications had reached 387, and the average annual growth rate for the interval from 1969 to 1989 was 16 publications per year.

After 1990, the annual number of publications increased significantly, from 30 in 1990 to 1241 in 2021 (an increase of more than 41 times), with an average annual number of 413. Overall, the cumulative number of publications from 1942 to 2021 increased exponentially over time (Figure 2), with an average annual growth rate of 10.40%. The exponential fitting formula is as follows, with the coefficient of determination (R^2) of 0.99.

$$y = -31.21 + 4.66 \times e^{\frac{x-1941.95}{9.88}} \tag{1}$$

where y is the number of cumulative papers, and x presents the year of publication.

Especially as for the publications of each year, it is worth noting that there was a surge in the number of publications in 2003, followed by a drop to an average level in 2004. Concretely, the total number of publications in 2002, 2003, and 2004 were 268, 454, and 242, respectively. A literature survey revealed that the reason for this sudden increase was the successful holding of the 8th International Conference on Permafrost in Zürich, Switzerland, 21–25 July 2003 (https://www.permafrost.org/event/icop8/, accessed on 20 December 2022). To better spread knowledge and expand impact, all the papers from this conference were included in a special issue of Permafrost and Periglacial Processes (Volume 15, Issue 3) titled the nature and dynamics of mountain permafrost.

Table 2 shows the key information for the 13,697 documents on permafrost studies from 1942 to 2021, obtained from the bibliometrics analysis summary. Among all the collected publications, articles (including journal articles, book chapters, data papers, etc.) accounted for the largest share with 82.31%. It is followed by proceedings papers, accounting for 11.08%. The total number of the review publications is 478, with the rate at 3.49. Other types of literature, such as abstracts of published items, biographical items, discussions, editorial material, letters, meeting abstracts, news items, and notes, accounted for less than 3.12%.

Table 2. Main information about the collected literature obtained from the bibliometric analysis.

Elements	Description	Results
Timespan	A period with the min and max published year of the literatures	1942 to 2021
Documents	The total number of the literature collected	13,697
Sources	Statistical frequency distribution of literature sources (e.g., journals, books)	1910
References	The total number of references cited from the literature collection	294,686
Author's Keywords (DE)	The total number of the keywords obtained from the literature	19,139
Keywords Plus (ID)	Total number of phrases frequently appearing in document titles	13,636
Authors	The total number of authors in the analyzed literature data set	27,785
Authors Appearances	The frequency distribution of authors	69,678
Authors of single-authored documents	The number of authors for single-authored articles	920
Authors of multi-authored documents	The number of authors for multi-authored articles	26,865
Single-authored documents	The total number of documents with a single author	1325
Co-Authors per Documents	Average number of co-authors in each document	5.09
Average citations per article	Average number of citations in each article	30.06
Collaboration Index	The mean number of authors per joint paper	2.17

According to the statistical parameters in Table 2, over the past 80 years, the average annual number of publications was 171, with an average of 30.06 citations per paper. This body of literature involved a total of 27,785 authors, 26,865 authors in the multi-authored documents and 1325 single-author papers. For all publications, on average, each article involved two authors (2.03), while for the multi-authored papers, five (5.09) authors were contained in each publication. The collaborative index is the mean number of authors per joint authored paper, calculated as the total number of authors of multi-authored articles divided by the total number of multi-authored articles [39,40,87], which was 2.17, which indicates that the permafrost study is a typically multi-author cooperative field. In addition, the papers generated a total number of 19,139 author keywords (DE) and 13,636 keywords plus (ID), which is the number of keywords that frequently appear in an article's title [39].

3.2. Characteristics of Research Categories

The WoS research areas specified by Clarivate Analytics are used to classify papers for research [40,49]. In the WoS database, each paper can be classified into at least one research area, with a total of about 252 subjects, including science, social sciences, and arts and humanities [48]. The articles on permafrost research obtained in this study were contained in a total of 96 categories, with the number of research areas ranging from one in 1942 to 61 in 2021 (Figure 3a), with a linear increase rate (at 0.788). The top 15 most productive research fields were geology (6281), environmental science and ecology (3488), physical geography (2613), engineering (2379), meteorology and atmospheric science (1185), water resources (954), agriculture (652), science and technology—other topics (625), geochemistry and geophysics (616), microbiology (504), remote sensing (504), energy and fuels (403), imaging science and photographic technology (344), biodiversity and conservation (231), and astronomy and astrophysics (222). The top 15 research fields contained 12,922 papers, accounting for 94.34% of the total (13,697 papers). The main top five research areas represented 10,398 of the 13,697 documents, accounting for approximately 75.91% of the total, with more than 1000 publications in each of them.

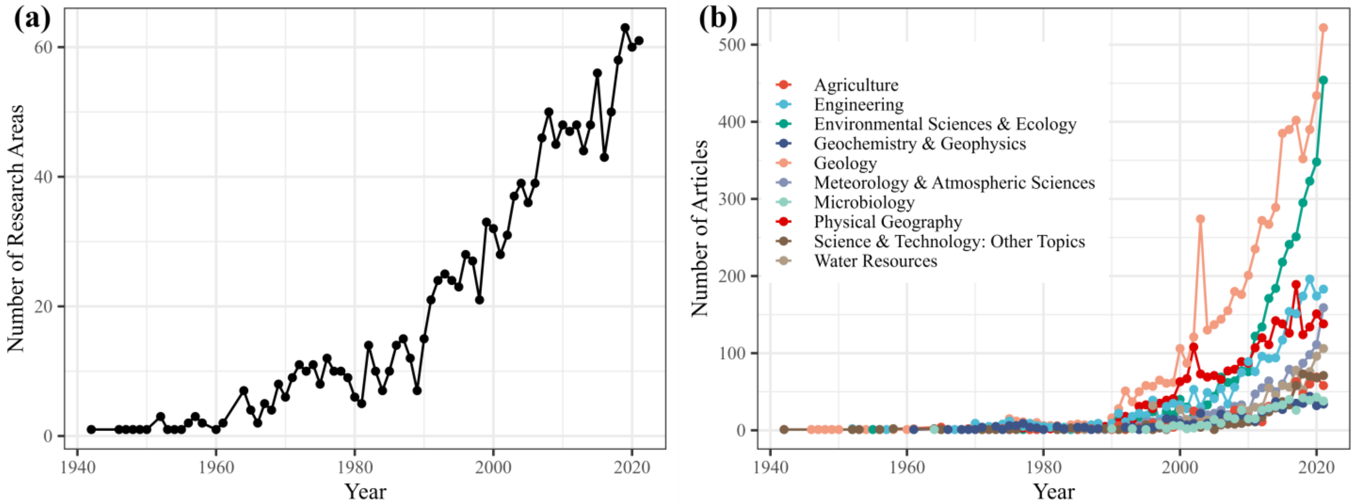

Figure 3. Features of WoS research areas for permafrost-related publications: (**a**) number of WoS research areas by year and (**b**) the temporal evolution of the top 15 most-productive WoS research areas.

Figure 3b shows the change in the focus areas (top 15 publications) of permafrost research over the years. The first papers published in 1942 belonged to science and technology: other topics, after which, until 1990, the number of publications in each category was relatively small and mostly concentrated in geology, although the number of research areas slowly increased. After 1990, the number of publications in each of these fields increased significantly, with geology, environmental sciences and ecology, physical geography, engineering, meteorology and atmospheric sciences, and water resources being the most obvious. These research areas are closely related to the improvement of monitoring technology, the maturity of the theory, the development of computer and remote sensing technologies, and concern for environmental issues.

In order to display the information of research field more intuitively, the overlay map of research field on the basis of a global map of science, which is made based on the aggregated journal citation data collected by WoS in 2015 (http://leydesdorff.net/wc15/, accessed on 9 November 2022) [75,76]. More specifically, its purpose is to classify the given articles to the set of WoS, which divides all the WoS research areas into five main categories, including Biology and Medicine, Chemistry and Physics, Ecology and Environmental Science and Technology, Engineering and Mathematics, and Psychology and Social Sciences. After the superposition analysis, overlay information was created on the ground of the network with a suitable basemap. The result is shown in Figure 4.

As shown in Figure 4, most studies on permafrost are focused on Ecology and Environmental Science and Technology, Engineering and Mathematics, and Biology and Medicine categories but less on Psychology and Social Science. Concretely, for Ecology and Environmental science and Technology, most papers focus on geology, engineering, environmental, remote sensing, oceanography, forestry, ecology, plant sciences, and evolutionary biology; for Engineering and Mathematics, publications mainly belong to engineering, aerospace, computer science, artificial intelligence, mathematics, computer science, interdisciplinary applications, and multidisciplinary engineering fields; for Biology and Medicine, the related papers are mainly distributed in agriculture, dairy and animal science, cell biology, mycology, toxicology, and immunology. With the attention paid to the cultural landscape in permafrost regions in recent years, a breakthrough is expected in the Psychology and Social Science regard.

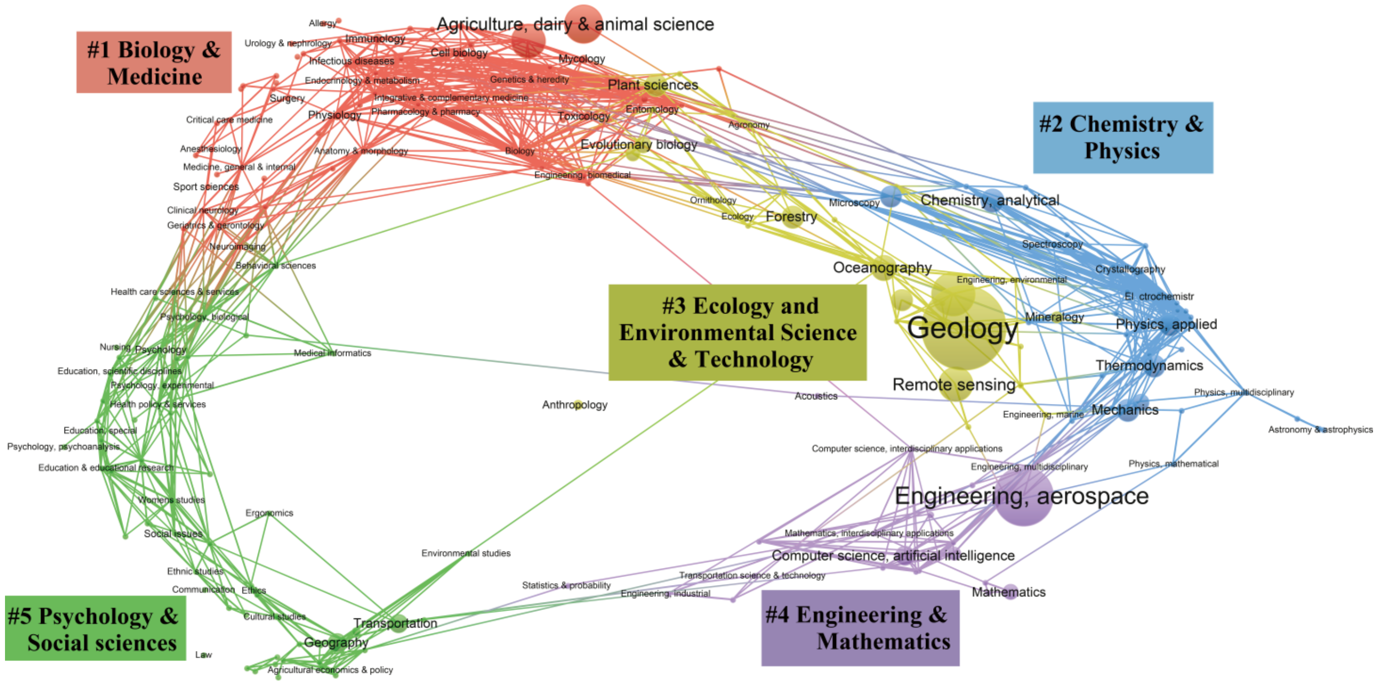

Figure 4. Superposition analysis of the distribution of the research fields of permafrost according to the aggregated journal citation data in 2015. Different colors represent different research categories, five in total, including Biology and Medicine, Chemistry and Physics, Ecology and Environmental Science and Technology, Engineering and Mathematics, and Psychology and Social Sciences.

