

## Article

# The Heat Pulse Method for Soil Physical Measurements: A Bibliometric Analysis

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Received: 4 August 2020; Accepted: 2 September 2020; Published: 4 September 2020



**Abstract:** Heat pulse method is a transient method that estimates soil thermal properties by characterizing the radial transport of short-duration line-source heat applied to soils. It has been widely used to measure a wide range of soil physical properties including soil thermal conductivity, thermal diffusivity, heat capacity, water content, ice content, bulk density, water flux and evaporation in laboratory and field environments. Previous studies generally focus on the scientific aspects of heat pulse method based on selected publications, and there is a lack of study investigating the heat pulse publication as a whole. The objective of this study was to give an overall view of the use of heat pulse method for soil physical measurements from the bibliometric perspectives. The analyses were based on the Web of Science Core Collection data between 1992 and 2019 using HistCite Pro and VOSviewer. The results showed an increasing trend in the volume of publications on this field and Dr. Robert Horton was the most productive researcher coauthoring papers on the heat pulse method. The co-authorship analysis revealed that researchers from soil science are closely collaborated, but this is not true for researchers in other fields. There is a lack of new young scientists committing to this field while the older generation of researchers are retiring. The United States Department of Agriculture Agricultural Research Services (USDA-ARS), the China Agriculture University and the Chinese Academy of Science were the top three organizations applying the heat pulse method, while the USA, China and Canada were the top three countries. The *Soil Science Society of America Journal*, *Water Resources Research* and *Agricultural and Forestry Meteorology* were the most widely used journals. The con-occurrence and citation analysis could be used to map the development of the field and identify the most influential publications. The study showed that the bibliometric analysis is a useful tool to visualize research status as well as to provide the general information of novices and experts alike on the heat pulse method for soil physical measurements.

**Keywords:** scientometrics; science mapping; VOSviewer; HistCite Pro; heat pulse method

## 1. Introduction

Soil physical properties are critical parameters determining soil's physical, biological and chemical processes, including seed germination and plant growth, decomposition of organic matter, nitrification and denitrification, and surface energy balance [1–3]. At present, heat pulse is the only automated

and accurate method that can be used to continuously measure soil thermal conductivity, thermal diffusivity and heat capacity [4–6]. The heat pulse method is a transient/non steady-state method that estimates soil thermal properties by characterizing the radial transport of short-duration line-source heat applied to soils [7–9]. Compared to the steady-state methods (e.g., guarded hot plate, heat flux meter, and divided bar method), the heat pulse method is a more amenable approach with respect to accuracy, measurement time, cost, and portability [10,11]. Therefore, the heat pulse method has been widely used to measure soil's physical properties in disciplines such as earth and environmental sciences, planetary science, and engineering [12–19].

The heat pulse method can be divided into single-probe heat pulse (SPHP) and dual-probe heat pulse (DPHP) methods [20,21]. Probes of SPHP and DPHP are composed of a heater that functions as a heat source and one or more temperature sensors that are used to record temperature change. SPHP differs from the DPHP probe mainly in two aspects: (1) Probe design: the temperature sensor and heater of the SPHP probe are mounted together within the same probe needle instead of in separate needles. The sensor developed by de Vries [10] to measure soil thermal conductivity was considered as the prototype of the SPHP probe, while the probe developed by Campbell et al. [9] was considered as the prototype of the DPHP probes. (2) Heating strategies and analytical solutions: the SPHP method generally applies a longer period of heat pulse than that of the DPHP method (e.g., 8–15 s for DPHP [9,21–24] vs.  $\geq 1$  min for SPHP [10,25,26]). The DPHP is not affected by probe characteristics as SPHP and all three soil thermal properties can be simultaneously estimated using DPHP. Wang et al. [6] reviewed the theory and solutions of SPHP and DPHP methods for determining soil thermal properties. Recent developments have also coupled the heat pulse method with other probes (e.g., time domain reflectometry (TDR), frequency domain reflectometry (FDR) and porous media) to measure a wide range of other soil physical properties (e.g., water content, ice content, bulk density, water flux, heat flow and evaporation) in addition to soil thermal properties in laboratory and in situ. He et al. [4] reviewed the development and application of the heat pulse method for soil physical measurements over a period from 1888 to 2018, with a focus on probe design, construction, calibration, applications, and limitations and perspectives on future studies. Other studies reviewed the advances of heat pulse from different aspects [5,27,28].

