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A Scientometric Review of Research Status on Unfrozen Soil Water

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Abstract: Unfrozen soil water affects the physical, chemical, hydrological, and mechanical properties of frozen soils, and climate change makes these relationships more complicated. The objective of this study was to investigate the research status of unfrozen soil water using scientometrics. Publications on unfrozen water in frozen soil (UWFS) retrieved from the Web of Science were analyzed with scientometric software tools including VOSviewer, CiteSpace, and HistCite Pro. The annual publication trend, co-authorship of authors, organizations, and countries, and the co-occurrence of keywords were analyzed. The most utilized journals and high-impact publications were identified. The results showed that 2007 (the year the "Bali Road Map" was released) represents a turning point (from slow to rapid) in the development of research on unfrozen water in frozen soil. Researchers and organizations from China and the United States are the major contributors, while Cold Regions Science and Technology is the most utilized journal for publishing research pertaining to UWFS. Currently, there is still a lack of reliable and user-friendly methods and techniques for measuring unfrozen water content. Future efforts are required to understand the mechanisms governing the magnitude of unfrozen water content and to develop new approaches to accurately and rapidly measure unfrozen water content in both laboratory and in situ.

Keywords: bibliometric analysis; science mapping; VOSviewer; HistCite Pro; frozen soils; liquid water

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1. Introduction

Frozen soil, which is defined as a complex system of rock or soil containing ice at temperature of 0 °C or below, is distributed worldwide [1]. Frozen soil can be divided into permafrost and seasonal frozen soil according to the time period of freezing/thawing processes. Permafrost remains in a frozen state for more than two consecutive years with the top layer (also referred to as active layer) thawing in summer and refreezing in winter, while seasonally frozen soil only freezes in winter [2–4]. Over 55% of the land surface in the Northern Hemisphere undergoes seasonal freeze-thaw cycles and over 25% is occupied by permafrost [5,6]. It has long been recognized that unfrozen water (or liquid water) and ice coexist in frozen soils at subfreezing temperatures [7–9], even as low as −70 °C) [10]. The primary factor determining the magnitude of liquid water remaining unfrozen in frozen soils is temperature, followed by pressure, solute concentration, soil texture, and structure [11]. The coexistence of ice and unfrozen water remarkably influences the physical, chemical, hydraulic, and mechanical properties of frozen soil [12–16]. For instance, the phase change of unfrozen water to ice increases heat transport (thermal conductivities of ice and water are 2.2 and 0.6 W m^{-1} K^{-1}, respectively) [17,18], reduces hydraulic conductivity and permeability because ice impedes water flow [19], and increases soil strength [20]. Soil freeze-thaw dynamics result in a phase change between unfrozen water and ice [13,21], hydrothermal migration [22,23], release of greenhouse gas(es) [24], and salt accumulation [25,26] that alter energy and mass exchange at the soil–atmosphere interface. Frozen soil, therefore, impacts agricultural, engineering, and environmental practices and socio-economic development in cold regions [12,14,27–33]. Global climate change makes its effects more complicated [2,29,34–38].

The key to frozen soil studies is the determination of unfrozen water and ice content. Therefore, numerous efforts have been made to develop methods and instruments [13,15,39–43] to measure unfrozen water content and/or ice content. These achievements make it easier to investigate freeze-thaw effects on a wide range of soil processes and properties. However, there is a lack of overview on the research status of unfrozen water content at present, for the novice and expert alike. Scientometrics or bibliometric analysis is a scientific statistic and quantitative assessment of publications within a particular subject matter, based on data from citation indices [44,45]. It can be used to retrieve articles of interest, to identify research hotspots and seminal studies, to locate journals to read from or subscribe to, and to analyze interrelationships among authors from different institutions and countries, as well as schools of thought, etc. Scientometrics has been widely used to investigate the research progress in various disciplines, including soil science and hydrology [45–47]. However, to our knowledge, no such study has been conducted for unfrozen water in frozen soils (UWFS). The objective of this study was, therefore, to analyze the research status of publications on UWFS using scientometrics. Approaches including the co-authorship network visualization map, the citation network visualization map, cluster density visualization map, and the strongest citation bursts map were used to investigate global research trends in terms of publication volume, authors, institutions, countries, journals, and keywords. Discussions on the limitations of and applications in research of UWFS as well as perspectives on future studies are also given.