3.3. Impacts

3.3.1. The Impacts of Countries

The detailed address information of the first author's organization in each publication was used to extract the state and regional information regarding each article, and all documents were categorized by country and region. Due to the absence of information about the first author's institution in some documents, name changes of countries, and the imperfection of the semantic segmentation algorithm [40], there were some documents with undetected country or region geographical information, for which we performed a removal process and ignored. Except for the 571 publications with missing state information, the remaining 13,126 articles were categorized into 108 countries and regions, indicating that permafrost research has been conducted in 108 countries or regions from 1942 to 2021.

The cumulative number of publications [45] or the total number of publications (as of 31 December, 2021) is an important indicator of a country's scientific strength in a research area. The top 10 countries, in terms of cumulative publications on permafrost, were the USA (2688), China (2449), Canada (1759), Russia (1522), Germany (813), the UK (496), France (376), Switzerland (360), Japan (306), and Sweden (286). Information on their annual number of publications is shown in Figure 5a. Since 2000, the number of publications per year in China has grown rapidly, surpassing the USA in 2016 and taking a lead in the years since. Furthermore, the proportion of the numbers of papers issued per year to the total numbers of articles issued in a contemporaneous period was calculated for the particular four countries (the USA, China, Canada, and Russia) with cumulative number of articles over 1000, and the results are shown in Figure 5b. The results indicate that, since 1992, the share of China's annual issuance has been increasing annually, accounting for

29.90% of the total issuances in 2021, while the other three countries (the USA, Canada, and Russia) showed decreasing trends after 2000. Additionally, we calculated the total number of citations for papers published in each country and picked the largest top ten countries, which were used as reference to analyze the influence of country, combined with the total number of articles (including individual and collaborative publications) and the average number of citations. The results are revealed in Figure 6.

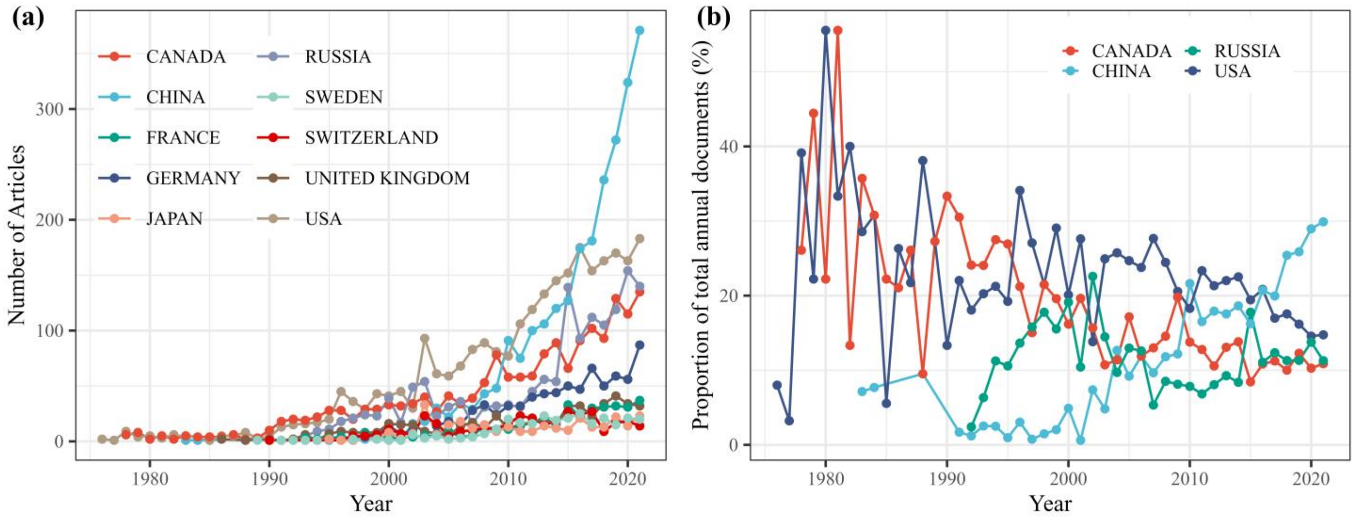

Figure 5. Statistical information about permafrost publications by country: (**a**) annual scientific production of the top ten countries and (**b**) annual proportions of the countries with a cumulative number of documents over 1000.

According to the total citations of all permafrost-related publications classified by country (Figure 6c), to date, the U.S. has had the highest number of citations of all countries (136,779), followed by Canada (56,400), China (46,944), Germany (28,037), Switzerland (20,469), United Kingdom (18,327), Russia (13,945), Sweden (13,085), France (11,521), and Norway (8778). In terms of average article citations (Figure 6b), the differences between the top ten countries were smaller for the other eight countries, except for Russia and China. Switzerland had the highest average number of citations (56.86), followed by the USA (50.89), Sweden (45.75), the UK (36.95), Germany (34.49), Canada (32.06), Norway (31.24), France (30.64), China (19.17), and Russia (9.16). Combined with the corresponding total number of publications (Figure 6a), we found that, although China has a higher total number of citations, the average number of citations was significantly lower than that of other countries due to the large number of papers and the low quality of many of them; a similar situation was also observed in Russia.

In addition, the top ten countries, in terms of the number of papers published (descriptions in the second paragraph) and in terms of total citations, did not exactly coincide. For example, Japan was ranked ninth among all countries with 306 total publications, but was not ranked in the top ten due to a small number of total citations, indicating that the quality of its published papers is poor. Conversely, Norway, for example, had fewer publications, but its total and average citations were higher (at 8778 and 31.24, respectively) and, thus, its total citations ranked tenth among all countries; therefore, its published papers are of high quality and are highly recognized by the industry. As for the USA, it had an absolute advantage in terms of total number of publications, total citations, and average citations, thus showing its leadership in the field related to permafrost research.

In addition to the number of published documents and total or average citations, the central and dominant position of national cooperation can also be applied as a reasonable and useful indicator to evaluate a country's research strength, competitiveness, and influence [40,46]. As shown in Figure 7, the top ten countries, in terms of centrality, were ranked as follows: the USA (93), Russia (93), France (93), Germany (91), the UK (91), Sweden (88), China (87), Canada (87), Switzerland (86), and Italy (86). The top five presented cooperation with more than 90 countries. Although the cooperation numbers of the U.S. and Russia were the same, the number of cooperation papers for the U.S. was more than double that in Russia. This result is further evidence of the leadership of the U.S. in permafrost research. Concretely, the U.S. mainly cooperated with China, Canada, Russia, the U.K., Germany, Switzerland, and Japan, whereas China mainly cooperated with the U.S., Canada, the U.K., Japan, Russia, Germany, Switzerland, France, and Australia, which is very similar to the U.S.

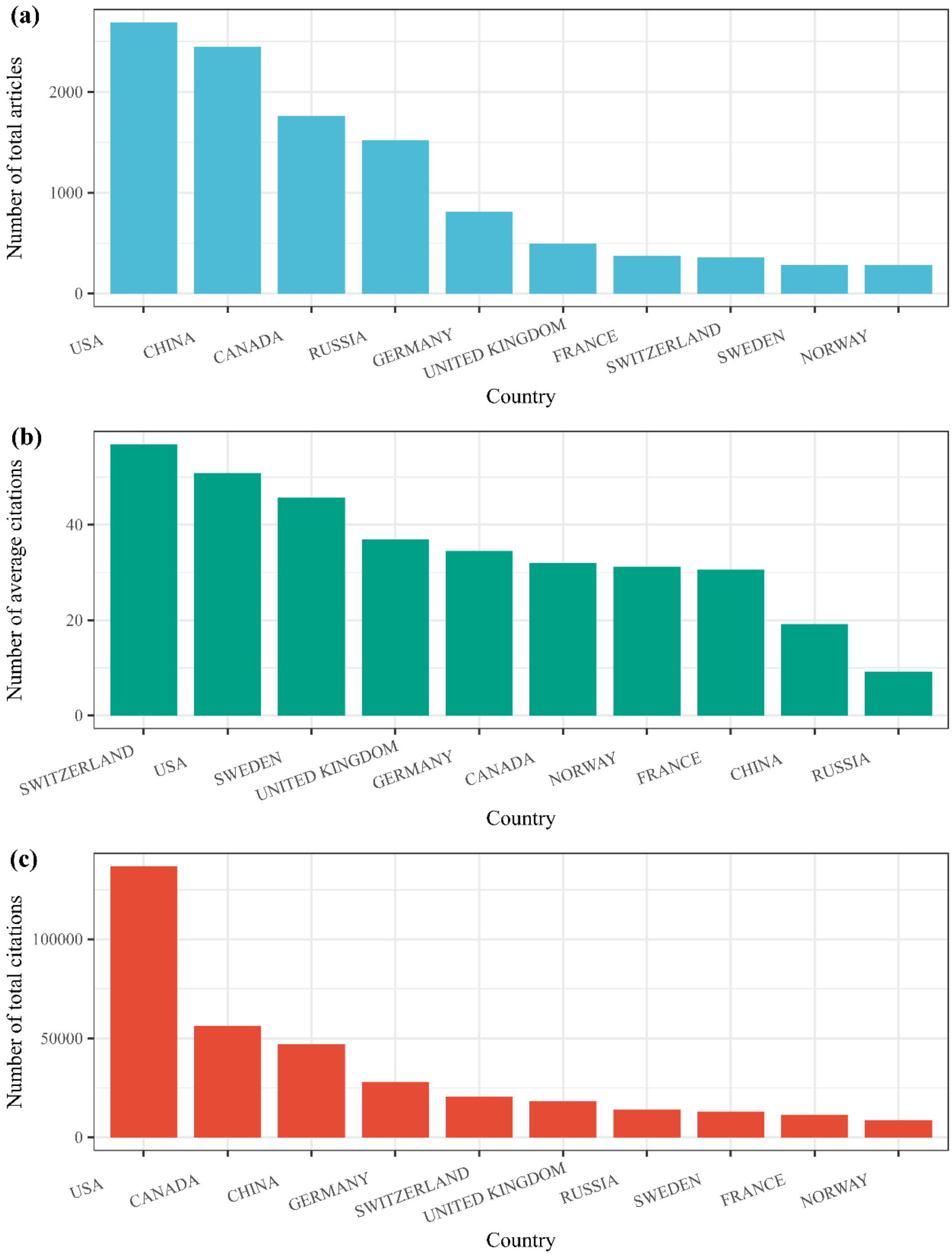

Figure 6. Total publications (**a**), average citations (**b**), and total citations (**c**) of the top ten most-cited countries. All are in descending order.

