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RESEARCH ARTICLE

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Hot trends and impact in permafrost science

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Abstract

An increased interest in Arctic environments, mainly due to climate change, has changed the conditions for permafrost research in recent years. This change has been accompanied by a global increase in scientific publications, as well as a trend towards open access publications. We have analyzed abstracts, titles and keywords for publications on permafrost from 1998 to 2017 to identify developments (topics, impact and collaboration) in the field of permafrost research in light of these changes. Furthermore, to understand how scientists build on and are inspired by each other's work, we have (a) developed citation networks from scientific publications on permafrost and (b) conducted an online survey on inspiration in permafrost science. Our results show an almost 400% increase in publications containing the word permafrost in the title, keywords or abstract over the study period, and a strong increase in climate-change-related research in terms of publications and citations. Survey respondents (n = 122) find inspiration not only in scientific journal publications, but to a large extent in books and public outreach materials. We argue that this increase in global-scope issues (i.e., climate change) complementing core permafrost research has provided new incentives for international collaborations and wider communication efforts.

KEYWORDS

Arctic, bibliometrics, climate change, inspiration, open access, publication trends, science communication

1 | INTRODUCTION

Across the globe, permafrost landscapes are warming and changing at accelerating rates.[1,2] In Arctic and alpine countries, permafrost degradation leads to increased costs for infrastructure development and maintenance,[3,4] and impacts living conditions for local communities, including indigenous peoples, and for wildlife.[5-7] The magnitude and timing of the permafrost carbon feedback on the climate system remains uncertain and is potentially considerable.[8,9] This growing need to understand permafrost as part of the global climate system, regional ecosystems and societal systems of the local communities has changed the context of permafrost research in the last decade.

The 4th International Polar Year (IPY; 2007/2008) promoted a substantial increase in the number and the multidisciplinary design of permafrost studies, and their publications.[10] Around the same time, the global media turned its attention to the Arctic region due to a record low sea ice minimum,[11] Russia's placement of its national flag on the seafloor at the North Pole[12] and Al Gore's film on the effects

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of global warming, "An inconvenient truth".[13] Even though these events did not directly relate to permafrost, the need to better understand cold regions in a global context was discussed with new interest by a variety of groups and a growing number of people. With these events and the increasing interest of stakeholders in national and international politics, shipping industry, natural resource management, environmental protection and local communities, the conditions and context for which permafrost research is undertaken have changed drastically during the last decade. Funding for targeting specific challenges related to permafrost in a climate change context have become available in several countries. For example, in North America, large projects such as the Next Generation Ecosystem Experiment (NGEE Arctic, 2012–2022), the Arctic Boreal Vulnerability Experiment (ABoVE, 2015–2025), ArcticNet (2003–2024), Arctic Development and Adaptation to Permafrost in Transition (ADAPT, 2011–2016) and Sentinel North (2015–2022) generated substantial funding for permafrost studies, while in Europe the EU funded the Carbo-North (2006–2010), PAGE21 (2011–2015) and Nunataryuk (2017–2022) projects. In China, major infrastructure projects on the Qinghai–Tibetan Plateau have spurred a rapid increase in permafrost research activities.

The greater world of science is constantly changing, too. The total spending on research and development has more than doubled in the EU and the US from 1998 to 2016, while in China it has increased even more.[14] This is reflected by a considerable rise in the number of scientific publications in recent years (based on data from 2003 to 2016) for these countries. There is also increasing pressure to change the way scientific results are published to ensure that scientific publications, data and codes are made freely available to scientists and the public for discussion, reproduction and challenge: principles which are at the core of empirical research. One recent example is Plan S, an initiative from 11 national research funding organizations and the European Commission, with a commitment that all publicly funded research should be published in open access journals or platforms, not including the so-called hybrid journals, by January 2020 (www.coalition-s.org). At the same time, traditional publishers of scientific literature have recently faced tougher negotiations with university libraries, and universities in several countries have quit subscriptions with large traditional publishers.[15-17]

These ongoing changes in the physical world and the scientific community determine some of the basic conditions for current research on permafrost, in terms of topics studied, collaborations, methods and scope. Our combined understanding of permafrost regions depends on the research produced and how well previous research outputs are communicated and incorporated into ongoing research efforts. To identify how the field of permafrost science has developed and to explore how scientists build on existing permafrost knowledge, we analyzed scientific articles published over two decades, before (1998–2007) and after (2008–2017) the fourth IPY. We compared this bibliometric data to results from an online survey in which respondents were asked to list the most influential and inspiring publications on permafrost in their view. The objectives were to illustrate the state and movement of permafrost studies in the publication landscape, to evaluate the connectivity of research fields over time, and to identify how scientists value and build on each other's work.

2 | METHODS AND DATA

Lists of publications with the word "permafrost" in abstracts, titles or keywords were downloaded from Web of Science (WoS) and Scopus for the period 1998–2017 (herein called "permafrost publications"). Records lacking accurate authors or publication years (e.g., "N/A," "40") were removed from the resulting lists. The two lists (WoS and Scopus) were merged and duplicate records, identified by identical DOI or titles, were removed. This generated a list of 10,883 publications (Supporting Information). The number of permafrost publications per year, per journal and per country (of first author's affiliation) were summed, and the journals with the most publications were classified into broad categories based on disciplinary focus. For the WoS list, abstracts for the publications were also downloaded, which was not feasible for the Scopus database due to the number of records and technical limitations.