However, it is noticeable that all the current studies focus on the scientific aspects of the heat pulse method using selected publications. There is a lack of investigating the research status of heat method with all the related publications. Bibliometric analysis (also referred to as science mapping or scientometric analysis) is a useful tool to quantitatively assess the status, development, trends and patterns of the literature of a specific research field [29]. The analysis is usually based on a literature database such as Web of Science or Scopus that contains a large amount of literature sources. Bibliometric programs are usually used to create, visualize and explore scientific mapping based on bibliometric network data. The bibliometric approach has been widely used to give insights into soil pollution [30–33], soil remediation [34,35] and soil health [36], for example. The objective of this study was to give an overall view of the use of the heat pulse method for soil physical measurements from the bibliometric perspectives.

## 2. Material and Methods

The Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (WoSCC) contains literature data from 1992 up to date. The data between 1992 and 2019 were downloaded from the WoSCC on May 11, 2020 for analysis. The query sets used for the literature search are: “TS = (heat pulse OR HPP OR dual probe heat pulse OR DPHP OR single probe heat pulse OR SPHP OR thermo-time domain reflectometry OR thermo-TDR OR KD2 pro OR Hukseflux thermal sensors OR heated needle OR TP01 OR TP02 OR TP08 OR ISOMET2114 OR TPA2000 OR Quickline 30 OR STP-1 OR TK04 OR thermal probe OR thermal needle OR needle probe OR cylindrical probe OR hot wire method OR line heat source OR distributed temperature sensing OR DTS OR nonstationary method OR non steady state method OR transient method) AND TS=(soil) AND TS =

(thermal properties OR thermal conductivity OR thermal resistivity OR thermal diffusivity OR heat capacity OR specific heat OR soil water content OR soil moisture content OR ice content OR water flux OR evaporation OR phase change)". Only articles, letter, book/book chapter and reviews written in English were retained. The results were further refined based on the Web of Science categories (e.g., Soil Science, Water Resources, Geosciences and Engineering). The refined data were then saved as a text file containing "full record and citation data" for bibliometric analysis.

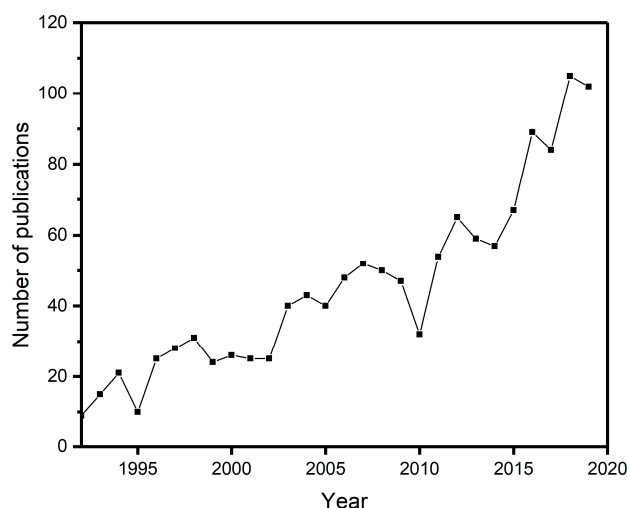
The VOSviewer (version 1.6.15 [37]) and HistCite Pro (history of cite) were used to do the analysis and visualization of the retrieved data. The VOSviewer is a cluster-based program developed by Nees Jan van Eck and Ludo Waltman from the Leiden University [29]. This software enables the user to create, visualize and explore scientific mapping in cluster format based on bibliometric network data. The co-authorship of authors, organizations and countries and the co-concurrence of keywords were analyzed with the VOSviewer. A full counting method was used, so that each co-authorship and co-occurrence has the same weight regardless of the order and number of authors in the coauthor list. Publications with 25 coauthors/countries or more were excluded for analysis by default, but no such case was found in this study. The co-authorship analysis determines the relatedness of items based on the number of co-authored publications. The co-occurrence analysis determines the relatedness of items based on the number of publications that occur together.