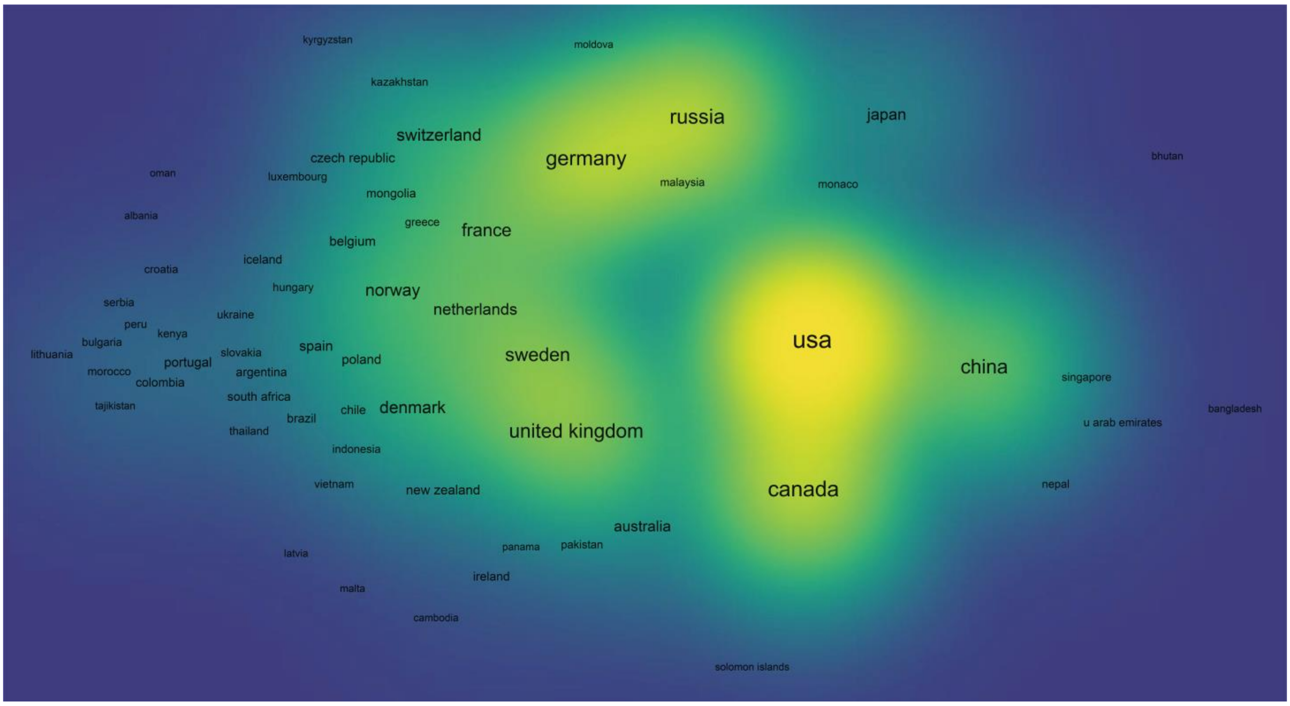

Figure 7. Cooperation density map on permafrost research regarding countries.

3.3.2. The Impacts of Institutions

Based on the key field "AU1_CO"—the country of affiliation for the first author of per document in the converted bibliometrix format—we extracted the institution information for every document (including the first author and cooperation achievements for each institution). The results indicated that 5419 institutions engaged in permafrost research. In terms of the total number of publications by each institution to evaluate its influence and the top 20 institutions with the relation information by country, the total citations are shown in Table 3.

Table 3. Top 20 institutions, ranked by total citations in permafrost research.

Institution	Country	TC	TA
University of Alaska Fairbanks	USA	15,632	1143
Cold and Arid Regions Environmental and Engineering Research Institute, CAS	China	11,930	543
University of Zurich	Switzerland	10,164	218
University of Alaska	USA	9014	439
University of Colorado	USA	6804	363
Stockholm University	Sweden	5106	531
Woods Hole Research Center	USA	5106	100
University of Alberta	Canada	4985	301
Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research	Germany	4653	198
University of Florida	USA	4404	138
University of Copenhagen	Denmark	4160	293
University of Oslo	Norway	4133	237
University of California, Berkeley	USA	3797	140
McMaster University	Canada	3763	128
University of Minnesota	USA	3239	72
Université Laval	Canada	3088	576
Vrije Universiteit Amsterdam	Netherlands	3051	145
McGill University	Canada	3016	226
Northwest Institute of Eco-Environment and Resources, CAS	China	2921	536
University of Wisconsin	USA	2752	169

Abbreviations: TC, total number of citations; TA, total number of articles; CAS, Chinese Academy of Sciences.

As shown in Table 3, among all institutions studying permafrost, the impact of papers from different institutions varied greatly. The University of Alaska Fairbanks was in an absolute leading position, with the total number of citations and publications being 15,632 and 1143, respectively. This was followed by the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) and University of Zurich, all with a total number of citations greater than 10,000. Although the total number of citations for the top three institutions did not differ greatly, the total number of publications was significant, increasing in a two-fold more incremental trend. Most of the research institutions were concentrated in the U.S. (8), followed by Canada (4) and China (2), while all other countries had one. Furthermore, the institutions were dominated by universities. Although the number of institutions in China was two, these two institutions are actually part of one unit—the Chinese Academy of Sciences (CSA)—and the CAREERI is the predecessor of the Northwest Institute of Eco-Environment and Resources (NIEER; funded by integrating CAREERI and other four institutions in June 2016; http://www.nieer.cas.cn/ accessed on 4 November 2022), which were not combined in the statistical analysis of this paper but, instead, are grouped together in the conclusion section as CAS. A similar situation applied among universities, such as the University of Alaska. Although Denmark and the Netherlands did not rank high according to the number of papers published, these countries have had a significant impact and located a dominant position in permafrost research, with a higher competitive edge among all countries, due to their large number of citations.

Furthermore, an institution collaboration map was generated, as visualized in Figure 8. The University of Alaska Fairbanks (1162) had the largest number of institution connections, followed by Alfred Wegener Institute, Helmholtz Centre for Polar (894), University of Alberta (854), Stockholm University (851), University of Colorado (742), University of Gothenburg (724), University of Copenhagen (720), and Vrije Universiteit Amsterdam (704). Other institutions showed less cooperation in permafrost research, with the number of mutual cooperations among them less than 700. However, since there is a character length limit for the software to extract organization information, the identification and categorization of some large-volume research institutions are just passable. In addition, due to the different expressions in the detail level of the institution in authors' papers, it is not very friendly to large research institutions containing many sub-branches, e.g., the Russian Academy of Sciences and the Chinese Academy of Sciences. Specifically, for Russia, the number of collaborating institutions for Earth Cryosphere Institute, Russian Academy of Sciences, and Melnikov Permafrost Institute are 588, 324, and 274, respectively.

The international cooperation among Chinese research institutions was relatively low and was mostly focused on exchange between domestic institutions. Specifically, the main collaborations were among CAREERI (616), University of CAS (336), NIEER (294), Lanzhou University (264), and Institute of Tibetan Plateau Research, CAS (225), which are the leading institutions for permafrost research in China. Hence, according to the cooperation network on county and institution, the study of permafrost study is typically a multi-country and multi-institution cooperative research field.