To visualize the diversity of permafrost research, we used the bibliometric mapping software VOSviewer[18] on the data from WoS. VOSviewer uses a similarity matrix which is a normalized co-occurrence matrix (e.g., co-occurrence of terms or keywords in documents, or number of co-authored publications) to map items in two-dimensional space so that the distance between the items reflects their similarity. Thus, the distance reflects the strength of the relationship between items, with a smaller distance indicating a stronger relationship.[18] This method is similar to multidimensional scaling methods such as principal components analysis or non-metric multidimensional scaling. In the bibliometric map, links between items are shown as lines and represent the strength of connection between items.[18] For better visibility we only show the 200 strongest links. A detailed description of the software concepts and methods is available from the software distributor.[18,19] We tested a large number of software settings and chose the settings providing the best compromise between information content, spread and readability (as outlined below), while staying as close as meaningful to the default settings. Other settings would provide similar interpretation of the results. The distribution of key terms in permafrost science is presented by creating a co-occurrence map that counts the articles in which a term occurred at least once in the title or abstract (binary counting; default). Co-occurrence maps show the relatedness of terms based on the number of documents in which they occur together.[19] A limited number of terms (n = 105) were homogenized for spelling and singular/plural, and others were excluded if they had no scientific implication (e.g., "paper") or if they were general to the field (e.g., "permafrost," "permafrost region"). We also excluded country names (n = 23, e.g., Switzerland), but kept geographical regions (e.g., Swiss Alps). We applied a setting of 50 minimum occurrences of a term for the entire period, 15 for the first period (1998–2007) and 40 for the second period (2008–2017). This normalized the amount of terms to ~750 per time period, while avoiding overrepresentation of rare terms. Using standard settings, the visualizations would be difficult to compare, as the WoS database does not contain the same number of publications for the different periods used. Normalization was necessary to achieve similar orientation and spread for all three

periods (1998–2017, 1998–2007 and 2008–2017). We then chose to display the 200 most relevant of these terms, using the layout settings attraction = 2.0 and repulsion = 0.0. Overall, this approach provided the best visual comparability between the three periods while providing an overview of the depth of the field and maintaining readability. Automatically generated color clusters of related terms were produced for both periods. The cluster resolution can be adjusted and we increased the default value from 1.0 to 1.3 for both time periods to differentiate major themes and name larger clusters. The main theme of each cluster was interpreted and displayed. Furthermore, we generated a bibliometric term map for keywords mentioned at least 200 times (n = 15; layout settings: attraction = 3.0 and repulsion = 2.0). This includes keywords set by the authors and WoS database keywords.

We applied methods for quantifying the so-called lexical diversity of keywords to address whether the field has become more diverse in topics over time. Keywords that occurred with more than one spelling, such as "active layer" ("active-layer") and "climate change" ("climate-change") were merged into the most commonly occurring spelling in the WoS data (i.e., "active layer" and "climate-change" respectively for these two examples). The most basic metric for lexical diversity is the ratio of unique words to the total number of words in a text, the so-called Type to Token Ratio (TTR). This metric has the disadvantage of being sensitive to the total length of the text, and therefore several methods have been proposed that apply some correction for this bias. There is currently no consensus on which method most accurately quantifies the topical diversity of a text, which is partly related to the fact that the concept of topical diversity is elusive to define.[20] We applied three of the most commonly used methods on the keywords of papers for the 1998–2007 and 2008–2017 periods. The Measure of Textual Lexical Diversity (MTLD) method measures the mean length of a text string that maintains a certain TTR.[21] With the Maas method the data are log-transformed to correct for the text length bias, and the lexical diversity is estimated by[22,23]:

$$a^2 = \frac{(\log Tokens - \log Types)}{\log^2 Tokens} \quad (1)$$

The Hypergeometric Distribution D (HDD) method calculates the probability of encountering any of each unique word in the text, in a sample of 42 words, using a hypergeometric distribution. The sum of the probabilities gives the HDD score.[21] The higher the score for these metrics, the higher the lexical concentration, which is the opposite of the lexical diversity.

To further explore potential diversification in topics, we compared the frequency of relevant keywords for the two periods. We include keywords that would be typical for classic core permafrost research, such as "thermal regime," "active layer" and "ice," as well as those typical for the new direction towards climate-carbon research, such as, "climate-change" and "carbon." We include all of the top five keywords for both periods: "climate," "climate-change," "temperature," "model" and "ice."

Research collaboration was investigated using VOSviewer and the WoS database, by mapping research organizations based on their number of co-authored documents between 1998 and 2017. A cutoff was defined at a minimum of 30 publications and 300 citations per institution, resulting in 107 mapped institutions (layout settings: attraction = 2.0 and repulsion 0.0; clustering resolution: 1.13). The size of each institution reflects its research impact in the network. We merged institutions that were listed under several names, for instance the University of Alaska and University of Alaska Fairbanks. Clusters were assigned automatically based on the strongest co-authorship links. We also produced a map of the average publication year in this network within the period 1998–2017 to identify established and newly active institutions.

We investigated the key literature in the permafrost field until 2017 by generating a citation network using the software CitNetExplorer.[24] This software analyzes the cited references in each of the publications in a database. Following standard procedure, the WoS data from 1998 to 2007 were first reduced to all connected items (n = 10,559) using internal citations from within the database. This removed n = 858 items without citations (n = 828) or with few citations (<4 citations; n = 30). We then defined publication clusters based on citation relationships. Publications from the same cluster are more closely connected. Clusters were defined using two parameters: cluster resolution, which defines the level of detail, was set to 2.0 and the minimum cluster size was set to 500. Both parameters influence the size and number of clusters overall and the subset of key publications represented in the network graph. This resulted in nine publication clusters ranging in size from n = 1,941 to n = 501 publications, and 903 unclustered publications. The network was then visualized using the 50 most relevant publications represented proportionally to the size of the clusters. In addition, we display the 10 most cited publications published before 1970 to highlight early influencers of the field. This threshold was chosen because there was a marked increase of publications after 1970. VOSviewer and CitNetExplorer output figures were graphically modified for readability using Inkscape.

An online survey was distributed through list servers (e.g., CRYOLIST) to permafrost researchers and professionals worldwide in November 2018. The survey asked respondents to "Name one (or more) scientific paper(s) or book(s) that you find the most inspiring in your field" (Supporting Information). It also asked for some basic demographic information (organization, country, sex and career stage). Survey data were classified into scientific papers, books and comments. The comments category included responses that did not refer to specific publications (such as "All the works by …").

