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Trends in Research on Soil Organic Nitrogen over the Past 20 Years

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Abstract: Nitrogen (N), an indispensable mineral nutrient element for plant growth and development, is a major limiting source of productivity in many terrestrial ecosystems. Soil organic nitrogen (SON) is a crucial form of nitrogen (N) in the N cycle within terrestrial ecosystems, acting as either a "source" or a "sink" for environmental N release. In order to illustrate the research trends, evolution process and hotspots of SON, a bibliometric analysis was used to analyze 906 documents based on the ISI (Institute of Scientific Information) Web of Science (WoS) database. The results indicated that (1) the number of published papers on SON research showed a wavy growth from 2000 to 2022 and the research has entered a mature development period; China has been increasing its number of publications and has long been in the lead; (2) the most productive institutions and authors in this subject area are in the USA and China, with the Chinese Academy of Sciences being the key institution performing such research; (3) in the sample, *Soil Biology and Biochemistry*, *Science of the Total Environment*, and *Biogeochemistry* are the leading international journals that have played a key role in the evolution of the field and have laid a solid foundation for future research; (4) the characteristics and maintenance of SON in farmland and SON migration in small watersheds under forest conversion have become research hotspots. Through the in-depth analysis of SON research, this paper provides a better understanding of the development trends of SON over the past 20 years, which can also provide reference for future research.

Keywords: soil organic nitrogen; bibliometric analysis; organic nitrogen stability; nitrogen cycling; nitrogen pool management index

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1. Introduction

Nitrogen (N) is an irreplaceable essential life element for all living organisms on Earth, the most important nutrient in ecosystems, and an important part of the global ecosystem material cycle [1,2]. As a key element in biogeochemical systems, nitrogen affects material circulation in ecosystems in the context of global change [3–7]. Soil nitrogen is an important indicator of ecosystem health in the process of forest vegetation restoration [8,9]. Nitrogen is the mineral element that plants absorb the most from soil, and it is an important factor that limits the growth of forest vegetation and forest primary productivity [10–12]. Soil nitrogen reserves in ecosystems usually account for more than 90% of the entire ecosystem nitrogen reserves [7], and 92–98% of the nitrogen in soil is in the form of organic nitrogen [13]. Soil organic nitrogen (SON) is transformed into inorganic nitrogen available to plants through microbial mineralization [14], which affects vegetation productivity and is the main limiting source of productivity of many terrestrial ecosystems [6,15]. The turnover change [16], occurrence state, and chemical form of soil organic nitrogen have an important effect on soil nitrogen sequestration [17,18] and play an important role in understanding the nitrogen cycle mechanism of an ecosystem [19] and improving ecosystem stability and productivity [20,21]. Therefore, in view of the prominent role of

soil organic nitrogen in physiology, biology, biogeochemical cycles, and plant–soil–microbe interactions in forest ecosystem structure and functions, this exciting and intriguing topic has attracted extensive research by many scholars, and after decades of development, the body of research continues to grow rapidly.

Although the study of soil organic nitrogen is receiving greater attention and enough empirical and qualitative articles by experts have offered overviews and synthesis of it, there are still limitations in some specific areas, such as regions, functional traits, and databases [2–6]. In traditional review articles, it is difficult to provide an effectively organized, summarized, and quantitatively analyzed development of a specific research field among a large number of studies on large spatial and temporal scales, as well as the trends and ideas of future researchers [22,23]. In particular, SON is an interdisciplinary research field, covering forestry, soil science, ecology, environmental science, geosciences, biodiversity conservation, atmospheric science, and other disciplines. Therefore, in order to create a comprehensive overview of the study of SON, bibliometric analysis is needed. Bibliometric studies provide a variety of quantitative data for research in specific fields and have been used to assess the performance of countries, institutions, and researchers [24,25]. A bibliometric study of such research can not only provide an overall map of this field, including the most important research topics, whether and how particular topics are related, who has a partnership with whom, how the field has been developing [26,27], and which topics might have been overlooked and thus may require more attention, but also allow institutions and policymakers to use these studies to plan science development in their own countries [28,29]. In summary, bibliometric analysis is urgently needed in order to provide a comprehensive overview of the study of SON.