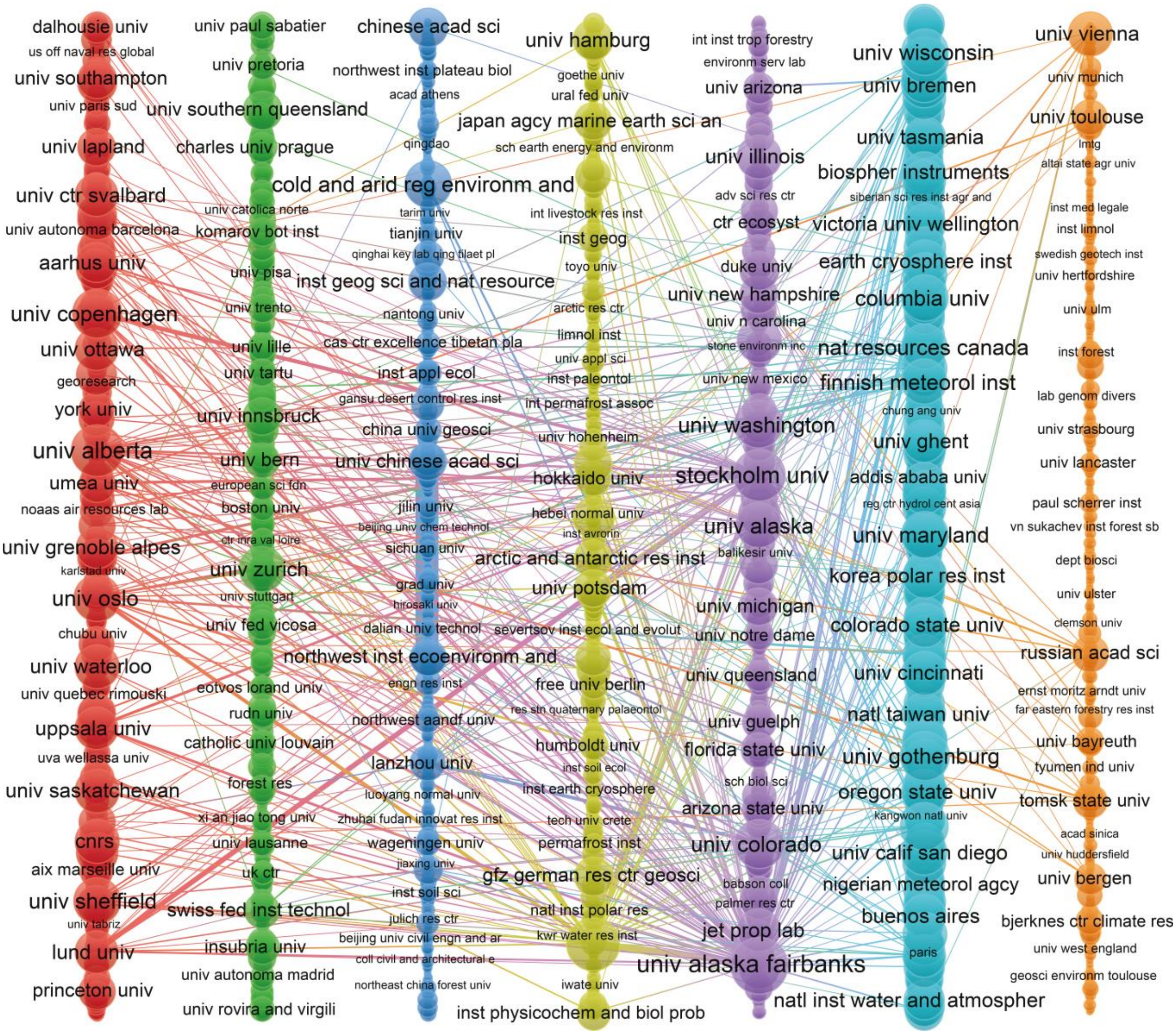

Figure 8. Map showing research collaboration between institutions. Different colors represent different clusters; the size of a circle represents the frequency of cooperation with other institutions, and the connection line indicates the amount of cooperation between institutions exceeding 100.

3.3.3. The Impacts of Authors

The h-index, also named a high citation count or the h-factor, is a hybrid quantitative index proposed in 2005, defined as follows: "A scientist publishes h of all papers with no less than h citations, while each of the remaining papers is cited no more than h times" [88,89]. The h-index can be used to appraise the quantity and level of academic outputs for each researcher worldwide and is a widely accepted measure of scientific performance [40]; the higher value, the more influence. By calculating the h-index, those authors who are more active, productive, or cited in permafrost research field (i.e., core authors) can be identified [46], thus further quantifying the contribution of the researcher to the permafrost research field. The top 20 core authors ranked by h-index, as well as the g-index (a variant of h-index which gives credit for the most-cited paper) [90,91], M-index (another variant of the h-index that displays h-index per year since first publication) [91,92], total number of citations, total number of publications based on the WoS core database [40], first year published, and country information, are shown in Table 4.

Table 4. The top 20 core authors on permafrost research ranked by h-index.

Author	H-Index	G-Index	M-Index	TC	NP	FY_P	Country
Romanovsky V.E.	60	114	2.069	14,080	114	1994	USA
Schuur E.A.G.	56	108	3.294	15,276	108	2006	USA
Grosse G.	48	98	2.526	9933	138	2004	Germany
Mcguire A.D.	48	81	2.182	10,434	81	2001	USA
Schirrmeister L.	43	69	2.048	5082	110	2002	Germany
Boike J.	42	66	1.615	4632	96	1997	Germany
Kuhry P.	41	75	1.64	8997	75	1998	Sweden
Kaab A.	39	61	1.5	4715	61	1997	Norway
Wu Q.B.	39	68	1.444	5518	155	1996	China
Hugelius G.	38	74	2.714	6909	74	2009	Sweden
Haeberli W.	38	66	0.864	4937	66	1979	Switzerland
Zhang T.J.	37	72	1.542	5501	110	1999	China
Etzelmuller B.	37	60	1.37	3757	72	1996	Norway
Cheng G.D.	37	66	0.925	4478	70	1983	China
Turetsky M.R.	36	59	1.565	6424	59	2000	Canada/USA
Zhao L.	36	58	1.565	4101	131	2000	China
Christensen T.R.	36	62	1.286	5052	62	1995	Denmark
Jin H.J.	35	62	1.458	4279	112	1999	China
Harden J.W.	34	45	1.417	5792	45	1999	USA
Nelson F.E.	34	58	0.944	6174	58	1987	USA

Abbreviations: TC, Web of Science Core Collection times cited; NP, number of publications; FY_P, first year of author's published papers.

The top seven authors with h-index greater than 40 (all others with indices less than 40) were Romanovsky V.E. (60), Schuur E.A.G. (56), Grosse G. (48), Mcguire A.D. (48), Schirrmeister L. (43), Boike J. (42), and Kuhry P. (41). Among them, Romanovsky V.E. and Schuur E.A.G. were the first and second, with h-indices greater than 50, and their total numbers of citations, based on the WoS core database, were also high (second and first among all authors of permafrost research) with 14,080 and 15,276, respectively. In addition, their number of citations based on local citations ranked second and first among all authors (8843 and 7354, respectively), and the number of publications for them was also relatively high (with 114 and 108, respectively), ranking third and ninth by number of publications among all related authors (Figure 9).

Considering the friendliness of the M-index for authors with short publication during [91,92], the M-index can identify those relatively young authors who have made great contributions to permafrost research. The M-index-ranked top 15 authors are extracted from this paper in Table 5, and their M-indices are all greater than two.

From Table 5, we can find that, except for Romanovsky V.E., all the authors' first publication years were included after 2000. Romanovsky V.E.'s publications were included since 1996, with an M-index of 2.069, ranking 14 among all authors, and an h-index, 60, ranking first among all authors, indicating that Romanovsky V.E.'s publications are not only highly cited and voluminous but also relatively long-lasting, making him an "absolute bull" in the field of permafrost research. As for Schuur E.A.G., his first publication was in 2006, and his h-index is also high at 56, indicating that Schuur E.A.G. is also an absolute powerhouse in the field of permafrost research and that he may have more publications in the near future.

Among the top 15 authors according to the M-index, four are from the U.S., four are from China, three are from Germany, and one each is from Sweden, Norway, Canada, and the Netherlands. The young scholars from China are Hu G.J. (2015), Luo D.L. (2014), Wu X.D. (2012), and Zhu X.F. (2016), all of whom have published for relatively short periods of time, but they have made significant contributions to the study of permafrost, which indicates that China has a significant advantage in future permafrost research.

Table 5. The top 15 core authors on permafrost research ranked by M-index.

Author	M-Index	H-Index	G-Index	TC	NP	FY_P	Country
Schuur E.A.G.	3.294	56	108	15,276	108	2006	USA
Hugelius G.	2.714	38	74	6909	74	2009	Sweden
Grosse G.	2.526	48	98	9933	138	2004	Germany
Hu G.J.	2.375	19	33	1259	56	2015	China
Westermann S.	2.357	33	51	2809	73	2009	Norway
Luo D.L.	2.333	21	38	1486	40	2014	China
Mcguire A.D.	2.182	48	81	10,434	81	2001	USA
Wu X.D.	2.182	24	39	1837	83	2012	China
Zhu X.F.	2.143	15	22	546	34	2016	China
Sonnentag O.	2.125	17	26	876	26	2015	Canada
Natali S.M.	2.083	25	51	4401	51	2011	USA
Langer M.	2.071	29	44	1971	52	2009	Germany
Vonk J.E.	2.071	29	47	4325	47	2009	Netherlands
Romanovsky V.E.	2.069	60	114	14,080	114	1994	USA
Schirrmeister L.	2.048	43	69	5082	110	2002	Germany

Abbreviations: TC, Web of Science Core Collection times cited; NP, number of publications; FY_P, first year of author's published papers.

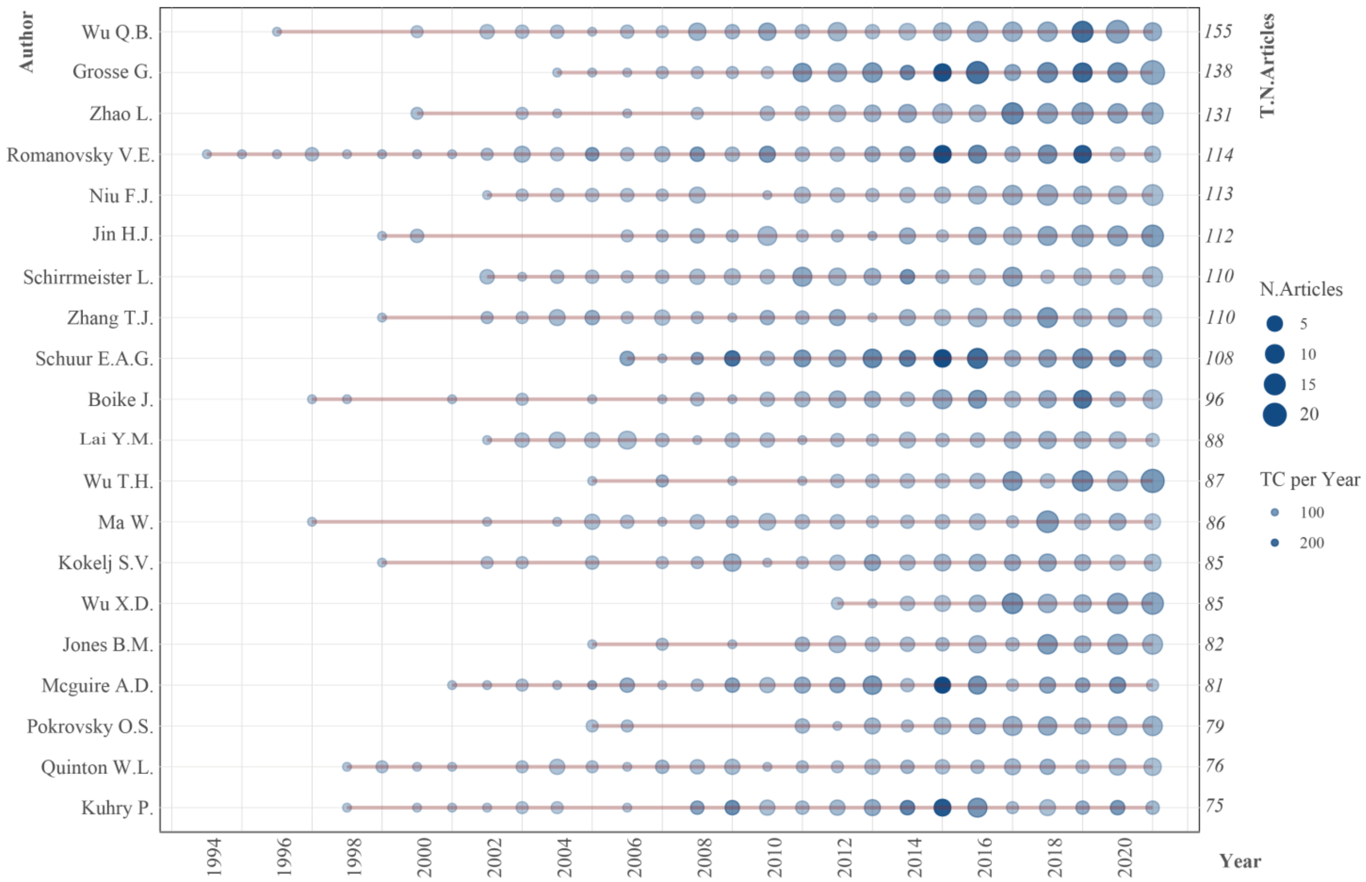

Figure 9. Top 20 authors by production over time, ranked in terms of the total number of publications. The circle size presents the annual total number of articles; the color from light blue to blue indicates increasing total citations per year, and the italic value in the right y-axis is the total number of publications for every author. N.Articles and TC per Year mean the number of published papers and total citations for each author within one year, respectively.