2. Materials and Methods

The Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (WoSCC) contains literature data since 1992. The data between 1992 and 2020 was downloaded from the WoSCC on January 20, 2021 for analysis. The query sets used for the literature search are: "TS = (soil) AND TS = (subfreezing OR freezing OR thawing OR melting OR frozen OR freeze-thaw cycle OR freeze/thaw OR * frost) AND TS = (liquid water content OR unfrozen water content OR ice content)", where TS indicates "topics" on the Web of Science. The search results were further restricted by languages and document types, so that only articles, letters, notes, books, book chapters, data papers, database reviews, and reviews written in English were retrieved. This search process returned a total of 1117 publications and they were saved as text files containing "full record with citation data". Each publication was then carefully reviewed to ensure that the majority pertained to unfrozen water content, a total of 719 publications were retained for scientometric analysis.

VOSviewer 1.6.15 [48] (The Centre for Science and Technology Studies, Leiden, Netherlands), CiteSpace 5.7.R1 [49] (Drexel University, Philadelphia, PA, USA), and HistCite Pro that was modified from the out-of-service HistCite [50,51] were used to perform scientometric analysis. VOSviewer 1.6.15, a Java-based software developed in 2009 by Eck and Waltman [48], is a tool for building and visualizing a scientometric network, which can quickly observe knowledge and research of a specific field. It was used to export the author collaboration network, the citation network, and density visualization map of keywords. Indices of VOSviewer include links (L, connection or a relation between investigated authors, countries or organizations) and total link strength (TLS). It was used to export the author collaboration network, the citation network, and density visualization map of keywords. HistCite Pro can be used to count the number of publications (N), total local citation score (TLCS, times cited by the 719 publications), and total global citation score (TGCS, times cited by the WoSCC), as well as to identify the high-impact studies in this field. CiteSpace is a software tool to present the rules and structure of scientific knowledge, which is used to analyze burst time of a keyword that reflects the development and revolution of research hotspots. "Burst time," indicates a time period when a keyword shows significant increase in publications. OriginPro 9.0 (OriginLab Corporation, Northampton, MA, USA) was used to illustrate annual change of publication volume on unfrozen soil water.

3. Results and Discussion

3.1. Annual Publication Trend

Using scientometrics, we can better understand the development of research on UWFS by examining the annual volume of papers published on the subject. Figure 1 shows the major research areas and annual number of publications from January 1992 to December 2020. These publications were generally from the Web of Science categories of geology (N = 332), engineering (N = 231), environmental sciences ecology (N = 149), water resources (N = 112), agriculture (N = 99), and physical geography (N = 98). Note that the total numbers of publications in these six categories are greater than 719, because some journals belong to two or more categories. In general, the annual number of publications shows an upward trend with some fluctuations. Between 1992 and 2007, the number of publications pertaining to UWFS was <20 per annum. However, 2007 marked an inflection point. Since that year, the number of publications on the subject has increased significantly, with a maximum of 99 publications in 2020 (Figure 1). The uptick in research on UWFS coincides with the release of "The Road Bali Map" [52,53], a two-year process of climate-related initiatives and commitments adopted by the United Nations toward finalizing a binding climate agreement at the 2009 United Nations Climate Change Conference. It would suggest that 2007 marks a period when climate change gained political and environmental recognitions with increased research interest in frozen soils as indicated by topics related to permafrost thaw and greenhouse gas emissions. Additional reasons for the increase in research on frozen soil are likely related to the overall increase in the volume of research journals pertaining to the subject matter, e.g., The Cryosphere.