As a statistical technique for quantitative analysis, bibliometrics is widely used in scientific publications such as books and patent documents [30]. It is worth noting that using the bibliometric method can help us to understand the knowledge status, features, and development process of a specific research field or discipline quickly and comprehensively [6,31]. Bibliometric analysis includes qualitative and quantitative analysis of publications indexed by databases based on statistics and computing technology [32,33]. This technique has been widely used to measure performance in various disciplines [33,34]. In addition, knowledge graphs combine information visualization technology with traditional scientometrics citation analysis to visually display the current research status and development process of knowledge of a subject or field through data mining, information processing, scientific measurement, and graphic drawing with visual network maps [35]. Therefore, knowledge maps can be used to explore the development and relationships between different pieces of scientific knowledge [36,37]. Currently, many studies, involved in various fields of ecology, use bibliometric methods to discuss the related characteristics and research topics [38,39]. In order to provide a systematic and objective overview of the scientific research development of SON, bibliometrics was used to identify, compile, and analyze the publications on SON from 2000 to 2022 in this study, and it visualizes the relationship between articles in this field published in the journals of Web of Science to fill this research gap and contribute to a better understanding of trends and prospects of SON research. The goals of this study are as follows: (1) create a comprehensive understanding of SON with regard to the number of articles and citations, research subject categories and representative journals, and keywords; (2) identify the research power of this research area, such as representative countries, institutions, and authors; (3) reveal the evolution of knowledge structure and networks of SON through highly cited articles and frequent and bursting keywords; and (4) explore the current research status and future hotspots of SON.

2. Methods

2.1. Data Sources

ISI Web of Science (WoS) has gradually become the world's largest comprehensive and multidisciplinary academic retrieval platform and is the main reliable sources of citation data [16]. WoS includes Science Citation Index Expanded (SCI), Art & Humanities Citation

Index (A&HCI), Social Science Citation Index (SSCI), Conference Proceedings Citation Index—Social Science & Humanities (CPCI-SSH), and Conference Proceedings Citation Index—Science (CPCI-S) [31]. Based on the SCI database, we gathered relevant publications under the theme of "Soil organic nitrogen". The search term was "Soil organic nitrogen". We refined the "document types" options to "article" and "review", because it indicated the most studies with complete research results [25]. "Language" was set to "English". SON and inorganic N are two significant nitrogen (N) forms in the cycling of N within ecosystems [40], acting as either a "source" or a "sink" in environmental N release [41]. It has attracted attention in various research fields. The time span of the research data was set from 2000 to 2022. After merging and deduplication, a total of 930 publications were collected on 31 December 2022. Then, the publications outside the research time scope were excluded, and a final total of 906 publications was obtained.

2.2. Data Analysis

According to a time series network formed by the annual number of publications, CiteSpace 6.2.R2 takes a set of bibliographic records as the input and models the basic intellectual structure of a research field [22]. CiteSpace 6.2.R2 supports several types of bibliometric research, including collaboration network analysis, geospatial visualizations, co-citation analysis, author co-citation analysis, and co-word analysis [22]. Duplicated publications were filtered and deleted via CiteSpace 6.2.R2; then, the important information was extracted, including authors of the publications, institutions, countries, keywords, cited references of the publications, and cited articles and their relationship matrices; finally, Bibexcel was used for further mapping network. The parameters of CiteSpace 6.2.R2 were set as follows: The time span of the research data was set from 2000 to 2022, while the time slice was 1 year, 3 years, or 5 years, as needed. According to research content, collaboration network analysis of authors, countries, institutions, and co-citation analysis of institutions, journals, and references cited, co-word analyses were selected separately. The "Pruning the merged network" was pruned to the function of Pathfinder. Log likelihood ratio (LLR) was used for clustering analysis of co-words. Other parameters were based on the system default settings.

3. Results and Discussion

3.1. Overall Status of SON

The trend of the number of articles related to SON identified by the WoS over the past 20 years is shown in Figure 1. The total number of published documents increased rapidly from 2000 to 2022. There are 906 SON publications in the WoS database, with an average annual publication of 41.1. Quantitatively, there were two turning points in publications related to SON. The first time (as an emerging research field) was in 2004, when the number of published articles exceeded 20 for the first time. The other time was in 2014, when SON topped 50 published articles in a single year for the first time. During the period from 2014 to 2022, the average annual publication was 63.4, with an average annual growth rate of 7.1%, and the number of papers in 2020 reached a peak of 86. The increasing number of publications indicates that SON research is in a "growth stage" and has great potential for development. The number of publications increased linearly from 2000 to 2008, and exponentially from 2008 to 2016 and 2016 to 2022. The continuous increase in nitrogen deposition and the increase in the amount of available nitrogen in the terrestrial ecosystem produced a series of effects on ecosystem components [42]. The first published papers mainly focused on the sources and dynamic processes of soil organic nitrogen in different ecosystems such as farmland and forest [43]. Later, more attention was paid to the effects of land use change and land management on soil organic nitrogen change, and more and more studies were conducted on soil organic nitrogen components [44,45]. In particular, research on soil organic nitrogen under different land use changes and management under the background of global change has attracted increasing attention [46].