3 | RESULTS

There has been a steady increase in permafrost publications over the study period (Figure 1), from 238 annual publications in 1998 to 1,174 in 2017. This is an increase of almost 400%. Looking only at WoS records, this increase is more than 550% (due to fewer publications at the start of this period, data not shown), while the WoS

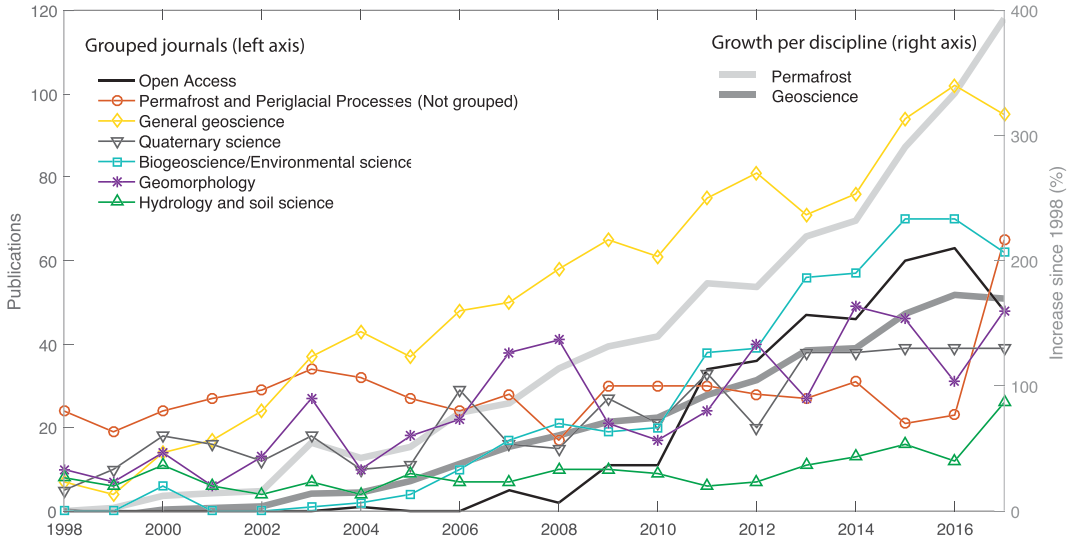

FIGURE 1 Top 21 permafrost journals grouped by disciplinary focus (*except for the journal *Permafrost and Periglacial Processes*, left axis) and relative increase in permafrost publications and in total publications for the top three WoS categories in which permafrost publications are registered (geoscience publications = "geosciences, multidisciplinary," "physical geography," "environmental sciences," right axis). Journals are grouped as follows: open access = *Biogeosciences*, *Cryosphere*, *Environmental Research Letters*; general geosciences = *Cold Regions Science and Technology*, *Earth's Cryosphere*, *Geophysical Research Letters*, *Cryosphere*, *Arctic Antarctic and Alpine Research*, *Geografiska Annaler Series A - Physical Geography*; Quaternary sciences = *Quaternary International*, *Quaternary Science Reviews*, *Boreas*, *Catena*; biogeosciences environmental science = *Journal of Geophysical Research - Biogeosciences*, *Biogeosciences/Environmental Research Letters*, *Global Change Biology*; geomorphology = *Geomorphology*, *Zeitschrift für Geomorphologie*, *Earth Surface Processes and Landforms*, *Journal of Geophysical Research-Earth Surface*; hydrology and soil science = *Hydrological Processes*, *Eurasian Soil Science* [Colour figure can be viewed at wileyonlinelibrary.com]

disciplinary categories "Geoscience, multidisciplinary," "Physical Geography" and "Environmental Sciences" increased by 170% for the same period. This shows that permafrost has become an increasingly hot research topic within the geosciences over the past two decades.

Permafrost studies are published in a wide range of journals: in total 1,746 (of which 374 with more than five publications) for the studied period. When ranked by the number of permafrost publications, the top 71 publishing journals account for only 50% of all publications. The remaining publications are distributed across a large variety of journals. In 1998, 10% of all permafrost publications were published in the journal *Permafrost and Periglacial Processes* (*PPP*). By 2017, this number had decreased to 6%, even though the absolute number of publications per year in *PPP* had increased from 24 to 65 between these years. An increase in publication numbers can be seen in most journals, and the creation of new journals (i.e., *The Cryosphere* in 2008) has led to further expansion. The most noticeable increase is found in biogeoscience and environmental-themed journals. For example, the *Journal of Geophysical Research – Biogeosciences* is the sixth most productive journal for permafrost publications for the period 1998–2017 but had no permafrost publications before 2005. The increasing interest in permafrost is also seen in high-impact journals, with five permafrost publications in the journal *Nature* for the period 1998–2007 and 26 publications for the period 2008–2017. Full open access journals (i.e., journals that only publish open access material) show a rapid increase in permafrost publications, taking off in 2006. The median permafrost publication has seven citations and was published in 2011. Ten per cent of publications have more than 46 citations, and 40% have fewer than five citations.

Figure 2 shows network clusters based on text in abstracts and titles of publications from the WoS list. It shows a diverse research field composed of several connected thematic clusters. The words with the oldest average publication year are related to geomorphology, glaciation and Mars. A biology cluster (e.g., DNA, species, sequence, abundance, bacterium) includes words of highly varying average publication years and citation numbers. A cluster with many engineering-related words (e.g., embankment, stability and construction, but also ground temperature and thermal regime) has average publication years around 2010 and 2011, but relatively low average citations. An outlier in this cluster is the Qinghai-Tibetan plateau, which has a recent average publication year, but still a relatively low average citation. The cluster with the youngest average publication year and the highest citation impact includes words such as atmosphere, carbon, decomposition and emission. "Climate change" is the most mentioned keyword (n = 1,435; except permafrost: n = 2,889) in the field of permafrost science, and together with "active layer," "carbon" and "tundra", yields the highest research impact. Looking at topical research clusters for the two periods 1998–2007 and 2008–2017, it is apparent that more distinct clusters have developed over time. The research related to Mars and the origin of life is less prominent in the field and research relating to carbon is starting to differentiate into niches. A relatively empty center for the second period compared to the first period can be interpreted as decreased relationships between the clusters over time[18] However, the overall