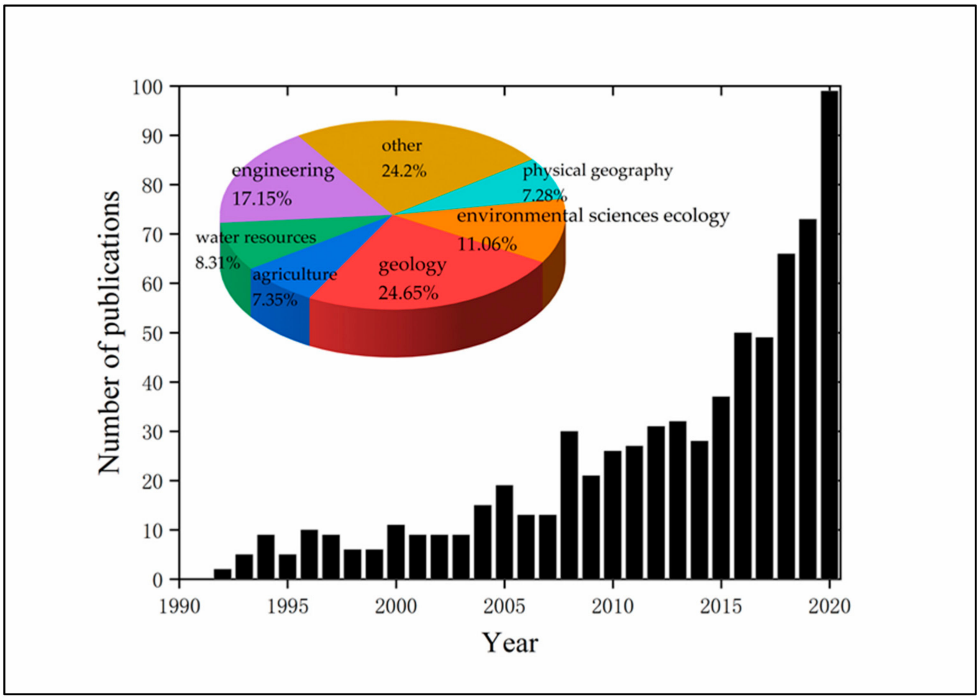

Figure 1. Number of annual publication on unfrozen water in frozen soils (UWFS) from January 1992 to December 2020 of Web of Science Core Collection. The pie chart is the top six major research areas.

3.2. Co-Authorship of Authors, Organizations and Countries

A total of 2023 authors participated in studies of UWFS. The top 10 authors are mainly from China, the United States, and Canada (Table 1). Figure 2 shows that there are 18 groups or clusters (i.e., the same color) of authors that have at least five publications on UWFS. Among them, eight groups of authors have co-operative relationships as their nodes connect (Figure 2). These authors demonstrate different impact as well. For instance, Dr. Yuanming Lai from the Chinese Academy of Science (Lanzhou, China) ranked first in terms of the number of publications (N = 19) and total local citation score (TLCS = 76), which indicates the times cited by the 719 publications retrieved for analysis. The high TLCS indicates that the publications of Dr. Lai were highly cited by researchers investigating UWFS (Table 1). Dr. Yuri Shur from the University of Alaska Fairbanks has the highest total global citation score (TGCS), which indicates that his publications were highly cited by research beyond this field (Table 1). Dr. Lin Zhao (Chinese Academy of Science) has greater total link strength (TLS) according to VOSviewer results (Table 1), suggesting that he has more coauthored publications. They lead the top three most productive teams in studies pertaining to UWFS.

The top 10 organizations belong to countries such as China, the United States, Russia, Canada, and Japan. The Chinese Academy of Sciences ranked first. It should also be noted that there are five authors who belong to the same institute (Table 1), which suggests a high level of expertise and overall experience for the Chinese Academy of Science in studies of frozen soil. Similarly, the same institute had the highest total for publications and the highest TCGS, which may be related to the fact that over 75% of China's landmass is affected by seasonally frozen soil and permafrost [54,55]. It is noteworthy that the number of publications from the University of Alaska (United States) ranked second, but their average indices are relatively higher, which may indicate that their publications have greater impact on studies of UWFS and other fields as well (Table 1).

All the 44 countries in the world that contributed to the study of frozen soils are widely distributed in the middle to high latitudes in the northern hemisphere. The majority of landmass in China, the United States, Canada, Japan, and Russia are subjected to seasonal freeze-thaw cycles or occupied by permafrost [5]. As the increasing concern of climate change on permafrost thaw or degradation [56,57] and its feedback to climate and engineering applications, it is not surprising to notice that these countries published the most studies on UWFS (Table 1). Prior to 1992, many pioneering working in Russia, Canada, the United States, and many European countries greatly promoted the study of frozen soil, including the mechanism of liquid water phase transition [58,59], measurement methods [43,60], and engineering applications [61], which was also related to the development plan for frozen soil areas in these countries at that time. For instance, the increasing research in China from the 1990s may be closely related to engineering projects [62,63], such as the construction and maintaining of the Qinghai–Tibet Railway [64] and Highway [65–67].

Figure 3 shows the mutual citation relationship among the 23 countries with minimum five publications. China, the United States, and Japan have published a large number of articles in this field (Table 1, Figure 3), which may represent that they have a greater impact in this field. In addition, China, the United States, and Canada have stronger collaborative relationships as indicated by the thicker lines between them compared with other countries (Figure 3).