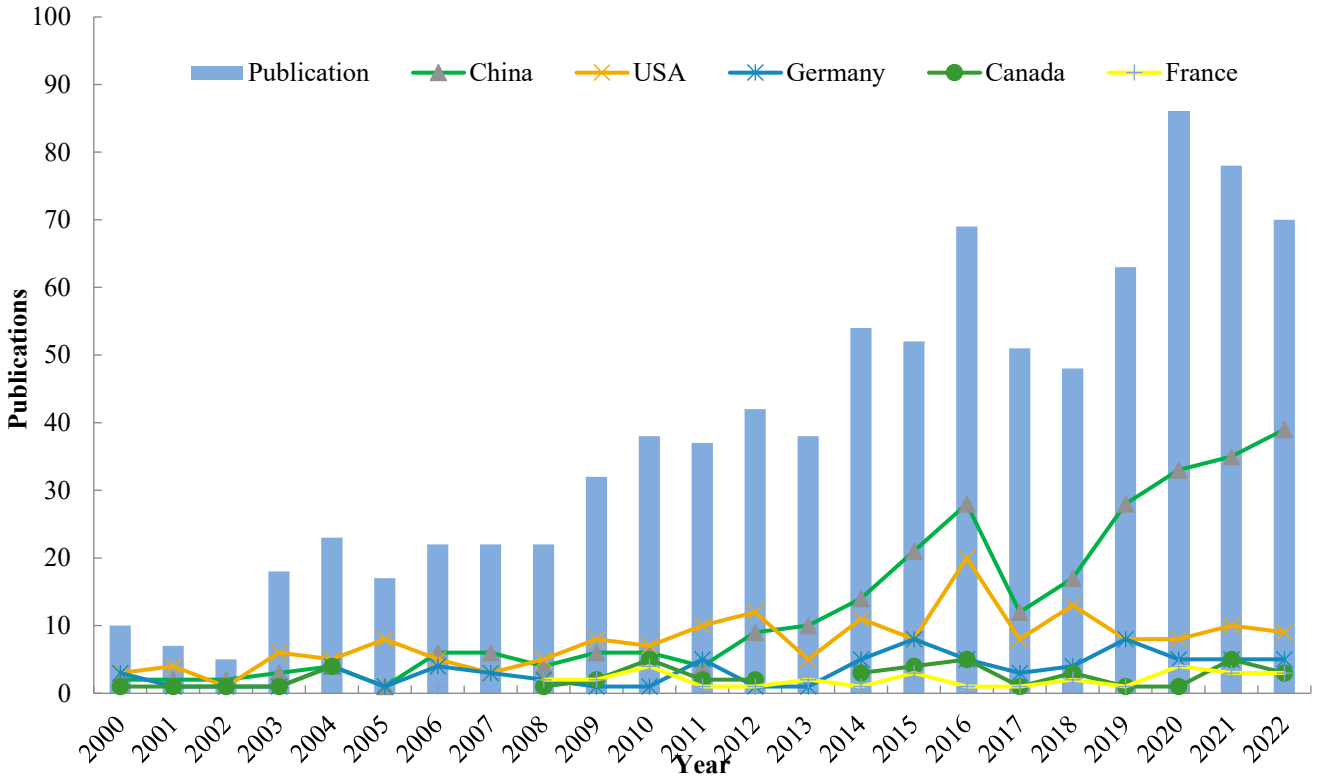

Figure 1. Number of SON publications by year from 2000 to 2022.

China and the USA were the first countries to publish the most SON research papers, as scientists, academicians, and practitioners in China have been leaders in the field of SON in general. Although China appears to have only begun publishing articles in the early 2000s, the number of its SON research papers has increased rapidly in recent years. From 2000 to 2022, a total of 292 studies were published in China, while relatively few studies were published from 2000 to 2011. In 2013, the number of annual publications in China ranked first in the world, and the total number of publications ranked third in the world. More and more Chinese researchers are focusing on research into the impact of land use on soil organic nitrogen in China, and the number of studies has increased rapidly.