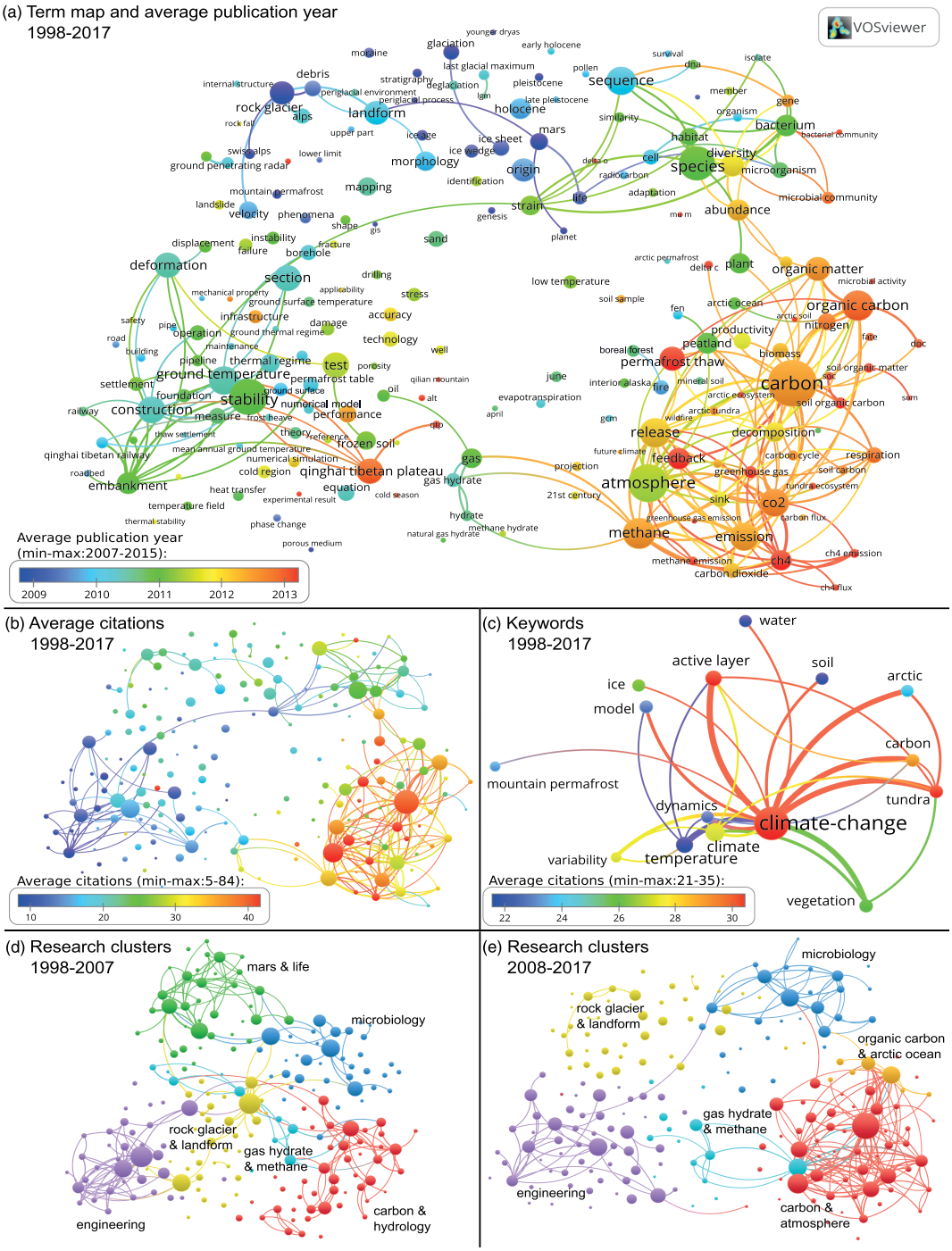

FIGURE 2 Bibliometric term maps of permafrost science research using the 200 most relevant terms defining permafrost research (a, b ,d, e). (a) 1998–2017 colored by average publication year, (b) 1998–2017 colored by average citations, (c) bibliometric term map for keywords mentioned at least 200 times between 1998 and 2017 colored by average citations, (d) 1998–2007 colored by research clusters, (e) 2008–2017 colored by research clusters. Sizes of objects are scaled by occurrences of terms, while locations of objects in clusters and width of links are determined by co-occurrence of terms [Colour figure can be viewed at wileyonlinelibrary.com]

connectedness within the community may have increased, while at the same time specialization may have occurred.

We found a decrease in lexical diversity of 0.2%, 1.6% and 17.6% using the HDD, Maas and MTLD methods respectively. This suggests that there has not been an increased diversity in topics, but perhaps instead a slight decrease over these 20 years. "Climate-change" is the keyword that has increased the most in frequency, followed by "carbon" (Table 1). In the first period, 5% of all articles included "climate-change" as a keyword and 2% included "carbon," while in the second period 11% included "climate-change" and 3% included "carbon" as keywords. The frequency of the keywords "thermal regime" and "model" did not change between the periods, while the

TABLE 1 Percentage of articles containing the listed keywords, for the two periods 1998–2007 and 2008–2017. Keywords with more than one common spelling have been combined, such that the listed words "active layer" and "climate-change" also include "active-layer" and "climate change"

Keyword	Frequency 1998–2007 (% of articles)	Frequency 2008–2017 (% of articles)	Relative change in frequency (%)
Temperature	3.9	4.9	26
Model	3.6	3.6	−1
Ice	3.5	3.6	3
Active layer	3.8	4.3	13
Thermal regime	1.6	1.6	2
Climate	6.1	6.5	7
Climate-change	5.1	10.6	108
Carbon	1.8	2.9	56

keyword "active layer" showed a slight increase. These results indicate that while publications focusing on climate-change and carbon-related issues increased considerably, there was no decrease in classic permafrost topics. In absolute terms, there has been an increase in articles with any of these keywords due to the increase in articles published between the two periods.