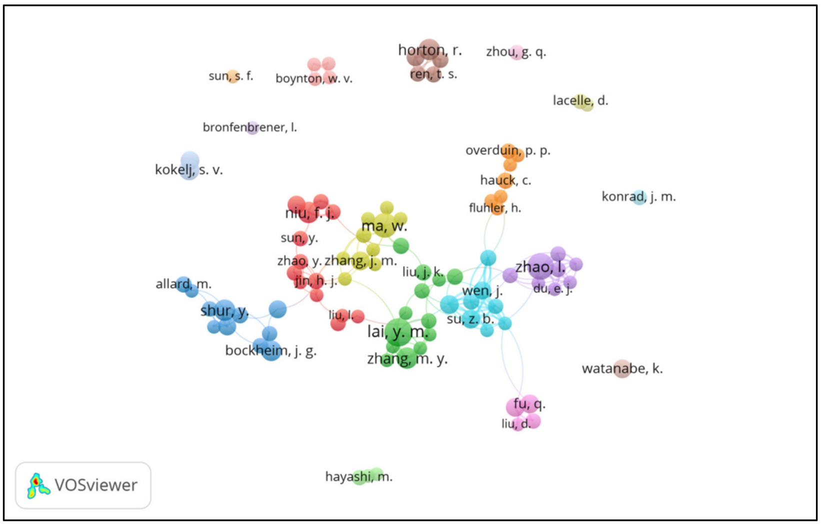

Figure 2. The co-authorship network visualization map of 95 authors out of 2023 authors with more than five publications as produced by VOSviewer. The size of circle and font in the map depends on the degree of nodes, the strength of links, and the amount of citations. The color of a circle represents the cluster to which it belongs and different clusters are represented by different colors.

Table 1. Top 10 authors, organizations, and countries published publications of unfrozen water in the frozen soil (UWFS). HistCite Pro is used to analyze and count the number of publications (N), total local citation score (TLCS), and total global citation score (TGCS). VOSviewer is used to count indices of links (L), total link strength (TLS), and citations (C). The TGCS in HistCite Pro is the same as C in VOSviewer and they are, therefore, merged.

No.	Items	N	TLCS	TGCS/C	L	TLS
	Top 10 authors					
1	Lai, Yuanming (Chinese Academy of Science, China)	19	76	326	8	26
2	Zhao, Lin (Chinese Academy of Science, China)	17	44	345	9	38
3	Ma, Wei (Chinese Academy of Science, China)	15	41	261	8	16
4	Shur, Yuri (University of Alaska, United States)	11	37	484	7	21
5	Zhang, Mingyi (Chinese Academy of Science, China)	11	65	276	5	18
6	Niu, Fujun (Chinese Academy of Science, China)	11	26	176	4	13
7	Horton, Robert (Iowa State University, United States)	11	18	111	4	25
8	Bockheim, Jams G (University of Wisconsin, United States)	10	22	522	2	7
9	Kokelj, Steven V (Carleton University, Canada)	10	51	361	1	7
10	Burn, C R (Carleton University, Canada)	9	58	401	1	7
	Top 10 organizations					
1	Chinese Academy of Science, China	143	313	2066	34	135
2	University of Alaska, United States	53	109	1960	33	50
3	University of Chinese Academy of Sciences, China	49	98	539	10	72
4	Russian Academy of Sciences, Russia	25	22	336	10	17
5	University of Laval, Canada	20	30	535	9	13
6	Hokkaido University, Japan	17	49	318	5	12
7	University of Alberta, Canada	16	45	431	14	19
8	University of Washington, United States	16	64	1123	9	14
9	University of Saskatchewan, Canada	16	69	379	10	15
10	University of Colorado, United States	16	43	420	15	23
	Top 10 countries					
1	China	270	487	3180	15	108
2	United States	223	629	7509	20	157
3	Canada	127	320	3201	20	77
4	Japan	48	231	1347	7	40
5	Russia	47	42	753	14	51
6	Germany	33	57	870	15	47
7	Sweden	26	166	1124	17	44
8	Switzerland	25	168	910	11	25
9	France	22	28	565	14	29
10	Italy	18	10	380	14	27