Combining Tables 4 and 5 and Figure 9, it can be found that, among the top 20 most influential researchers, six were from the U.S. (Romanovsky V.E., Schuur E.A.G., Mcguire A.D., Turetsky M.R., Harden J.W., and Nelson F.E.); five were from China

(Wu Q.B., Zhang T.J., Cheng G.D., Zhao L., and Jin H.J.); three from Germany (Grosse G., Schirrmeister L., and Boike J.); two from Sweden (Kuhry P. and Hugelius G.); two from Norway (Kaab A. and Etzelmuller B.); and one each from Denmark (Christensen T.R.), Switzerland (Haeberli W.), and Canada (Turetsky M.R.; also in USA). Furthermore, the ranking of the top 20 authors by the volumes of publications indicated that most of them were from China, nine in total, mainly from NIEER, CSA, or previously CAREERI (Wu Q.B., Zhao L., Niu F.J., Jin H.J., Lai Y.M., Wu T.H., Ma W., and Wu X.D.) and Lanzhou University (Zhang T.J.), four from the U.S. (Romanovsky V.E., Schuur E.A.G., Jones B.M., and Mcguire A.D.), three from Germany (Grosse G., Schirrmeister L., and Boike J.), two from Canada (Kokelj S.V and Quinton W.L.), and one each from France (Pokrovsky O.S.) and Sweden (Kuhry P.). Wu Q.B. published the highest number of articles (155), 17 more than the second-ranked author, Grosse G. (138). Other authors with the largest number of publications (e.g., Niu F.J., Lai Y.M., Wu T.H., Ma W., Kokelj S.V., Wu X.D., Jones B.M., Pokrovsky O.S., and Qui W.L.) do not appear in Table 4, due to their relatively low number of citations. However, considering that the number of article citations is correlated with the length of time since its publication [45,58] and that the h-index itself is insensitive to highly cited articles [90,92–94], the fact that these authors are not ranked in the top 20 by the h-index does not detract from their significant contributions to permafrost research.

3.3.4. The Impacts of Journals

Articles related to permafrost research have appeared in 1503 journals, and the number of published sources per year increased from 1 in 1946 to 56 in 2021. We also examined the frequency distribution of permafrost research papers among primary sources, and the results indicated that the top 10 journals published a total of 2886 papers (21.75% of all papers), while 693 journals (46.11% of all journals) published just one study related to permafrost out of the total number of journals. A total of 1280 journals (85.16% of all journals) published no more than 10 papers, with a total volume of 3034 papers, accounting for 23.02% of all papers published.

As shown in Figure 10, the top ten journals, in terms of published paper numbers, were Permafrost and Periglacial Processes (730), Cold Regions Science and Technology (435), Journal of Geophysical Research: Biogeosciences (257), Environmental Research Letters (236), Geomorphology (232), Geophysical Research Letters (218), the Cryosphere (217), Biogeosciences (200), Remote Sensing (171), and Science of The Total Environment (170). Permafrost and Permafrost Processes had the highest annual growth rate in terms of the number of papers published, followed by Cold Regions Science and Technology, while the other eight were comparable. Papers from Remote Sensing mainly focused on large area change of water in permafrost zones [95–97], post-fire monitoring and frost recovery [98], ice velocity estimating [99,100], surface change detection [101,102], and surface features classifying [100,103,104].

According to Bradford's Law [40,46,105], the source journals for permafrost research papers were highly dispersed, with a large proportion published in 23 journals. These journals, in addition to the 10 with the highest number of publications, included Quaternary Science Reviews, Global Change Biology, Hydrological Processes, Arctic Antarctic and Alpine Research, Journal of Geophysical Research: Earth Surface, Eurasian Soil Science, Journal of Geophysical Research: Atmospheres, Scientific Reports, Quaternary International, Canadian Journal of Earth Sciences, Catena, Geografiska Annaler Series A: Physical Geography, and Journal of Hydrology, as the core sources in permafrost research.

Citation statistics are also scientifically significant statistical indicators that are often used to evaluate the relative influence of an academic journal [40,46,48]. The top ten most influential journals were selected based on the total number of local citations, as shown in Table 6. The journals marked with an asterisk are the core journal sources in the permafrost research field as determined by Bradford's law, including Permafrost and Periglacial Processes, Geophysical Research Letters, Global Change Biology, Journal of Geophysical Research: Atmospheres, Cold Regions Science and Technology, Journal of Geophysical

Research: Biogeosciences, and Quaternary Science Reviews. These results indicate that these journals not only publish a large body of literature but also had a significant impact and played an important role in permafrost research during the study period.

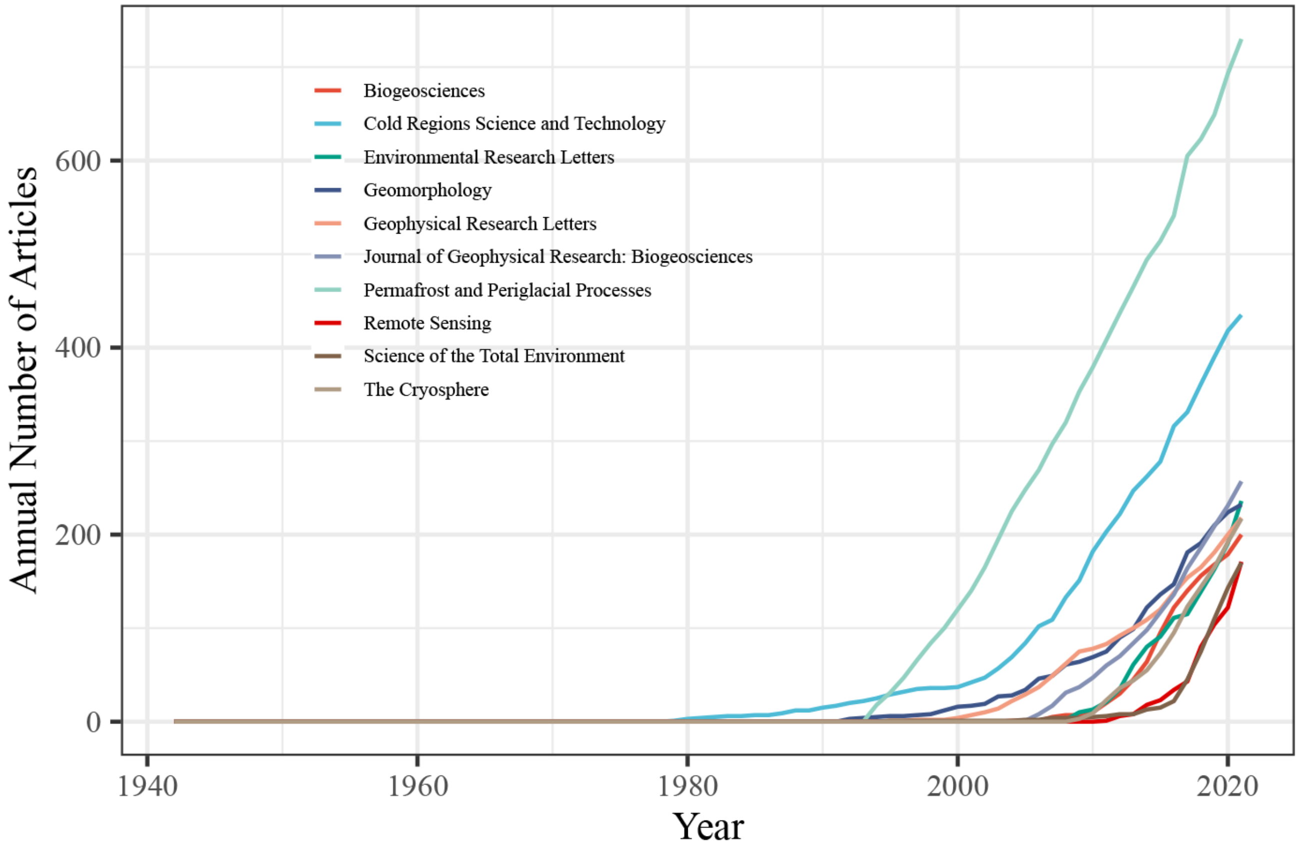

Figure 10. Temporal analysis of the top ten publication sources of permafrost-related research, according to the cumulative publications.

Table 6. Top ten journals ranked by the number of local citations in permafrost research.

Source	N.LC	ND	IF	H Index
Permafrost and Periglacial Processes *	20,734	730	-	79
Geophysical Research Letters *	14,854	218	5.576	63
Nature	13,874	50	69.504	33
Science	11,285	28	63.714	17
Global Change Biology *	10,873	148	13.211	62
Journal of Geophysical Research: Atmospheres *	8756	109	5.217	46
Cold Regions Science and Technology *	8378	435	4.427	49
Journal of Geophysical Research: Biogeosciences *	8148	257	4.432	57
Quaternary Science Reviews *	7538	156	4.456	47
Global Biogeochemical Cycles	6678	81	6.500	41

Note: X *, the journal is a core resource based on Bradford's Law [40,46,105]; N.LC, number of the total local citations; ND, number of the documents about the journal; IF, impact factor for 2021–2022. IF and H indices were collected from LetPub (https://letpub.com.cn/, accessed on 23 October 2022).