3.2. Co-Occurrence Analysis of Journals

The 101 journals of soil organic nitrogen research literature included in the WoS database were statistically analyzed, and each journal was analyzed from 2000 to 2022. Table 1 lists the most highly published journals in terms of the number of SON publications. In general, the number of citations (TC) of a paper reflects its impact. The influence of a journal may vary depending on the research field, so the average number of citations per paper in a journal (TC/PC) is a relatively good indicator of the relative importance of the journal in a particular field. A quarter of the categories in the table are derived from the Thomson Reuters Journal Citation Reports database. This classification is usually based on the subject of the journal; all the journals in a subject are sorted in descending order according to the impact factor of the journals in a given year, and then divided into four categories (25% each), namely Q1, Q2, Q3, and Q4 [25]. The status of a journal among its peers can usually be understood by this division. Moreover, the impact factor of these journals can also be measured in terms of their role and position in science communication. Therefore, all values of these parameters for the journals in the sample are shown in Table 1.

As can be seen from Table 1, 27 articles were published in *Science of The Total Environment*; 26 in *Geoderma*; 26 in *Plants and Soils*; 22 in *Agricultural Ecosystem Environment*; 20 in *The Journal of Applied Ecology*; 19 in *Catena*; and 15 in *Soil Science Society of America Journal*. SON is one of the active components involved in soil nitrogen mineralization and

plays an important role in the nitrogen cycle of a soil ecosystem under the disturbance of climate change [41–43]. These journals have been publishing the latest research in these areas. The journals mainly focus on SON research works related to environmental science and engineering, agricultural environmental science, environmental biology, and forestry ecology. For example, *Soil Biochemistry*, *Total Environmental Science*, *Geoderma*, *Plants and Soils*, *Agroecosystem Environment*, *The Journal of Applied Ecology*, *BioGeochemistry*, *Catena*, *Soil Science Society of America Journal*, *Soil Farming Research*, *Environmental Economics*, *Environmental Science*, and *Nutrient Cycling in Agroecosystems* are mainstream journals with a high level of influence. Overall, the top 10 high-yield journals cover relevant publications in the fields of forestry, biological sciences, ecological sciences, geographic sciences, and soil sciences. This shows that SON research is a multidisciplinary innovation, which also reflects the complex development of SON research. The top journals (7.31% of the total 369 papers) published 384 out of 906 papers (40%) and received 932 out of 5569 citations (31.38%). The highest TC/P score was for *Science of The Total Environment* (37.23), followed by *Geoderma* (28.65) and *Soil Biology Biochemistry* (23.26). SON research is cross-disciplinary and diversified, which also reflects the complex development of SON research. These journals have been publishing the latest research progress in these aspects.

Table 1. List of the most highly published journals on SON.

Journals	Publications	TC/PC	Rate JCR	IF
Science of The Total Environment	27	37.23	0.35 Q1	10.237
Geoderma	26	28.65	0.34 Q1	7.444
Soil Biology Biochemistry	26	23.26.	0.34 Q1	9.956
Plant and Soil	22	22.06	0.28 Q1	5.44
Agriculture Ecosystems Environment	20	21.38	0.26 Q1	7.089
The Journal of Applied Ecology	20	19.29	0.26 CSCD	*
Biogeochemistry	18	18.75	0.23 Q1	5.709
Biogeochemistry Dordrecht	18	17.63	0.23 CSCD	*
Catena	18	15.96	0.23 Q1	6.497
Yingyong Shengtai Xuebao	18	12.13	0.23 CSCD	*
Soil Science Society of America Journal	17	10.03	0.22 Q3	3.564
Soil Tillage Research	17	9.45	0.22 Q1	7.829
Huanjing Kexue	15	9.12	0.19 CSCD	*
Environmental Science	13	8.76	0.17 CSCD	*
Nutrient Cycling in Agroecosystems	13	8.29	0.17 Q2	4.504
Scientia Agricultura Sinica	13	7.34	0.17 CSCD	*
Communications In Soil Science and Plant Analysis	11	6.58	0.14 Q3	1.608
Journal Of Plant Nutrition and Fertitizer	11	5.78	0.14 CSCD	*
Archives Of Agronomy and Soil Science	10	4.38	0.13 Q2	2.157
Chinese Journal af Applied Ecology	10	3.54	0.13 CSCD	*

Notes: TC/PC—indicates average number of citations per paper for a journal; Rate—indicates the number of the journal publication accounts for the total number of publications; JCR—Journal Citation Reports™, journals were divided into four categories (25% each), namely Q1, Q2, Q3, and Q4; CSCD—Chinese Science Citation Database, journals in CSCED have always maintained a leading academic position in China; * a journal not indexed in either Journal Citation Reports (so having no IF).