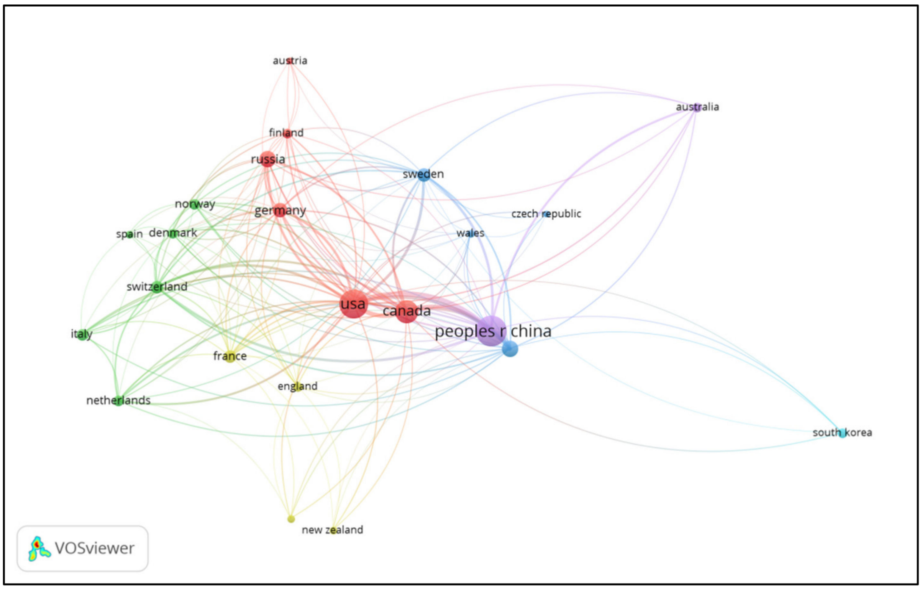

Figure 3. The citation network of 23 countries with minimum five publications (VOSviewer 1.6.15). The size of the circle and font in the map depend on the degree of nodes, the strength of links, and the amount of citations. The color of the circle represented [sic] the cluster to which it belonged, and the cluster was represented [sic] by different colors.

3.3. The Most Recognized Journals

There are 217 journals that published 719 publications on UWFS, with the top 10 journals accounting for 38.66% of the total publications (278, Figure 4). The most utilized journal is Cold Regions Science and Technology that published 103 papers on UWFS, followed by Permafrost and Periglacial Processes and Water Resources Research (Figure 4). The study of frozen soil and unfrozen water is of great significance in engineering [68,69], mechanics [70,71], and water resources or hydrology [72,73] in cold regions. It is understandable that these three journals carried a significantly higher volume of such studies compared to other journals. It should also be noted that there are two open-access journals, The Cryosphere that was launched in 2007 focusing on all aspects of frozen soils and ground on Earth and on other planetary bodies, while the Vadose Zone Journal that was published under the Open Access model since late 2017 has special sections focusing on cold region hydrology and frozen soil processes. These journals are expected to play an increasingly significant role in promoting frozen soil studies.

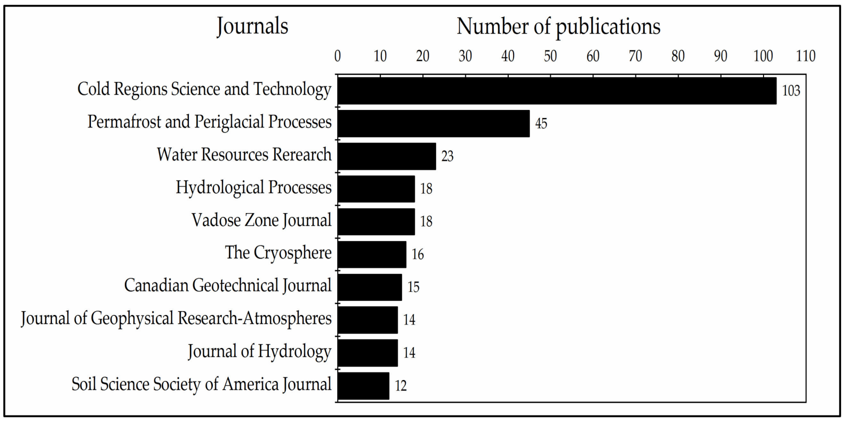

Figure 4. Top 10 journals published studies on unfrozen water in frozen soils (UWFS) from 1992 to 2020 based on Web of Science Core Collection.

3.4. The High-Impact Studies

Figure 5 shows the top 30 cited publications pertaining to UWFS using HistCite Pro, the number in each box within the figure references the paper's order in the database used for analysis. Examining the use of time domain reflectometry for measuring liquid water content in frozen soil (number 28, Figure 5) [39], which establishes a relationship between time-domain-reflectometry (TDR)-measured dielectric permittivity and gas-dilatometer-measured unfrozen water content, is the most cited publication. The method described in this article advances use of the TDR method in frozen soil studies, but the relationship (TDR to gas-dilatometry) is dependent on soil and known total water content (i.e., unfrozen water and ice content), for which there is no universal relationship [13,14,16]. Similarly, other articles in the top 30 cited list presented in Figure 5, e.g., the paper of 30 [60], 31 [74], 206 [40], and 352 [75] focus on the calibration of, or applications of, TDR in measuring unfrozen water content. In addition, publications referencing methods such as nuclear magnetic resonance (NMR) [40], Gamma-ray attenuation [75], and heat pulse (article 247) [76] to measure unfrozen water content and soil freezing characteristics were also highly cited. The papers of 143 [77], 54 [78], 57 [79], 105 [80], 129 [81], 152 [82], 247 [76], and 279 [83] incorporated effects of unfrozen soil water into heat transfer processes to better understand the characteristics of soil freezing and thawing processes and frozen soil permeability or infiltrability. However, the mechanisms defining the magnitude of unfrozen water content still remain unclear and more studies are required [84].