3.3.5. The Impacts of Papers

The impact of a paper can be determined based on the number of citations it has received [40]. The citations of a paper include the local citation score (LCS) and the global citation score (GCS), and the former measures the number of citations a document has received from documents included in the analyzed collection, which is calculated through the bibliometric analysis of the whole reference data set [82]; the latter measures the total number of citations of a publication has received from documents contained in the entire database (e.g., WoS or Scopus), which is provided by WoS/Scopus and is included in the metadata record [40,82]. Generally, for many documents, a large part of global citations could come from other disciplines and research fields, while local citations measure the impact of documents in the analyzed collection only [106]. The top ten papers, according to the LCS and GCS, were counted and shown in Tables 7 and 8, respectively; all of them were published after 2000 except only one paper (issued in 1991, with the article doi, 10.2307/1941811); the difference between LCS and GCS is worth noting and has been analyzed as follows.

The most influential paper according to the LCS was a review paper (also the fourth in GCS) regarding the feedback between permafrost carbon and climate change [14], issued in Nature in 2015, with the LCS and GCS at 975 and 1625, respectively. This paper focused on the magnitude and timing of greenhouse gas emissions in the permafrost zone (within the broad Arctic and sub-Arctic regions) and the uncertainty of their impact on climate, pointing out that present evidence demonstrates a gradual, persistent, and long-term release of greenhouse gas emissions under a warming climate and proposes a research strategy to address aspects of permafrost carbon dynamics that are poorly understood [14]. Furthermore, the first author of this paper is Schuur E.A.G., who is ranked the second according to the h-index in the above Section 3.3.3, the impacts of authors. This further proves the influence of Schuur E.A.G.

Table 7. Top 10 documents ranked by the local citation score.

Document	DOI	P_Year	LCS	GCS
Schuur E.A.G, 2015, *Nature* [14]	10.1038/nature14338	2015	975	1625
Tarnocai C., 2009, *Global Biogeochem Cy* [107]	10.1029/2008GB003327	2009	846	1553
Schuur E.A.G., 2008, *Bioscience* [108]	10.1641/B580807	2008	714	1008
Hugelius G., 2014, *Biogeosciences* [109]	10.5194/bg-11-6573-2014	2014	613	830
Schuur E.A.G., 2009, *Nature* [110]	10.1038/nature08031	2009	499	752
Zimov S.A., 2006, *Science* [111]	10.1126/science.1128908	2006	449	672
Jorgenson M.T., 2006, *Geophys Res Lett* [112]	10.1029/2005GL024960	2006	412	519
Serreze M.C., 2000, *Climatic Change* [113]	10.1023/A:1005504031923	2000	409	1472
Hinzman L.D., 2005, *Climatic Change* [114]	10.1007/s10584-005-5352-2	2005	408	1032
Jorgenson M.T., 2001, *Climatic Change* [115]	10.1023/A:1005667424292	2001	395	509

Abbreviation: DOI, digital object identifier; P_Year, the published year of the paper; LCS, local citation score; GCS, global citation score.

Table 8. Top 10 documents ranked by the global citation score.

Document	DOI	P_Year	LCS	GCS
Davidson E.A., 2006, *Nature* [116]	10.1038/nature04514	2006	327	3987
Schmidt M.W.I., 2011, *Nature* [117]	10.1038/nature10386	2011	106	3175
Gorham E., 1991, *Ecol Appl* [118]	10.2307/1941811	1991	269	2612
Schuur E.A.G., 2015, *Nature* [14]	10.1038/nature14338	2015	975	1625
Tarnocai C., 2009, *Global Biogeochem Cy* [107]	10.1029/2008GB003327	2009	846	1553
Tranvik L.J., 2009, *Limnol Oceanogr* [119]	10.4319/lo.2009.54.6_part_2.2298	2009	79	1538
Serreze M.C., 2000, *Climatic Change* [113]	10.1023/A:1005504031923	2000	409	1472
D'costa V.M., 2011, *Nature* [120]	10.1038/nature10388	2011	31	1328
Hinzman L.D., 2005, *Climatic Change* [114]	10.1007/s10584-005-5352-2	2005	408	1032
Schuur E.A.G., 2008, *Bioscience* [108]	10.1641/B580807	2008	714	1008

Abbreviation: DOI, digital object identifier; P_Year, the published year of the paper; LCS, local citation score; GCS, global citation score.

The second-most influential paper, according to LCS (also ranked the fifth for GCS), calculated the soil organic carbon (SOC) pool in the northern circumpolar permafrost region and showed that all soils in the northern permafrost zone cover an area of about 18,782 $\times$ 10^3 km^2, which is about 16 % of the soil area all over the world [107]. The highest average SOC contents (32.2–69.6 kg m^{-2}) was found in organic soils (peatlands) and cryoturbated permafrost-affected mineral soils. In total, the northern permafrost zone contains about 1672 Pg of organic carbon, of which about 1466 Pg (88%) is present in permafrost and sediments [107]. This 1672 Pg of organic carbon accounts for approximately 50% of the global sub-surface organic carbon reserves. The third-most influential paper, according to LCS (also ranked 10 for GCS), considered the vulnerability of permafrost carbon varying to climate change [108], published by Schuur E.A.G et al. in 2008. This paper provides an overview of the global permafrost carbon pool and the processes that may transfer carbon to the atmosphere with the phase transformation and the ecosystem changes associated with permafrost thawing, suggesting that the net effect of widespread permafrost thawing and degradation may have a positive feedback mechanism for climate warming [108].

The fourth-most influential paper, according to LCS, was focused on the estimation of permafrost carbon stocks and the quantification of the range of uncertainties in the identified data gaps [109], issued in Biogeosciences in 2014. This article presented revised estimates of permafrost SOC stocks, including quantitative uncertainty estimates, for soils in the zero to three meters depth range and for sediments deeper than three meters in the deltaic sediments of major river and the Yedoma region of Siberia and Alaska. The revised estimates were based on a larger database compared to previous studies [109]. The fifth-most influential paper, according to LCS, was focused on the effects of permafrost thawing leading to old carbon release and net carbon exchange from tundra in permafrost areas [110], published in *Nature* in 2009 by Schuur E.A.G. et al. For this paper, they measured net ecosystem carbon exchange and radiocarbon ages of ecosystem respiration in tundra landscapes undergoing permafrost thaw, in order to determine the effects of old carbon loss on ecosystem carbon balance. The results suggested that old carbon loss contributes to net ecosystem-wide carbon release [110]. The sixth-most influential paper, according to LCS, contained descriptions of permafrost and the global carbon budget, illustrating the importance of permafrost carbon in the global carbon budget by describing the past and potential future dynamics of frozen loess (windblown dust, termed Yedoma in Siberia) deposited during the ice age [111]. This paper was issued in Science in 2006, and Schuur E.A.G. is the co-author.

The seventh-most influential paper, according to LCS, was an article on the sudden increase in permafrost degradation in Alaska, Arctic, with an abrupt and dramatic increase in the extent of permafrost degradation witnessed in northern Alaska since 1982, associated with record warm temperatures interval from 1989 to 1998 [112]. In this paper, based on the methods, e.g., field studies, comparative analysis of aerial photographs, and spectral analysis, the results suggested that thermal karst may affect 10–30% of the Arctic lowland landscape and severely alter tundra ecosystems, even under moderate warming conditions [112]. The eighth-most influential paper, according to LCS (also ranked the seventh for GCS), was a review paper on the observational evidence for environmental change in the high northern latitudes, which, through a synthesis of research records and observations from different disciplines, suggested that, while these results paint a fairly coherent picture of change, their interpretation as a signal of enhanced greenhouse warming is open to debate [113].

The ninth-most influential paper, according to LCS and GCS, is an article on the evidence and impacts of recent climate change in northern Alaska and other Arctic regions, presenting a broad range of evidence through a holistic review that convincingly demonstrates that the Arctic is experiencing a system-wide response to altered climate states [114]. The results suggest that new extreme and seasonal surface climate conditions are being experienced, that a range of biophysical states and processes affected by freezing thresholds and phase changes are changing, that hydrologic and biogeochemical cycles are changing, and that additional human sub-systems are being affected. The tenth-most influential paper, according to LCS, describes permafrost degradation and ecological changes due to climate warming in central Alaska and, based on an analysis of aerial photographs, that the area of completely degraded permafrost (collapse scarred bogs and marshes) has increased from

39% to 47% within 46 years (from 1949 to 1995) [115]. Based on aerial photo analysis and radiocarbon dating rates of change, it was estimated that 83% of the degradation occurred before 1949. Evidence suggests that this permafrost degradation began in the mid-1700s, associated with a relatively warm climatic period in the mid to late 1700s and 1900s. If current conditions continue to develop, the remaining lowland birch forests will be wiped out by the end of the next century.

As for the remaining most influential papers according to GCS, the most influential paper described the temperature sensitivity of soil carbon decomposition and the feedbacks to climate change, addressing the disagreement about the impact of climate change on the soil carbon stocks all over the world [116]. The paper ranked second was a study on the persistence of soil organic matter (SOM) as an ecosystem property, which proposed to incorporate the understanding that “molecular structure alone does not control the stability of SOM: in fact, environmental and biological controls dominate” into a new generation of experimental and soil carbon modelling approaches to improve predictions of SOM responses to global warming [117]. The paper ranked third was an article describing on the role of boreal peatlands in the carbon cycle process and possible responses to global climate warming [118]. This paper pointed out that the long-term intense burning of boreal peatlands leads to CO_2 slightly greater than 0.0085 Pg per year of oxidation, while fuel peat burning contributes ~0.026 Pg per year approximately. CH_4 emissions are evaluated to release about 0.046 Pg of carbon per year. As such, the further attentions need to be paid to the effect of fire in the carbon cycle process of peatlands deserves.

The paper ranked sixth, according to GCS, was a study article on lakes and reservoirs as regulators of the carbon cycle and climate [119]. This paper explored the role of lakes in the carbon cycle process and global climate change, examined the mechanisms influencing carbon pools and transformations in lakes, and discussed how carbon metabolism in inland waters may be altered by climate. Their results demonstrated that: inland waters bodies are an important component of the global carbon cycle process and that their contribution to this cycle has changed significantly in recent years due to increased human activity. In addition, this change will continue in response to future global climate change, leading to changes in the number of lakes and increases in the number of aquatic weirs [119]. The paper ranked eighth was an article on antibiotic resistance research, which reported a targeted metagenomic analysis of rigorously characterized ancient DNA from 30,000-year-old Beringian permafrost deposits and identified a highly diverse collection of genes encoding antibiotics against beta-lactams, tetracyclines, and glycopeptides [120]. These results revealed that antibiotic resistance is a natural phenomenon that predates selection pressure against the modern clinical use of antibiotics.