Through an analysis of the literature on soil organic nitrogen with high citation frequencies in the Web of Science database, a literature data table showing the top 10 highest citation frequencies was obtained (Table 2). The effects of organic amendments on soil fertility, biotic and abiotic controls, soil properties and soil organic carbon storage, intercropping, bacterial community structure of agricultural land, and the combined effects of man-made and natural disturbances on SON structure and function were hot topics in the studied research fields. These highly cited references are all from different countries, indicating that SON research has gained worldwide attention. The studies with the first- and second-highest citations focused, respectively, on the long-term effects of organic amendments on soil fertility and on ecosystem carbon loss in woody plant invasion

of grasslands. The research topics show that the turnover change, occurrence state, and chemical form of soil organic nitrogen have an important effect on soil nitrogen sequestration [47] and play an important role in understanding the nitrogen cycle mechanism of an ecosystem, the dynamic changes of soil nitrogen content and density, and the proportion of different nitrogen components in soil total nitrogen content (i.e., soil nitrogen supply capacity) during vegetation restoration [48]. Among these highly cited studies, Diacono, Mariangela; Jackson, RB; Jackson, Robert B; and Wu, Gao-Lin are the scholars who have achieved the best results with a focus on the study of SON.

Table 2. List of the most cited articles in the WoS database.

Title	Author	Journal	Year	Citations
Long-term effects of organic amendments on soil fertility.	Diacono, Mariangela; Montemurro, Francesco	*Agronomy For Sustainable Development*	2010	932
Ecosystem carbon loss with woody plant invasion of grasslands	Jackson, RB; Banner, JL; Jobbagy, EG;	*Nature*	2002	804
How does fire affect the nature and stability of soil organic nitrogen and carbon?	Knicker, Heike	*Biogeochemistry*	2007	607
The Ecology of Soil Carbon: Pools, Vulnerabilities, and Biotic and Abiotic Controls	Jackson, Robert B.; Lajtha, Kate; Crow, Susan E.; Hugelius, Gustaf; Kramer, Marc G.; Pineiro, Gervasio	*Annual Review Of Ecology, Evolution, And Systematics*	2017	441
Influences of continuous grazing and livestock exclusion on soil properties in a degraded sandy grassland, Inner Mongolia, northern China	Su, YZ; Li, YL; Cui, HY; Zhao, WZ	*Catena*	2005	412
Pathways of Grazing Effects on Soil Organic Carbon and Nitrogen	Pineiro, Gervasio; Paruelo, Jose M.; Oesterheld, Martin; Jobbagy, Esteban G.	*Rangeland Ecology & Management*	2010	283
Microbially derived inputs to soil organic matter: Are current estimates too low?	Simpson, Andre J.; Simpson, Myrna J.; Smith, Emma; Kelleher, Brian P.	*Environmental Science & Technology*	2007	233
Long-term fencing improved soil properties and soil organic carbon storage in an alpine swamp meadow of western China	Wu, Gao-Lin; Liu, Zhen-Heng; Zhang, Lei; Chen, Ji-Min; Hu, Tian-Ming	*Plant and Soil*	2010	232
Intercropping enhances soil carbon and nitrogen	Cong, Wen-Feng; Hoffland, Ellis; Li, Long; Six, Johan; Sun, Jian-Hao; Bao, Xing-Guo;	*Global Change Biology*	2015	230
Changes in Bacterial Community Structure of Agricultural Land Due to Long-Term Organic and Chemical Amendments	Chaudhry, Vasvi; Rehman, Ateequr; Mishra, Aradhana; Chauhan, Puneet Singh; Nautiyal, Chandra Shekhar	*Microbial Ecology*	2012	223

3.3. Co-Occurrence Analysis of Authors

The social relationships of authors indicate the core elements of a research field and also act as an important embodiment of the research power of SON [28]. By analyzing the network of co-occurring authors, we can determine which scholars cooperate closely in this field and explore the effect of cooperation on their academic research [31]. Through co-citation analysis, we can reveal the academic community that has the greatest influence on SON [49].