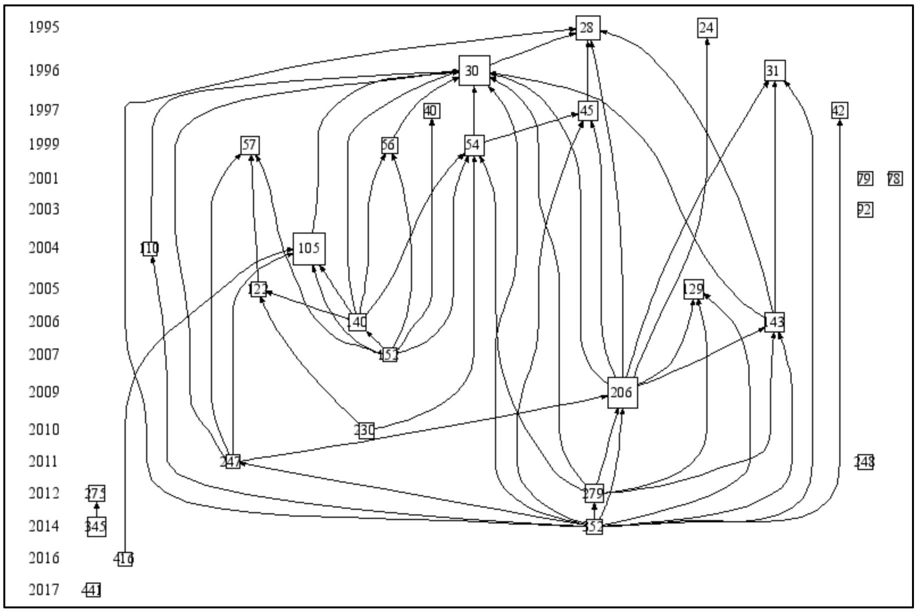

Figure 5. The citation (TLCS) analysis map of the top 30 publications on unfrozen water in frozen soils (UWFS) using HistCite Pro based on data retrieved from the Web of Science Core Collection. The left column is the year that corresponds to the node on the horizontal line. Each node represents a publication, and the number within represents the paper's order in the database used for analysis in the HistCite Pro. The size of the node corresponds to the number of citations, while the arrows represent the citation's relationship to other publications in the list; more arrows indicate more connectivity to other citations.

3.5. Co-Occurrence Analysis of Keywords

Figure 6 is a cluster density visualization map of keywords in the literature on unfrozen soil water research using VOSviewer 1.6.15. There are 114 keywords that occur more than 10 times. They are grouped into six clusters by VOSviewer that qualitatively show six research fields. For instance, the green-colored cluster mainly focuses on "permafrost" in "Qinghai-Tibet Plateau", "Alaska", "Canada", "Mackenzie Delta" under "climate change". The blue-colored cluster is related to "snow cover" or "snow" and their effects on "soil moisture" (as well as its measurement as indicated by "dielectric constant"), and "runoff". While the pink-colored cluster is characterized with soil mechanics and numerical modeling as indicated by keywords of "frost heave", "creep", "movement", "shear strength", "tensile strength", "strength", and "model".

Figure 7 reflects the development and evolution of trending topics in the research of UWFS between 1992 and 2020. For example, "Time domain reflectometry" (TDR) is a convenient and accurate method for measuring soil water content that has been in use since the 1980 s, and has become the predominant method for assessing soil moisture starting in the 1990 s. It is the keyword with the earliest and longest burst time, which indicates that this method had been widely used to measure unfrozen soil water content [12,13,15,16,39,74,75,85,86]. Other keywords including "porous media", "coupled heat" and "permittivity" are also related to the measurement of soil moisture content (Figure 7). "Frost", "permafrost", and "movement" [87] are keywords that have been concerned for a long period of time as indicated by their longer red lines. The research regions and climate type are "Alaska" [88], "Canada" [89], and "tundra" during the 2000s. In the 2010s, more problems [90,91] tend to run numerical "simulation" with "land surface model" by investigating "mass transfer", "thermal regime", and "coupled heat". The engineering-related "behavior", "thaw", or "vulnerability" of frozen soil or "embankment" terms also gained much attention [92,93]. Quantitative research on the relationship between frozen soil moisture content and soil mechanical stability is of guiding significance to the development of engineering construction. The interaction between climate change and the release of biochar from permafrost, and permafrost change has also attracted the attention of researchers. Examples associated with this may include the destruction of the subarctic landscape in northern Sweden [94,95] and the emergence of pink glaciers in the Alps [96,97] that are the manifestations of permafrost degradation and also a warning to mankind.