Because the original HistCite that was developed by Eugene Garfield [38] for analyzing WOS data is no longer in active development or officially supported by Clarivate Analytics [39], the HistCite Pro was used. The HistCite Pro ([40], in Chinese) is a click and run version modified by Qing Wang from Chinese Academy of Science based on the original HistCite. This was used to create the citation network. The citation network analysis determines the relatedness of publications based on the number of times they cite each other. It can be used to identify the most influential publications in a research field. In addition, the number of papers on heat pulse method for soil physical measurements published each year was assessed.

### 3. Results and Discussion

#### 3.1. Annual Publication Trend

A total of 1319 publications (1283 articles, 28 reviews and 8 others) written by 3892 authors from 291 journals were retrieved from the WoSCC following the preset procedure and control criteria (Figure 1). The volume of publications is much larger than the study of He et al. [4], who collected a total of 490 articles on this topic with the main focus on the heat pulse method. However, this study includes all publications that pertain to the use of the heat pulse method. Generally, it shows an increasing trend over the period from 1992 to 2019, with an annual fluctuation. A growing number of publications will be expected in the future, which indicates that the heat pulse has gained increasing acceptance and applications for soil physical measurements.



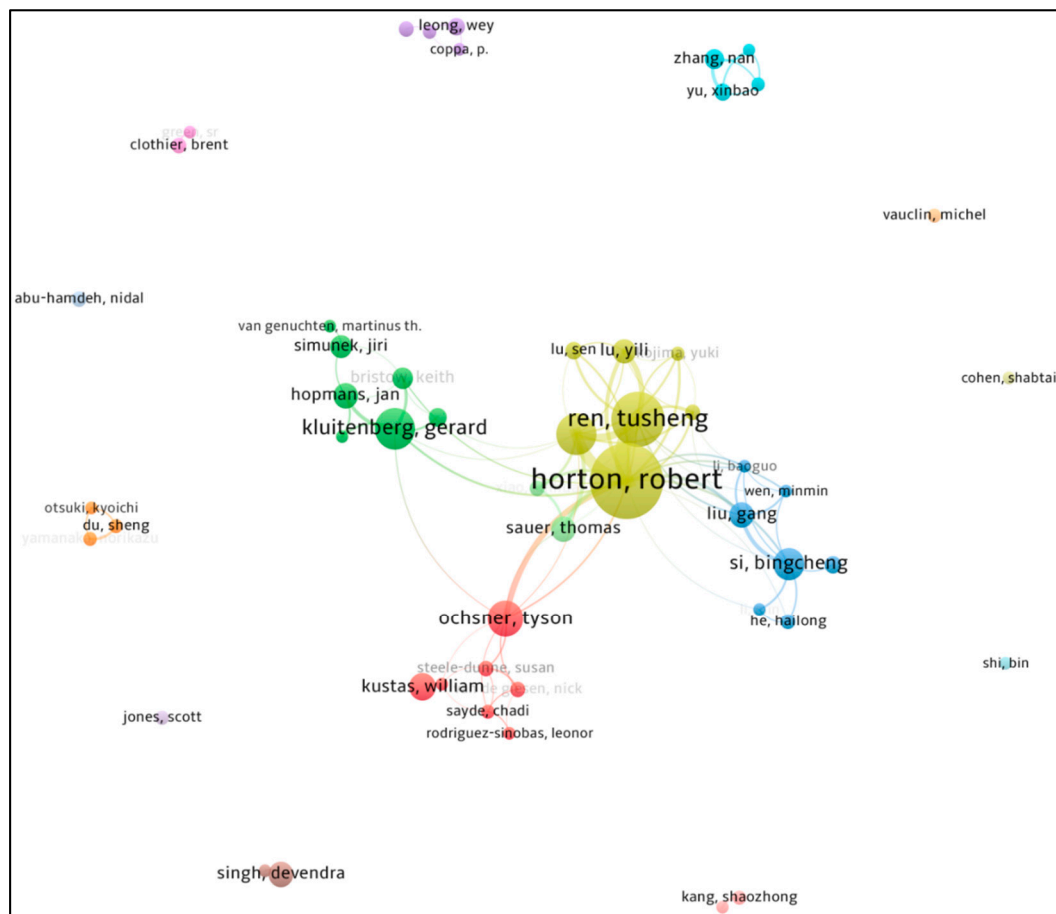
**Figure 1.** Annual publications on heat pulse method for soil physical measurements based on data from Science Citation Index Expanded (SCI-EXPANDED) database of the Web of Science Core Collection (WoSCC).