Figure 3 shows cluster networks based on co-authorships between institutions, colored by cluster (Figure 3a) and by average publication year (Figure 3b). Research collaboration mainly occurs between institutions located in the same country or wider geographic region, such as Scandinavia, as reflected in the automatically generated clusters (Figure 3a). The average publication year per institution helps to identify many institutions that have a long-standing tradition of permafrost research, most of which are still very active today (e.g., University of Alaska, Russian Academy of Sciences). Many of these are located near alpine regions (e.g., University of Oslo, University of Zurich and University of Colorado). Institutions with younger average publication years include (but are not limited to) US national laboratories, Stockholm University in Sweden and Chinese institutions.

The citation network (Figure 4) presents key research articles within permafrost science and how they are related to each other. Several automatic clusters were generated from which we identified the approximate main research theme. These show connectivity across themes and long-term research trends transitioning into newer topics. Some of the early most influential and most cited papers within the field are not about permafrost, but describe methods for example on isotopes,[25,26] or classic works on heat conduction and soil hydraulics.[27,28]

Most of the cited publications are recent (i.e., from the period 1998–2017). Earlier influencers provided groundbreaking descriptions

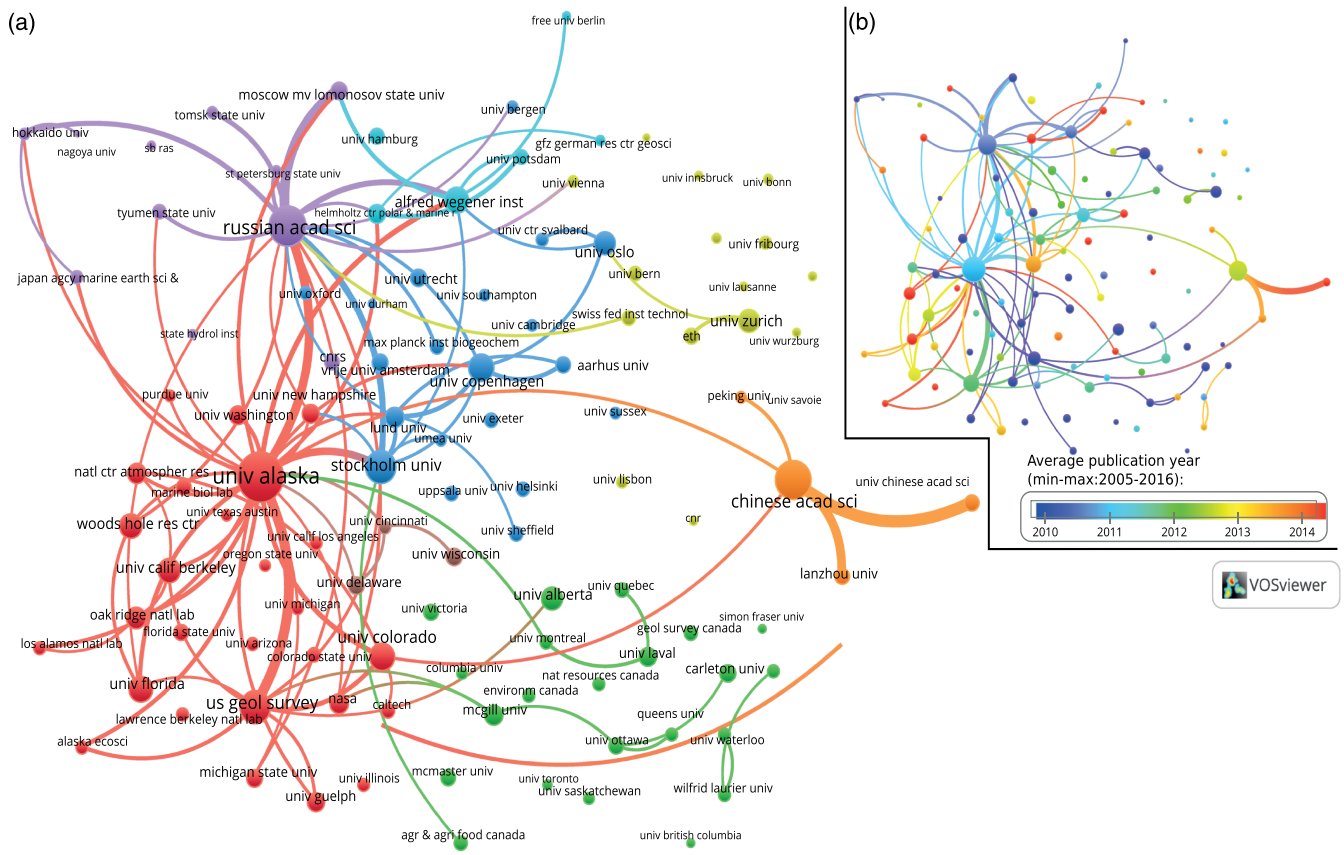

FIGURE 3 (a) Research collaboration investigated by mapping institutions based on their number of co-authored documents (1998–2017). The size of each institution reflects its research impact in the network. Clusters group the most related research environments. (b) The average publication year per institution and collaboration (lines) for the same term map [Colour figure can be viewed at wileyonlinelibrary.com]