Whether based on the LCS or GCS, most of the articles were focused on carbon and SOC soil organic carbon in the Arctic, sub-Arctic, and Alaska [14,107–119,121]; except for the article ranked 10th according to the GCS, which was about antibiotics [120]. Specifically, the main focus was on the study of carbon feedback mechanisms and state transitions in variable permafrost under the context of climate change. This indicates that most of the highly cited articles related to permafrost studies focus on carbon changes in permafrost in the context of climate change. In addition, the authors of these most influential papers are in accordance with the most influential authors in Section 3.3.3, specifically, some of the most influential authors are the first-author or co-author for the most cited papers.

3.4. Trends

For this paper, we collected 19,139 keywords from 13,697 papers published on permafrost research during the period 1942–2021. Figure 11 supports the historical trends of author keywords developed with time. In the graph, the authors’ keywords are shown on the y-axis and the date information (years) are revealed on the x-axis. For each keyword, the horizontal line presents the evolutionary process, specifically, the green dot in the head-end, the red dot in the end, and the blue dot in the middle position present the first quartile, the third quartile, and the median time of the year of publication, respectively [40].

Furthermore, the size of the blue dot reflects the frequency of the corresponding keyword contained in the publications [40], the bigger the circle, the more documents published related to the keyword. The longest duration was observed for digital terrain model and slope processes, which are key topographic factors; piles, gelifluction, climatic change, rock glaciers, mapping and water balance, which are the key study objects and contents; and Pleistocene, Holocene, and the last glacial maximum, which are all core geological periods. Furthermore, Alaska, Mars, west Siberia, and the Qinghai–Tibet Plateau were hot research areas and regions.

Before 2000, there were relatively few keywords, 12 in total, mainly climatic change, gelifluction, and west Siberia. Then, 35 major keywords appeared from 2001 to 2010, mainly permafrost, the active layer, rock glacier, Alaska, Mars, Holocene, boreal forest, and mountain permafrost. Furthermore, 18 major keywords appeared from 2011 to the present, focusing on climate change, arctic, thermokarst, methane, tundra, permafrost degradation, Qinghai–Tibet plateau, climate warming, Tibetan plateau, and permafrost thaw. The study of climate change on permafrost has been carried out early and has gone through climatic change (1998), climatic warming (2004), climate change (2011), and climate warming (2017). Although these four terms convey similar meanings, their descriptions and changes in form reflect a shift from an early basic understanding to the current unified perception of global warming.

Among all the keywords, the top ten keywords, according to frequency, were permafrost, climate change, arctic, active layer, thermokarst, Alaska, methane, tundra, permafrost degradation, and Qinghai–Tibet. Among these keywords, permafrost appeared most frequently, directly related to permafrost degradation, representing the increase in active layer and thermokarst, which is mainly attributed to the climate change. Studies on permafrost were mostly focused on the Arctic, Alaska, tundra, and the Qinghai–Tibet plateau regions, where the permafrost is richly developed. In addition, the degradation of permafrost leads to an increase in greenhouse gas emissions, such as methane and carbon dioxide, increasing the greenhouse effect and enhancing the impact of permafrost degradation.

More red dots to the right and larger blue dots in Figure 11 indicate the more recent publication of the corresponding keywords and a large number of published papers, respectively, thus reflecting the research trend [40]. In terms of technologies related to permafrost research, machine learning [122–127] and interferometric synthetic aperture radar (InSAR) [128–132] are new technological approaches developed in recent years, compared with the traditional conventional methods, e.g., geographic information system (GIS) [133–135] and ground-penetrating radar (GPR) [136–138]. Machine learning is used for deeper information mining and result prognosis, based on various and abundant field monitoring data [122], while InSAR is mainly used for surface deformation acquisition, topographic mapping, active layer inversion, moisture inversion, and so on, in permafrost areas [128,129]. In addition, combining deep learning (a major branch of machine learning) with InSAR has been carried out [139–141]; however, its application to permafrost has not yet been found. The number of papers with risks as keywords has increased significantly in the last three years, with 26 in the period 2019–2021 and most papers belonging to the thermodynamics research category. In terms of research content, the main focus is on pore water, sub-sea permafrost, microbial community, and warming, while the study area region has shifted from earlier regions, such as the Arctic, Alaska, Europe, and Canada, to the Qinghai–Tibet Plateau, known as the "Third Pole" and the "Asian water tower" [142].

To further understand the authors' keywords, hierarchical order relationships between keywords were generated through hierarchical clustering, which in turn led to a thematic dendrogram of keywords, with the results shown in Figure 12. The topic dendrogram does not intend to find the perfect level of association between clusters [39,143], but it aims to estimate the approximate number of clusters, with cuts and vertical lines in the graph in order to facilitate the investigation and interpretation of different clusters, thus further discussing the author keyword deeper meaning [39].

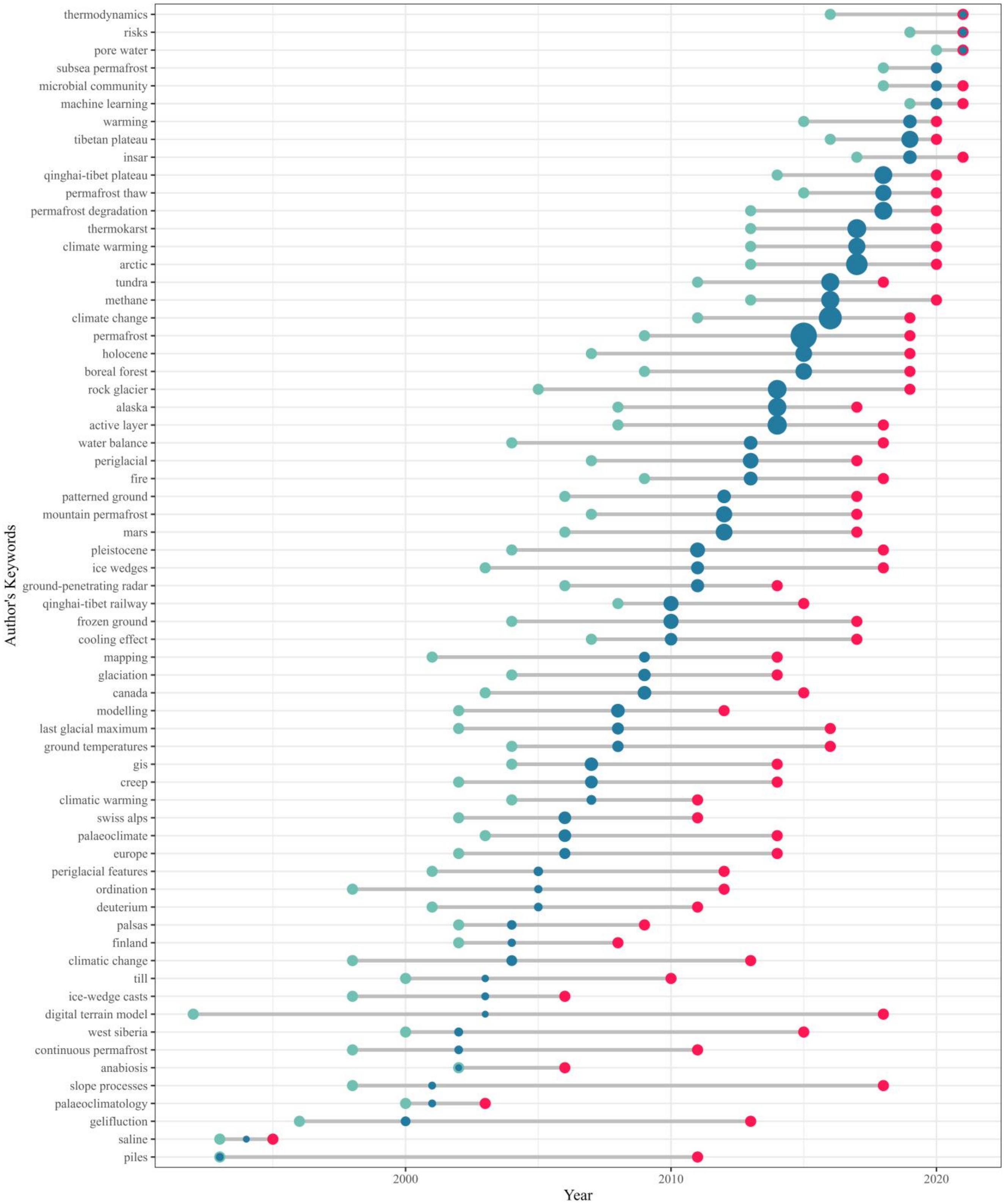

Figure 11. Temporal trends according to keywords. The x-axis presents the year, and the y-axis shows the keywords. The green dot, red dot, and blue dot indicate the first quartile, the third quartile, and the median year of the publications, respectively. The size of the blue dot reflects the number of papers; the bigger, the larger number.

For carbon dioxide (I), this is consistent with the results of the most influential literature analysis, which is divided into two main parts (II-a and II-b) (Figure 12). The first main part (II-a) focuses on the content, object, performance and region of the study, which is a cluster of larger concepts. The second main part (II-b) focuses on the specific regional research, mainly by specific research areas and research content, methods, and performance clustering.

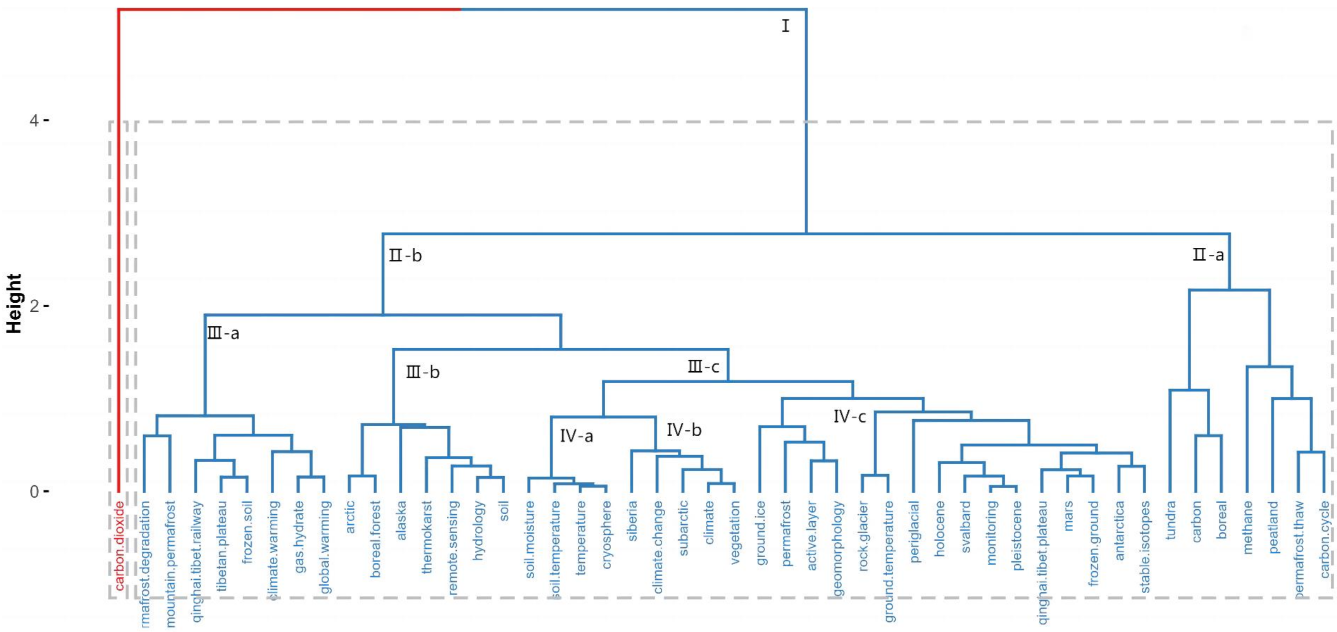

Figure 12. Topic dendrogram of authors' keywords based on the multiple correspondence analysis method. The cuts and vertical lines in the graph present different clusters. The name of each cluster is marked with a combination of Roman numerals and letters.