### 3.2. Co-Authorship of Authors, Organizations and Countries

A total of 52 authors met the threshold of a minimum of five publications per author in the co-authorship network map (Figure 2). There are 16 clusters, which indicate 16 closely worked groups highlighted in different colors. The middle five clusters have close connections between each other but the remaining 11 clusters did not show collaboration with the others. It is noted that Drs. Robert Horton, Tusheng Ren, Joshua L. Heitman Gerard J. Kluitenberg and Tyson E. Ochsner are the top five most productive researchers on the heat pulse method for soil physical measurements (Table 1). Their research was highly cited by both the heat pulse method community, as indicated by the high TLCS values, and researchers outside of the community, as indicated by the high TGCS/C values (accounting for ~16% of the total citation). It is interesting to note that the top 2–5 researchers were members of Dr. Horton’s research group in Iowa State University. Some of them still collaborate closely, as indicated by the thicker link between them (Figure 2 and Table 1).

However, there is a desire to attract more researchers to improve or apply the heat pulse method, because some of the researchers are going to retire or switch their research interests. For example, Dr. Keith Bristow moved his research interests to different fields after his many pioneering works on the heat pulse method [8,41,42]. Dr. Jan Hopmans recently retired from the University of California, Davis. However, it is good to see that some talented young scientists including Drs. Sen Lu, Yili Lu, Zhengchao Tian, Yuki Kojima and Minmin Wen are rising in this field. It is also noteworthy that researchers from Engineering such as Drs. Nan Zhang and Xinbao Yu (University of Texas at Arlington, USA) and Devendra N. Singh (Indian Institute of Technology, India) also applied the heat pulse method for the measurement of the thermal conductivity/resistivity of soil and other materials. However, other engineers, including Drs. Kathleen Smits and Benjamin M. Wallen (Colorado School of Mines, USA), were not detected by the VOSviewer [43–45].

The top productive authors, organizations and countries are closely related (Table 1). Five institutes in USA and three institutes in China were among the top 10 organizations committing to publications on the heat pulse method for soil physical measurement (accounting for ~34% of the total publications). Therefore, the USA and China were ranked as the top two countries on the number of publications, citations as well as links, and total link strength. This is followed by Canada, with contributions mainly from University of Saskatchewan, Saint Mary’s University and University of Alberta. Australia and Germany ranked as fourth and fifth on the number of publications.



**Figure 2.** Co-authorship network map of authors with a threshold of five publications per author and maximum 25 authors per publication (produced with the VOSviewer). There are 16 clusters (closely worked group) with a total links of 95 and total link strength (TLS) of 429. Researchers in the co-authorship network are linked to each other based on the number of publications they have authored jointly. The nodes (circles) and font in larger size indicate more publications and the thicker line indicates a stronger collaboration between researchers. Note that some labels were not shown in the figure because of overlap (e.g., label of Dr. Joshua Heitman was overlapped by the label of Dr. Tusheng Ren), while the labels in grey were assigned by the VOSviewer to avoid label overlap. The font size and capitalization cannot be adjusted in the VOSviewer.