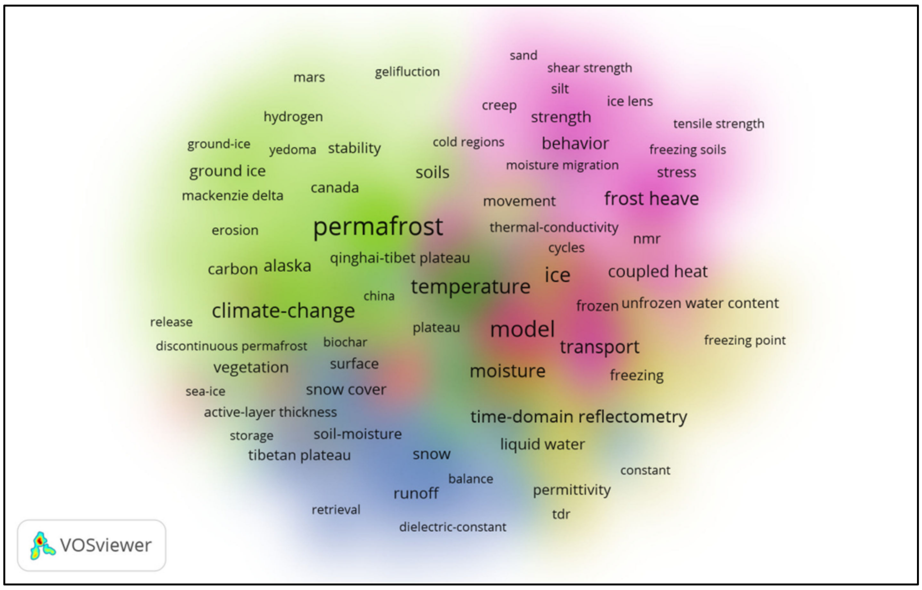

Figure 6. Cluster density visualization map of 105 keywords each occurs more than 10 times in the title, abstract, and keyword list (produced by VOSviewer1.6.15). Note: Font size and density (background color) of keywords are used to represent the total link strength (TLS). Greater font size [sic] indicates greater TLS, and TLS. The distances [sic] between each of the keywords indicate the relatedness of these research topics.