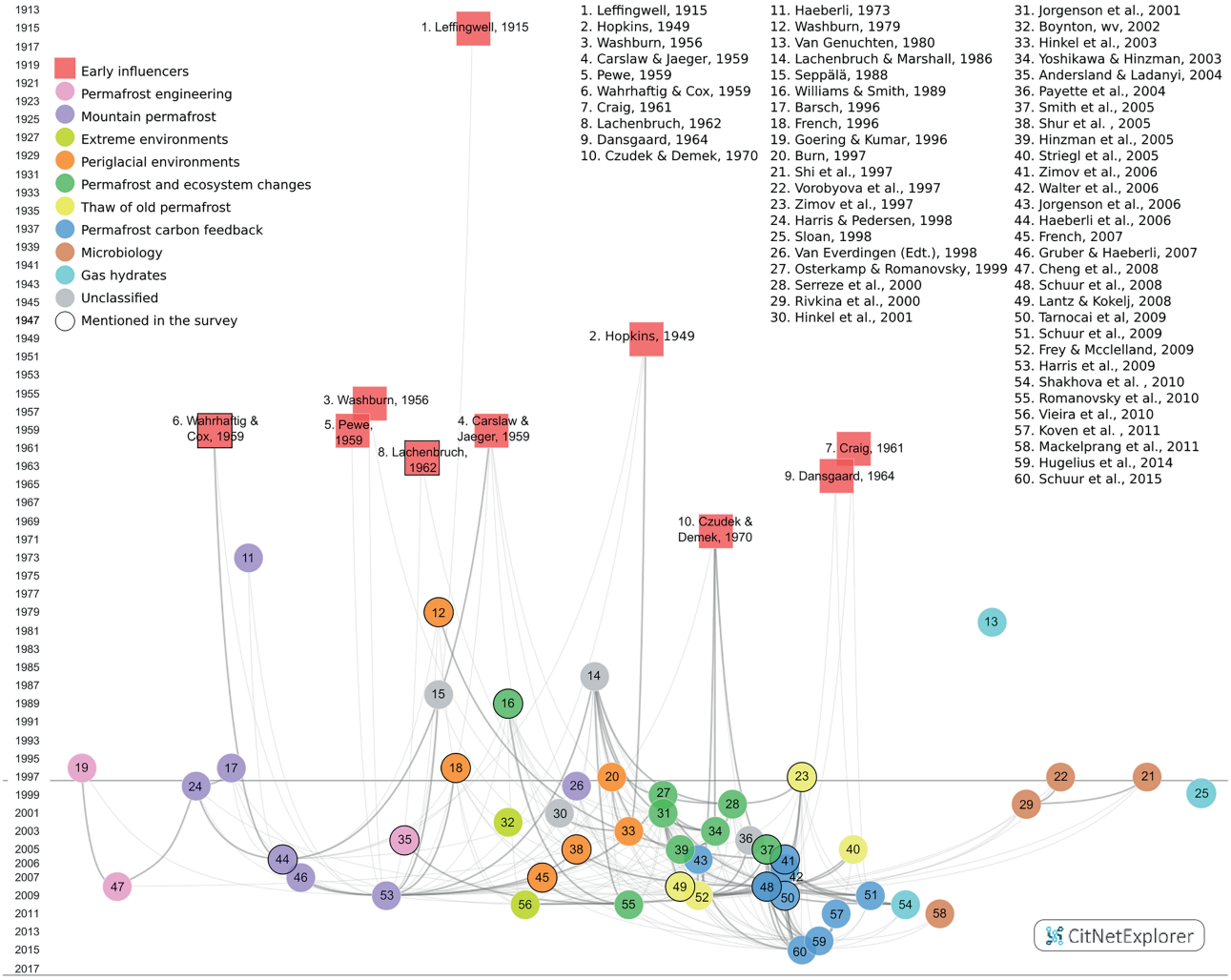

FIGURE 4 Citation network of permafrost science. The figure reflects the 50 articles that had most influence on permafrost research in the period 1998–2017, plus the 10 most cited articles within the network published until 1970 to reflect early influencers of the field. Colors reflect automatically generated clusters from the database showing relatedness of the articles. The number of displayed publications for each cluster is defined by the cluster size within the network. Publications that were also named in the survey are marked with black outlines. Connecting lines show direct and second-order citation links [Colour figure can be viewed at wileyonlinelibrary.com]

of periglacial landscape features such as thaw lakes[29] and ice wedges[30] as well as early work on oxygen isotopes[25,26] (Figure 4). Between 1970 and 1997, three textbooks on permafrost were published, which had a major impact on the field.[31-33] Publications providing a more detailed understanding of periglacial features and processes also made an impact,[34,35] and late in this period studies on microbiology[36,37] and carbon[38] can be seen in Figure 4.

3.1 | Survey responses

The survey yielded responses from 122 people (male = 69%, female = 30%, not answered: 1%) from 17 countries (6% not answered). Of the respondents, 46% were undergraduate or graduate students, 39% were post-doctoral researchers or research scientists, 16% had senior (> 5 years) positions in government or industry, and 18% were professors. The four most represented countries were USA (17%), Russia (16%), Canada (13%) and Germany (7%), cumulatively representing more than half of the total respondents (Figure 5). China is the largest permafrost community that did not provide survey replies. The used tool (Google survey) is not accessible in some countries, which might have affected the distribution of responses per country. The responses included 104 identifiable papers, all of which were on topics related to permafrost or nearby geoscientific fields (e.g., climate, hydrology, coastal processes), and 79 of which appeared in WoS (Supporting Information). Some respondents listed several publications. The most common keywords were "climate change" (n = 27), "temperature" (n = 8), "ground ice" (n = 6), "vegetation" (n = 6) and "ice" (n = 6). On average the WoS papers were highly cited (mean = 123, median = 58 citations), but papers with few or no citations were also included (Figure 5). The article with the highest number of citations (1,040), as listed in WoS, was by Tarnocai et al.[39] The oldest publication, by Wahrhaftig and Cox[40] was published in 1959, but most publications were recent (median = 2010, Figure 5). Some

respondents mentioned specific journals or authors rather than publications, for example

"The whole work by J. Ross Mackay. 201 papers. All worth reading, again and again."

The journals mentioned included *PPP* and *Biuletyn Peryglacjalny* (multilingual; Poland). Proceedings papers from permafrost conferences were also mentioned on several occasions.