The first main part (II-a) is divided into two subcategories, one focusing on the boreal tundra and its carbon distribution. The other category focuses on the release of greenhouse gases, such as methane, due to environmental changes in permafrost thaw and peatland, which in turn affect the carbon cycle. These studies are generally global in scope and involve a wide range of evidence and methods, mainly literature reviews and field monitoring data, as well as model simulations based on monitoring data [14,33].

The second main part (II-b) contains three subcategories, III-a, III-b, and III-c. The first subcategory (III-a) focuses on mountain permafrost (frozen soil), with the main focus on permafrost degradation, and the study area is mainly located on the Qinghai–Tibet Plateau and the Qinghai–Tibet Railway [36]. In addition, gas hydrate is also studied, and the factors that cause permafrost degradation are climate warming and global warming [31,144]. The second subcategory (III-b) focuses on the arctic, boreal forest, and Alaska [28,33,112,145]. Specifically, the thermokarst [126,144], hydrology [36], and soil [65,68,146,147] in these areas are monitored and studied on a large scale by means of remote sensing. The third subcategory (III-c) includes numerous specific case studies, which are described below.

The first part (IV-a) is a study of the subarctic and Siberia regions, where the impact of climate change on the cryosphere is reflected through the monitoring and analysis of soil moisture, soil temperature, temperature, and vegetation [32,67,69,108,116,123,144]. The second part (IV-b) is about ground ice, active layer, and geomorphology in permafrost [124,148]. The third part (IV-c) is about the study of rock glacier, mainly by monitoring ground temperature; the study of periglacial landforms [21], such as the Holocene and Pleistocene geological legacies of Svalbard [13,132]; the monitoring of frozen ground in the Tibetan Plateau, Mars and Antarctica [3,15,149]; and the study of frozen ground and stable isotopes of Antarctica.

4. Discussion

Through the bibliometric method, due to its simplicity and ease of operation, a large number of research results have been achieved [45,58,59,64,72,73,84,85]; since bibliometrics itself is a separate discipline [60], some simple theories and basic principles are necessary to master when performing bibliometric analysis. The necessary bibliometric knowledge is the basis for effective interpretation and description. Although the study in this paper goes as far as possible to analyze and refine the content, there are some limitations. Specifically, the following.

First, the studied publications were collected only from the single WoS core collection database, which limited the research scope of the processed literatures. To have a broader coverage of papers' bibliometric analysis, the collection of further materials and comparison with databases such as Google Scholar, Scopus, and so on [44,45], are needed, while in this paper, it is lacking. This is unfair for Russian researchers because many of their excellent publications are not included in the WoS core database due to the historical, political, and educational patterns and differences. For example, a lot of papers are published in Earth's *Cryosphere*, included by Scopus, (https://www.scopus.com/sourceid/5000160401, accessed on 20 December 2022) and non-core WoS journals (https://ice-snow.igras.ru/jour, accessed on 20 December 2022), as well as some journals in Russian. Moreover, since permafrost occupies 65% of Russian territory, Russian researchers have conducted a lot of research and have a long history [2].

The WoS core databases selected for this paper may differ, in terms of the depth of the units subscribed to [77,78]. Although a review analysis based on the bibliometric method of research on permafrost without considering external influences and additional databases is valid, the comprehensive and reasonable competitiveness, influence, and a collaboration analysis assessment of organizations, journals, sources, and authors require a wider coverage of database supporting than just internal data from a single cited database or closed studies. The richer and more comprehensive the data source, the more credible the results will be [46].

Second, the literature search strategy was the basis for further analysis, and the use of the topic "permafrost" only returns studies exclusively focused on permafrost, with very few studies involving frozen soil/ground. In fact, frozen soil or ground and permafrost studies are usually closely related, and, although they have been clearly defined and characterized, the scope of the former is significantly larger than that of the latter in practical investigations, observations, and engineering applications [2,3]. Therefore, a bibliometric analysis of permafrost research is necessary in the future based on different search strategies, e.g., richer keywords, searching with the wildcards and Boolean expression and classifying by research objects. Specifically, the keywords and expressions for research topics and literature searches related to permafrost research, shown in Table 9, mainly included five study topics.

Third, there are also some limitations in keyword analysis. The keywords are chosen to avoid duplicating the titles of some journals or some authors, in order to improve the resulting search. At the same time, some words may be repeated in the titles of other articles. We chose to conduct analysis according to the keywords, the author's keywords in addition to the actual Keywords Plus, which were not included in the analysis in this paper. In fact, some journal articles are lacking in keywords, and many articles before early 1990 did not include keywords [46,150]; generally, this problem is solved by terminology analysis, such as CiteSpace or another software [46,48,151–153]. However, the direct use of the original keywords for the analysis also has advantages, as these keywords were identified by the authors when they wrote the article, and they are keywords in the full sense of the word, rather than being obtained by extracting and merging them according to an analysis method.

Table 9. Literature searching strategy related to frozen soil research.

Research Topic	Searching Keywords and Expressions
Frozen ground/ frozen soil	*permafrost* OR "frozen soil*" OR "frozen ground*" OR "frozen rock*" OR geocryology* OR "icy soil*" OR cryopeg* OR "frozen earth" OR Gelisol*
Frozen ground engineering	engineer* OR embankment* OR roadbed* OR subgrade* OR foundation OR stability OR cold region*
Mechanics of frozen ground	mechanic* OR "frost heav*" OR dynamic* OR elastoplastic* OR strain OR stress OR "water migrat*" OR "moisture migrat*" OR "moisture transfer*" OR creep OR deform* OR strength criterion OR Compressive strength
Frozen soil Environment	environment* OR "ground ice" OR hazard* OR damage OR seasonal OR "active layer" OR "thermal state" OR "thermal regime" OR temperature* OR thermokarst OR talik* OR cryoturbation* OR "thermal stability" OR carbon* OR Tibet* Plateau OR freez* depth OR thaw* depth OR frost damage OR Alpine grassland OR Qinghai-Tibet*
Frozen soil physics	multigelation OR "cryogenic fabric" OR cryogen* OR cryostructure OR physics OR thermodynamics OR "water migrat*" OR "moisture migrat*" OR "moisture transfer*" OR "heat transfer*" OR "frost heav*" OR "unfrozen water" OR freezing OR "temperature gradient" OR "pore pressure" OR "segregated ice" OR Freez*-thaw* OR thermal conductivity OR Freezing point

Note: " " is used to turn off the word conversion search function to improve the accuracy of the search results. The * symbol is used as a wildcard for truncated searches to include more terms or wards for retrieval.

5. Conclusions

We reviewed the research on permafrost and analyzed future trends based on scientometric analysis (using the bibliometrix R-package). A total of 13,697 related papers from 1942 to 2021 were selected from the WoS core repository and were analyzed to provide insight into the development, impact, and future trends of permafrost research. Our most important findings are as follows.

(1) From 1942 to 2021, there were 13,697 articles in the field of permafrost research, with an exponential increase in the cumulative number of publications, having an average annual growth rate of 10.40%.

(2) By 2021, articles related to permafrost research belonged to 96 categories, with a linear increase rate of 0.788. The published articles were mainly in the research areas of geology (6281), environmental science and ecology (3488), physical geography (2613), engineering (2379), and meteorology and atmospheric science (1185), accounting for 75.91% of the total number of articles.

(3) The countries with the highest number of publications were the U.S. (2688), China (2449), Canada (1759), and Russia (1522). Since 2000, China has seen rapid growth in the number of publications per year, surpassing the U.S. in 2016 and leading in the years since then. However, the total number of citations in China is not high.

(4) The University of Alaska Fairbanks, the Northwest Institute of Eco-Environment and Resources, CAS, and the University of Zurich were the most influential institutions in the world, in terms of volume of publications, citations, and collaboration between institutions.

(5) When ranked by h-index, Romanovsky V.E., Schuur E.A.G., Grosse G., Mcguire A.D., Schirrmeister L., and Boike J. were the most influential authors, who mostly come from Europe and North America. However, Chinese scholars accounted for most of the publications, including Wu Q.B., Zhao L., Niu F.J., and Jin H.J. As for the young authors with a short publication during the time period, Hu G.J., Luo D.L. and Wu X.D. from China, were excellent.

(6) The top ten journals, in terms of the published papers, were Permafrost and Periglacial Processes (730), Cold Regions Science and Technology (435), Journal of Geophysical Research: Biogeosciences (257), Environmental Research Letters (236), Geomorphology (232), Geophysical Research Letters (218), the Cryosphere (217), Biogeosciences (200), Remote Sensing (171), and Science of the Total Environment (170).

(7) The most influential studies (Schuur E.A.G. et al., 2015, Tarnocai C. et al., 2009, and Schuur E.A.G. et al., 2008) in permafrost research were mainly focused on carbon feedback

mechanisms and state transitions in variable permafrost, within the context of climate change, and the year of publication of them are after 2000.

(8) According the trend analysis of authors' keywords, climate warming is the hot point of permafrost study, which change from the format "climatic change" in 1998 to "climatic warming" in 2004, "climate change" in 2011, and "climate warming" in 2017.

(9) Compared with traditional technology, machine learning and InSAR are new technological approaches developed in recent years. In terms of research content, the main focus is on pore water, sub-sea permafrost, microbial communities, and warming, while the study area region has shifted from earlier regions, such as the Arctic, Alaska, Europe, and Canada, to the Qinghai–Tibet Plateau.

(10) Bibliometric analysis on permafrost research combining the WoS core database with other databases, e.g., Google Scholar and Scopus is needed. The results of a single data source are unfair to the contributions of certain researchers, especially Russian scholars. The integration of different databases for bibliometrics is expected in the future.

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