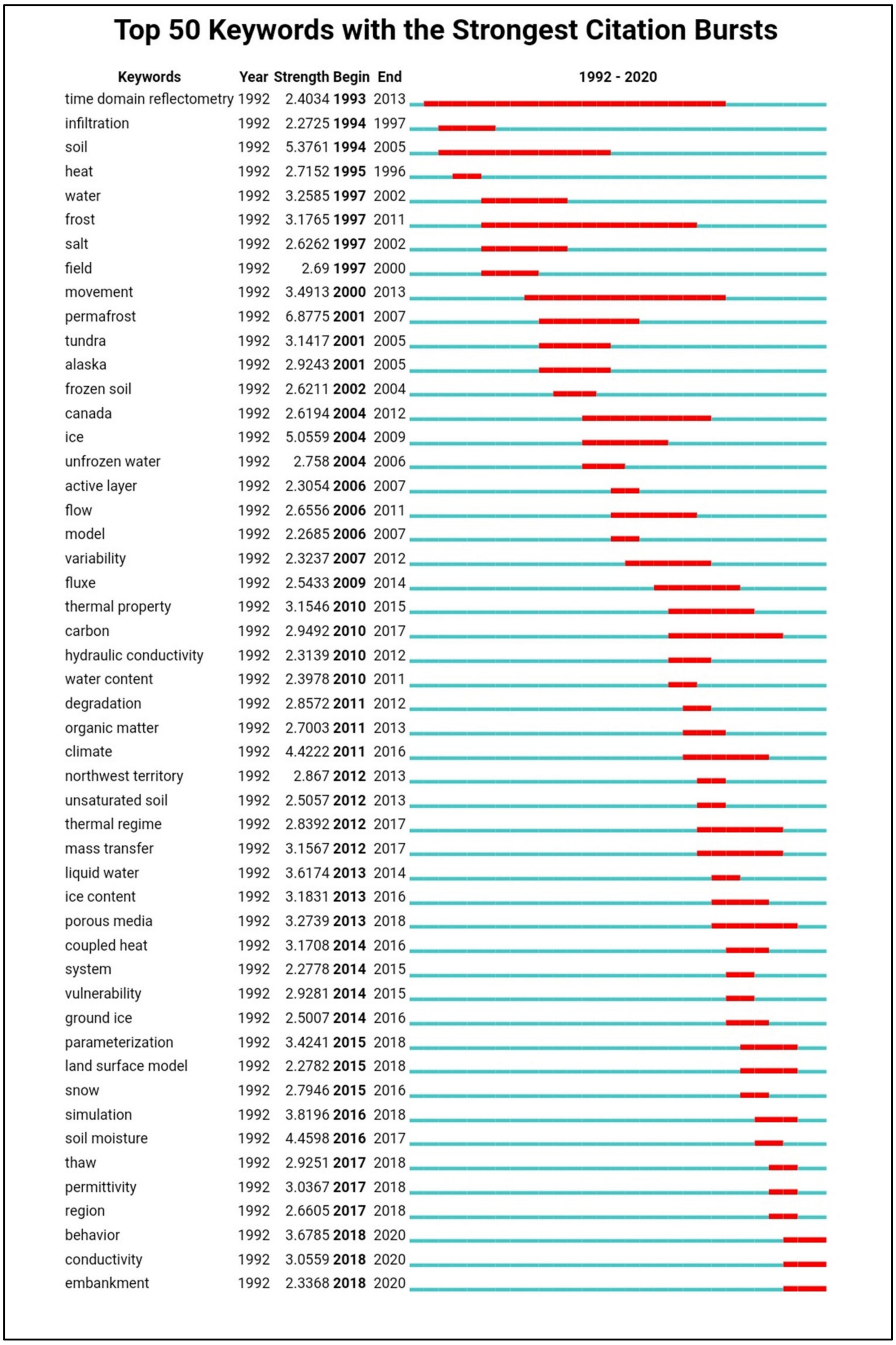

Figure 7. The strongest citation bursts map showed the top 50 keywords in frozen soil from 1992 to 2020 by CiteSpace. Blue indicates the time when keywords appear, and red indicates the time when keywords burst.

4. Conclusions and Perspectives

Publications on unfrozen water in frozen soil (UWFS) were analyzed by scientometric analysis from 1992 to 2020 based on data from the Web of Science Core Collection. Our analysis shows that the publication trend for research of UWFS can be divided into two periods. Prior to 2007, there was slow, but steady progress in the field (<20 publications per year), but thereafter, it appears there was an almost explosive interest in UWFS as the average annual number of publications on the subject increased almost 5-fold by 2020. Clearly, there was a renewed interest in UWFS that paralleled broader societal concerns regarding climate change and frozen landscapes. The United States, China, and Canada make the greatest contributions and have relatively high influence on this research field. At present, subjects on UWFS focus primarily on the measurement and modeling techniques, initiation of projects in frozen soil regions, and the impact of climate change on permafrost degradation. Scientometric analysis is an effective tool for visualization of unfrozen water research status in frozen soil.

In recent decades, great progress and breakthroughs have been made in the measurement of unfrozen water content. For instance, although NMR is not a widely-used method, it has been used successfully in both lab- and field-scale measurements of frozen ground, both with borehole tools as well as surface methods that offer a greater depth of investigation at lower resolution. It is noteworthy that determination of ice content presents a great challenge, but there are promising measurements combining neutron logging with gamma-gamma logs to distinguish ice content stratigraphy [75,98]. However, applications of these tools are challenged by the access and use of strictly regulated radioactive-sources. There is still a lack of ease of use, portable, and reliable method for accurate measurement of unfrozen water content both in laboratory and in-situ and no single method can be used to simultaneously measure both unfrozen water and ice content. The recently developed heat pulse method and its combination with time/frequency domain reflectometry method may provide a solution for this [15,99–101]. Mechanisms for determining the magnitude of unfrozen soil water content in frozen soils are still not clear and models used to predict unfrozen water content or soil freezing/thawing characteristics are still at their infancy [84,102]. In addition, more studies are required to understand how unfrozen soil water content and the increased freeze-thaw cycles would affect microbial activity, carbon and nitrogen cycles and the associated greenhouse gas emission, thickness of active layers [103,104], and landscape change [62,105–107] under climate change.

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