The survey results revealed the importance of books as sources of inspiration in the field. Thirty-seven books were mentioned, in total 56 times. Classics in the field, such as *The Periglacial Environment*[33] and *Geocryology*,[32] were mentioned by several respondents, but also popular science books and novels were mentioned (e.g., *Silent Spring*[41] and *Arctic Dreams*[42]). Permafrost outreach materials (comics, videos), photos, movies, news articles and conferences were also sources of inspiration for our respondents.

4 | DISCUSSION

We have traced the development of permafrost science from a relatively small niche topic to a research field engaged in global challenges that receives attention from media and policy-makers. The field has grown, in terms of publications and citation-based impact. In our lists of permafrost publications from 1998 to 2017, we can trace back influential permafrost research to 1915[30] (Figure 4). Influential publications have since then presented findings on a range of permafrost landscape features and processes, as well as new tools and methods. From our survey, about 20% of the articles and 25% of the books mentioned by the respondents date from before 1998, and several of these books are also seen in the citation network (Figure 4), highlighting their importance for researchers today. A number of non-permafrost-related publications appear in the citation network,[25,27] indicating how influences from other disciplines have advanced the field from several directions. During the period 1998–2017, the field has experienced rapid growth and a shift in topics. The data show increased focus on the global carbon cycle and greenhouse gas emissions at different spatial and temporal scales, which has gained considerable attention also in terms of citations (Figure 2). Given the context of increased interest in Arctic areas and permafrost regions as part of the global climate system, as well as funding of large projects with this focus, this should be expected. Based on our analysis of keyword frequency, the growth of this climate change-related research has not been at the expense of research on traditional permafrost topics. However, with the growing number of publications, the absolute number of keywords has increased, and permafrost publications appear in an increasing number of journals. This could suggest a topical diversification of the field, but our quantification of diversity based on keywords instead indicate little change or a decrease in diversity. There is, however, no objective way to accurately quantify topical diversity based on text data, such as keywords.[20,43]

It is not only changes to the natural environment that explain the increase in permafrost publications. There has also been a considerable increase in publications on permafrost at the third pole (i.e., the Qinghai–Tibetan Plateau). The location of this topic in Figure 2 suggests that this is more strongly linked to engineering than to climate change topics, and the motivation for much of this research is

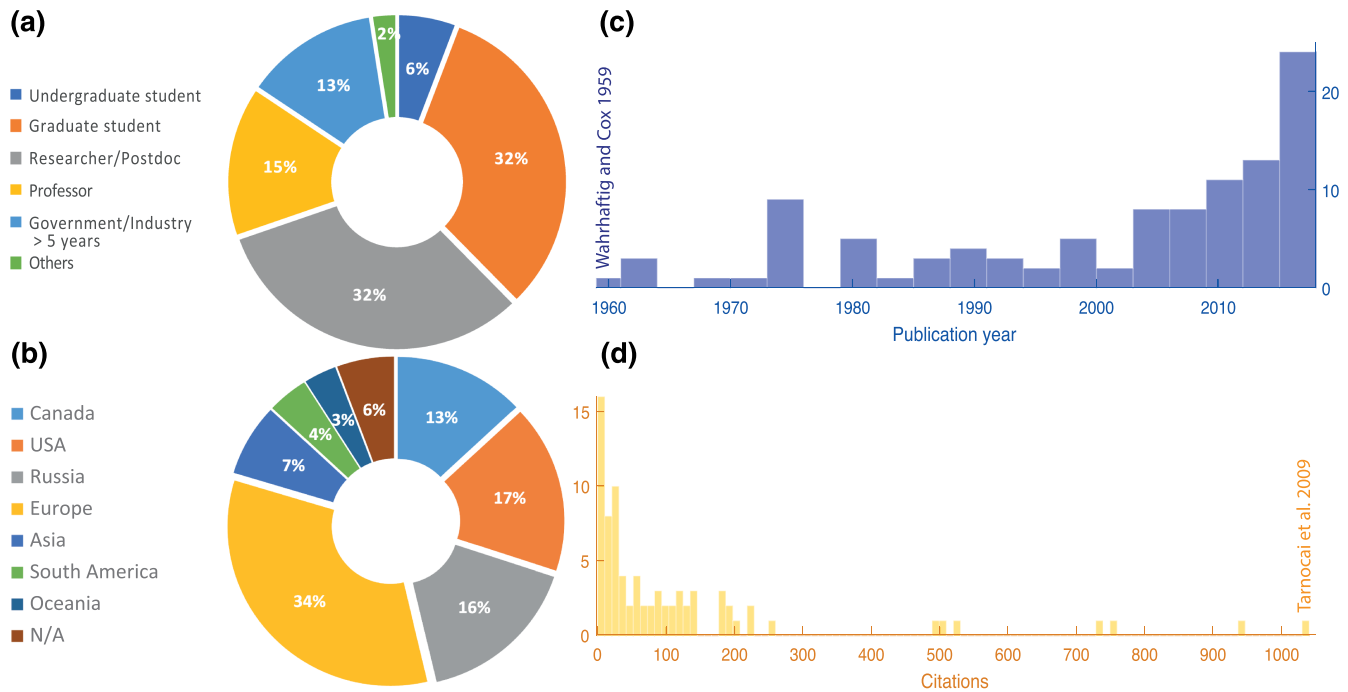

FIGURE 5 (a) Career stage of respondents; (b) respondents' country of residence; histograms for publication years (c) and citations (d) for the scientific publications mentioned by survey respondents. Note that only data that could be identified in WoS are used in the citations histogram (yellow), while the 25 publications that were not found in WoS (mainly due to old publication year) are also included in the publication year histogram (blue) [Colour figure can be viewed at wileyonlinelibrary.com]

probably related to major infrastructure developments in the region. Engineering-related research has on average low citation numbers compared to carbon-related topics (Figure 2), but has an impact through other forms of communication (e.g., reports) with relevant stakeholders, including government agencies, such as through technical guidelines.[44,45] Engineering research related to large infrastructure projects in North America, such as the Alaska Pipeline and Inuvik experimental pipeline, still inspires permafrost researchers today, as is evident from our survey (Supporting Information).