It is interesting to notice that the majority of the soil scientists (e.g., Robert Horton, Keith Bristow, Gerard Kluitenberg, Jan Hopmans, Tusheng Ren, Joshua Heitman and Bingcheng Si) focused on the development and application of dual-probe heat pulse (DPHP) method to measure a wide range of soil physical properties [46,47], while the engineers (e.g., Devendra Singh) applied the single-probe heat-pulse (SPHP) method to measure soil thermal conductivity or thermal resistivity, which is the inverse of thermal conductivity [48–50]. However, more and more engineers are applying the DPHP method nowadays [17,51], which is probably because the DPHP method can be used to estimate all three soil thermal properties (i.e., thermal conductivity, heat capacity and diffusivity) and water content. In addition, researchers have also combined the heat pulse method with other probes (e.g., time domain reflectometry (TDR), frequency domain reflectometry (FDR) and porous media). For instance, Noborio et al. [52] first combined heat pulse probe and TDR (hereafter thermo-TDR) to measure soil thermal properties and water content. Ren et al. [19] advanced the thermo-TDR to measure a wide range of soil physical properties, including soil thermal properties, heat flux, water flux, evaporation, water content and bulk density. Sheng et al. [53] proposed a new design by coupling a heat pulse probe and FDR to make a thermo-FDR that can get a better estimation of soil water content and thermal properties

at a cheaper price. Reece [54] combined a heat pulse probe with porous media (e.g., gypsum or ceramic cup) to construct a line heat dissipation sensor that can be used to determine matric potential. Studies [55–57] have also extended the heat pulse method to measure soil water content at the middle scale by using actively heated fiber optics.

**Table 1.** Top 10 authors, organizations and countries commits to publications on heat pulse method for soil physical measurement with a threshold of minimum five publications per author. The HistCite indices are number of publications (N), total local citation score (TLCS, times to be cited by the 1319 papers) and total global citation score (TGCS, times to be cited by the Web of Science Core Collection). The VOSviewer indices are links (L, the number of collaborations or lines between investigated author/country/organization), total link strength (TLS) and citations (C). Value of TGCS is equal to C (TGCS/C).