Our results can give insights not only into the development through time of permafrost science, but also to some extent to spatial trends. While many of the questions that motivate permafrost research today are global or pan-Arctic in scope, collaborations mainly occur within countries or regions but with strong ties to scientists in other countries (Figure 3). Research in northern Europe, Russia and the USA is relatively well integrated, while Canadian research is more isolated or linked to US research, and similarly, China is relatively isolated but with some ties to US institutions (Figure 3). It should be noted, however, that the bibliometric data used in this survey are not optimized for capturing literature published in languages other than English, meaning that Figure 3 does not necessarily provide a full view of the permafrost publication landscapes in, for example, Russian, German, French, Polish or Chinese. Russian and Western scientists have long published partly in different journals and languages, but international conferences have provided a forum for scientists from different countries to meet and exchange ideas. Our survey respondents mentioned the importance of International Permafrost Association permafrost conference proceedings as sources of inspiration, especially the earlier ones (Supporting Information). More recent international collaboration efforts include developments of databases, such as the databases for permafrost region soil carbon, ponds and the thermal state of permafrost.[1,46,47] Pan-Arctic and global datasets such as these are crucial for targeting the global questions that have been the growing focus for permafrost research during our study period, together with efforts for open scientific data. Other recent international collaborative efforts are the creation of early career researcher (ECR) networks such as PYRN and APECS.[48,49] These networks have fostered a new generation of permafrost scientists, who started their careers during this expansion of climate change-motivated permafrost research often in connection with the 4th IPY, in international collaborations through workshops, summer schools, online resources, and ECR-driven research and outreach projects.[50-52] The activities of such networks provide opportunities for ECRs to understand early on how to successfully collaborate across national borders and academic systems.

Beyond the growth in publication numbers and the topical shift in permafrost research, there has been a policy push toward making science more accessible in many countries, during our period of study. Publishing in open access literature makes scientific results accessible for more people, mainly within, but also outside of, the academic research community. Most of the top permafrost journals offer open access publishing options, but only a few journals qualify as so-called gold open access. The majority of the journals belong to the major scientific publishing houses, such as Wiley & Sons and Elsevier and offer so-called hybrid solutions for open access. It was not possible to extract from our data if publications in hybrid open access journals were published as open access. Therefore, the full increase in open access permafrost publications could not be assessed. However, gold open access journals show a strong increase in permafrost publications over the period 1998–2017, which we can anticipate to continue with persistent and increased pressure for open access of publicly funded research (Figure 1). One of the top journals for permafrost research, *Arctic, Antarctic and Alpine Research*, became full open access in 2018. The increasing pressure to publish in (gold) open access varies between countries and funding organizations, and will therefore impact scientists differently depending on in which country they work. It could also affect the perceived impact of publications, as the scopes and the so-called impact factors of journals will no longer be the main factors when deciding where to publish. The value of journal impact factors has been debated.[53] Studies show that the reliability of scientific results is not affected by or possibly even decreases with increasing impact factor of the journal in which the results are published.[54] However, the journal impact factor remains an important consideration for researchers when they publish findings, as it often affects the number of citations a publication receives and possibilities for the researcher's career advancement.[55,56]

The increased attention and funding towards permafrost research has resulted in a rapid increase in research output and thereby, hopefully, a better understanding of permafrost environments. However, the rapid growth in publications presents in itself a challenge for scientists, and especially those new to the field. With more than 1,000 permafrost publications per year, it becomes almost impossible both to keep up with the latest research and to read up on earlier publications. Although our survey results indicate that permafrost researchers value the earlier works of the field, retaining and building on this earlier research requires time to identify, access and read the relevant papers among an increasing number of publications. The paradox is that future researchers could end up spending more time reading but still read less of the relevant information for their own research. With the "publish or perish" pressure of today's academic and research institutions, we should expect this trend of increasing publication numbers to continue.

In contrast to our results from the bibliometric analysis, our survey results indicate that scientific publications can be a crude measure of impact, as scientists are inspired by information presented in a range of formats. Books were mentioned several times by the survey respondents—mainly permafrost and natural science textbooks. The importance of textbooks in the field is further illustrated in Figure 4, which shows how later influential publications build on these books. Media directed to non-scientists, such as photos and outreach material (Supporting Information), are also mentioned by the survey respondents. Exactly how this impacts research is not possible to deduce from our data, but it might motivate and help scientists to put their work in a broader context and to make it relevant and accessible to a larger group of people. With increasing interest in permafrost research and a changing funding landscape encouraging outreach activities, it can be argued that engaging with a wider audience

becomes more important. Books and public outreach materials also tend to synthesize information from scientific publications, which could help not only non-experts but also permafrost researchers themselves to navigate through the growing body of scientific literature.

Numbers of publications, citations and impact factors are common currencies for career advancement and funding for scientists. However, permafrost researchers have a much broader and nuanced view of scientific communication, and also highly value books and outreach materials, as our results illustrate. As the discipline increasingly focuses on questions of global societal interest, a broad communication targeting audiences beyond our scientific community is arguably of greater importance. International collaboration and open science can help advance permafrost science and has been increasingly used for tackling climate-related permafrost science issues.[46,47] Simultaneously, permafrost scientists, and in particular early career scientists, face some growing challenges. The pressure to publish together with increased research funding leads to a rapidly growing number of permafrost publications from which researchers need to extract relevant information. Researchers can either find more efficient ways to extract relevant information from the literature, spend more time on finding and reading the literature, or accept to read less of the relevant literature available. While large collaborative research and open data efforts can condense results from many studies and locations—and thus decrease the potential number of publications—it can be more difficult for single scientists to get traditional recognition for their work in such publications, such as first-authorship. Our study thus provides motivation to re-evaluate how our scientific output should be valued by research funders and employers. With a system that encourages high publication rates, we risk getting a less efficient uptake of existing scientific knowledge in new research.

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SUPPORTING INFORMATION

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