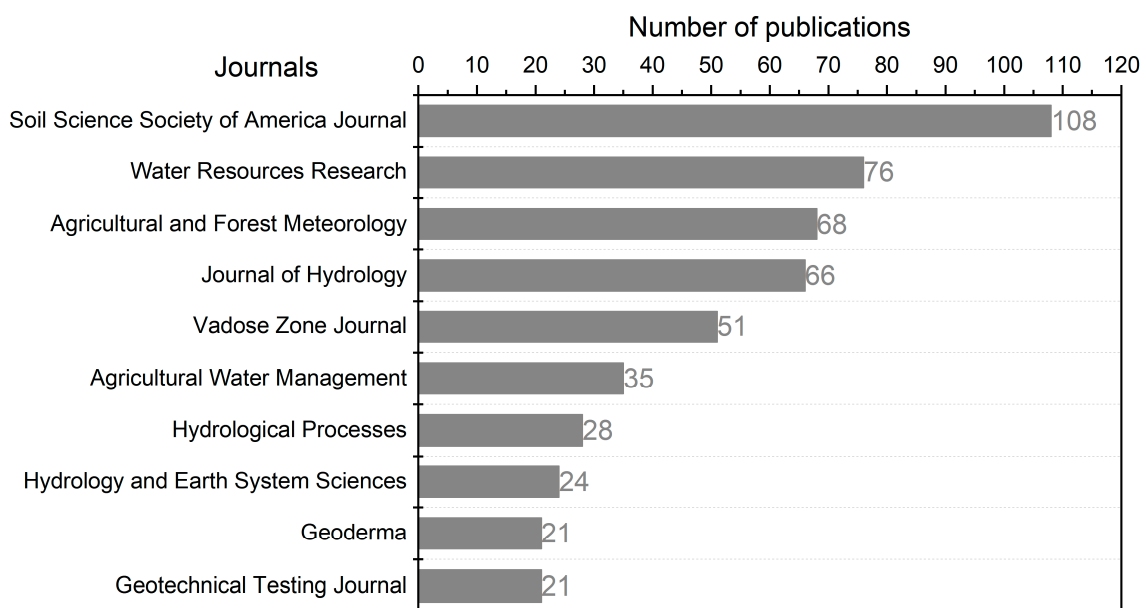
No.	Items	N	TLCS	TGCS/C	L	TLC
<b>Top 10 authors</b>						
1	Horton, Robert (Iowa State University)	69	928	2031	17	145
2	Ren, Tusheng (China Agriculture University)	43	365	825	13	95
3	Heitman, Joshua L. (North Carolina State University)	29	-	668	10	75
4	Kluitenberg, Gerard J. (Kansas State University)	29	835	1323	7	31
5	Ochsner, Tyson E. (Oklahoma University)	24	-	901	9	33
6	Si, Bingcheng (University Saskatchewan)	20	-	214	8	33
7	Kustas, William P. (USDA-ARS)	16	33	702	1	1
8	Hopmans, Jan W. (University of California Davis)	14	170	980	4	16
9	Liu, Gang (China Agriculture University)	14	88	138	6	31
10	Sauer, Thomas J. (USDA-ARS)	14	123	571	5	27
11	Singh, Devendra Narain (Indian Institute of Technology)	14	42	260	1	3
<b>Top 10 organizations</b>						
1	USDA ARS (USA)	87	334	2698	32	96
2	China Agriculture University (China)	77	449	1302	20	124
3	Chinese Academy of Science (China)	66	227	1089	28	88
4	Iowa State University (USA)	62	649	1642	18	114
5	Kansas State University (USA)	34	496	992	12	27
6	University Saskatchewan (Canada)	28	84	347	8	32
7	University Arizona (USA)	25	50	1120	19	27
8	Northwest A&F University (China)	23	46	255	13	46
9	Delft University Technology (Netherlands)	21	31	417	8	18
10	North Carolina State University (USA)	21	149	666	11	49
<b>Top 10 countries</b>						
1	USA	475	2119	15,903	34	312
2	China	278	846	4099	24	202
3	Canada	112	176	2243	17	76
4	Australia	99	487	3334	20	70
5	Germany	84	106	2074	28	92
6	France	82	106	2543	23	70
7	Italy	78	100	1808	24	76
8	UK	64	30	1264	16	32
9	Japan	59	211	923	13	48
10	Spain	56	49	996	15	51

### 3.3. The Most Recognized Journals

There were 291 journals that publish 1319 studies on the heat pulse method for soil physical measurements. The top 10 journals publishing this topic are generally in the categories of Soil Science, Hydrology and Agriculture, with one in Engineering (i.e., *Geotechnical Testing* journal), as shown in Figure 3. This is understandable because the main applications of this method are for soil physical measurements (e.g., thermal properties and water content). The journals also cited each other



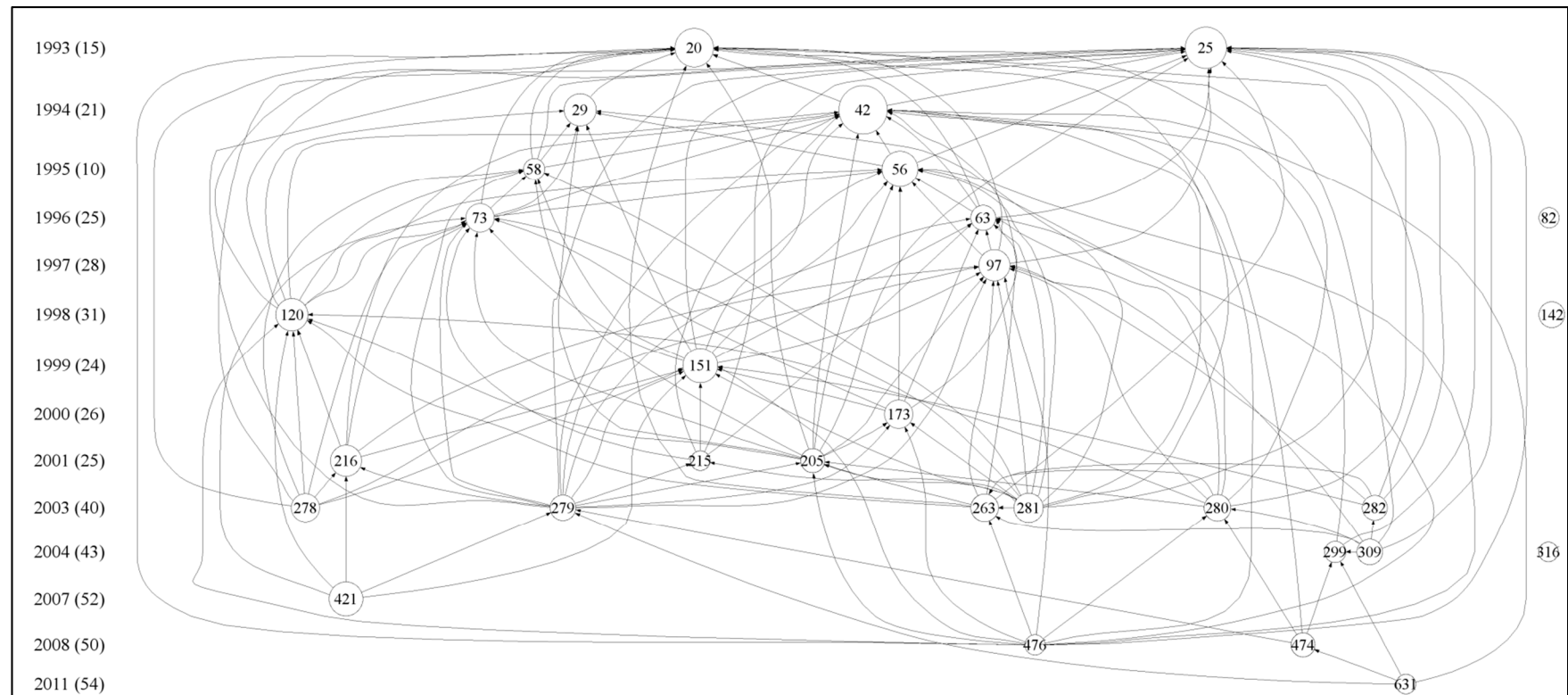
intensively compared to other journals (data not shown), which indicate that these journals are highly recognized by researchers in the community of the heat pulse method.



**Figure 3.** Top 10 journals publish research on heat pulse method for soil physical measurements.

#### 3.4. History of the Heat Pulse Method and the Highly Impacted Studies

The citation analysis with HistCite Pro showed that the papers numbered 20 [8], 25 [58] and 42 [59] are the most influential pieces of research in the area of the heat pulse method (Figure 4). These studies established the widely applied approaches for data interpretation and error analysis of soil thermal properties. The papers of 97 [60], 151 [61] and 278 [62] highlighted the extended use of the heat pulse method for the measurement of soil water content and electrical conductivity. The papers of 173 [46] and 279 [19] extended the heat pulse for soil water flux measurements. The papers of 280 [63] and 474 [64] extended the use of heat pulse method to estimate soil evaporation. The papers of 216 [65] and 421 [66] were marked as the modelling of soil thermal properties. While the papers of 82 [67], 142 [68] and 316 [69] only highlighted the significance of this method and were only highly cited by the researcher outside of the field, as indicated by no lines between these three papers and the other 27 papers in Figure 4. Because only data from 1992 up to date are available for SCI-EXPANDED of the WoSCC, some of the pioneer works [9,10,70–77] were not included. However, it should be noted that de Vries [10] and Campbell et al. [9] were among the pioneers applying the single-probe heat-pulse and dual-probe heat-pulse method, respectively, to determine soil thermal properties. A detailed history of the development and evolution of heat pulse method is referred to by He et al. [4].



**Figure 4.** Citation network of top 30 publications on heat pulse method for soil physical measurements produced by Histcite based on data (1992–2019) downloaded from the Web of Science Core Collection (WoSCC). The left column is year (number of publications of that year on this topic) corresponding to the nodes/circles shared the same horizontal lines. Each circle represents a top cited publication and the inside number is the publication ID (ordered by year and author's name) given by the Histcite. The size of a node/circle is associated with the number of times it was cited, and a larger node had more citations. The more arrows around a noodle/circle indicate that it was more often cited. The numbers inside the circles and their respective publications are: 20 [8], 25 [58], 29 [41], 42 [59], 56 [78], 58 [42], 63 [79], 73 [80], 82 [67], 97 [60], 120 [81], 142 [68], 151 [61], 173 [46], 205 [82], 215 [18], 216 [65], 263 [83], 278 [62], 279 [19], 280 [63], 281 [84], 282 [85], 299 [86], 309 [87], 316 [69], 421 [66], 474 [64], 476 [88] and 631 [89].





properties of extra-terrestrial bodies [12–15] was not detected in Figure 5, which could be due to the comparably small number of applications.

#### 4. Conclusions and Perspectives

We analyzed the publications of the heat pulse method over the period of 1992 and 2019 with bibliometric methods. The result showed an increasing trend in the number of publications in this field. The co-authorship analysis showed that Dr. Robert Horton from Iowa State University is the most productive researchers and he has a close collaboration with other top ranked authors. The USDA-ARS, the China Agriculture University and the Chinese Academy of Science were the top three organizations applying the heat pulse method. The USA, China and Canada were the top three countries and the *Soil Science Society of America Journal*, *Water Resources Research* and *Agricultural and Forestry Meteorology* were the most widely used journals. The con-occurrence and citation analysis could be used to map the research topics and landmark publications. We concluded that the bibliometric analysis is a useful tool to visualize the research status of the heat pulse method for soil physical measurements.

Although great progress in the development and application of heat pulse method has been made in recent decades, future studies should focus on the following aspects:

- (1) A new design of heat pulse probes with good performance at a lower cost and higher energy efficiency. The cost of the currently available heat pulse sensors impedes the wide application of the heat pulse method and the high energy consumption hinders the continuous measurement of soil thermal properties at remote locations with limited access to a power grid. This may explain why none of the meteorological stations install heat pulse sensors, but sensors of soil water/moisture and temperature. In addition, the thermo-TDR is limited by the short length of the probe needle that affects the accuracy of estimating soil water content [91,100]. Because FDR is less likely to be affected by the probe length [53,101] and Acclima Inc. developed the TDR 305 with TDR needles of 5-cm length, operating at 2 GHz, to accurately estimate soil water content. Possible solutions to this are to combine the heat pulse probe with FDR operating at dual frequencies (e.g., KHz and MHz) or TDR operating at a high frequency (e.g., ~2 GHz);
- (2) The development of a database on soil thermal properties. Soil thermal properties affect agricultural microclimates and therefore influence seed germination, seedling development and the subsequent establishment of stand, soil thermal regime, and the development and calibration of soil thermal conductivity models [102–107]. They also play a key role in the mass and energy exchange through porous media and interactions between the ground and atmosphere, influencing climate at regional and global scales [108–116]. Unlike the hydraulic properties [117–119], there is no database on experimental measurements of soil thermal properties. There is an urgent call to establish such a database.

**Author Contributions:** Conceptualization, H.H. and J.L.; methodology, H.H.; software, H.H.; validation, M.D., H.H. and J.L.; formal analysis, H.H.; investigation, H.H.; resources, J.L.; data curation, M.D.; writing—original draft preparation, H.H.; writing—review and editing, M.D. and J.L.; visualization, H.H.; supervision, J.L.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** Funding for this research was provided in part by Natural Science Foundation of China (NSFC, Grant No. 41877015) and the Key Laboratory for Agricultural Environment, Ministry of Agriculture, P.R. China (Grant No. KLA201603). The authors also greatly appreciate the valuable and insightful comments by the anonymous reviewers.

**Acknowledgments:** The authors thank Xiaoyan Pan for data collection and word processing.

**Conflicts of Interest:** The authors declare no conflict of interest.

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