There were 906 scientific and technological studies on SON in the WoS database, with 8321 authors. Among them, the scholars with the highest publications included Liu Man (12), Han, Guilin (10), Xu Zhifang (6), Jiang Hao (4), Amelung W(4), Ciurli Stefano (2), Huang Xin (2), Li Si-Liang (2), Anderson SJ (2), Duval Matias E (2), Makarov M I (2), Antonio Torres-Martinez Juan (2), and Di Hongjie (2). Using the high-yield analysis of papers, we demonstrate how the authors of high-frequency publications co-appear in the network (Figure 2). The results show that the research of SON has formed an influential

global scientific research cooperation, with the group including Liu, Man; Amelung, Wulf; Makarov, M I; Antonio Torres-Martinez, Juan; li, Hongjie; Diacono, Mariangela; Matsumoto, S; Liu, Wenjing; Deneve, S; Wang, Zhong-Jun; Billings, Sharon A; Noll, Lisa; Onipchenko, V G; Wanek, Wolfgang; Malysheva, T; Chang, Longran; Chen, Zhenhua; Farwell, Sherry O; An, Ke; Hen, Lijun; Hadwick, David R; and Jin, Menggui. These authors with strong academic influence are demonstrating increasing scientific research cooperation, which promotes the development of SON research.

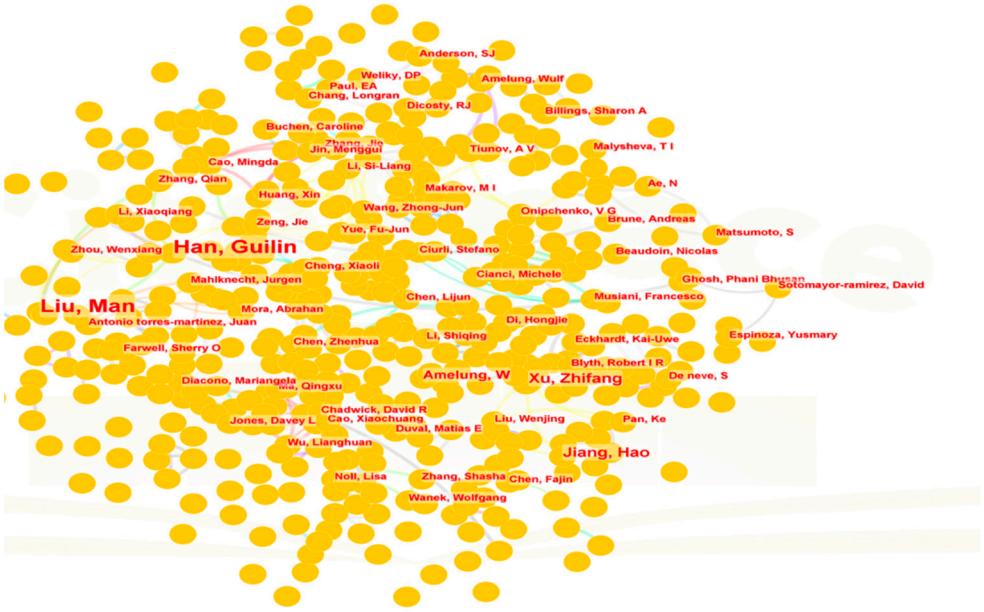

Figure 2. Knowledge map of the top coauthors during 2000–2022. Notes: Nodes represent authors. The size of the font is proportional to the number of papers produced by the author. The links represent the collaborative relationship between different authors.

3.4. Collaboration Network Analysis of Countries and Institutions

The papers included in the sample were from 76 countries worldwide, mainly in Europe, the Americas, Asia, and Oceania. The countries with a high publication frequency over the past 20 years were selected for statistical analysis, and the co-occurrence network analysis of the published countries was carried out using Pajek software. The top countries with the highest number of publications were China (417), the United States (177), Germany (76), Canada (45), France (32), Australia (31), and India (24). The results show that SON research has resulted in more influential research collaborations around the world.

In general, nodes and lines represent keywords and their co-occurrence relations, respectively [50]. The larger the node and the closer it is to the center, the stronger the cohesion of the node [3]. The issuing countries represented by other nodes are developed around this node. The results show that the research of SON has formed more influential scientific research cooperation globally. Group One refers to a group of countries with China as the core, including Australia, Canada, New Zealand, etc.; Group Two refers to a group of countries with Germany as the core, including France, South Africa, etc.; Group Three refers to a group of countries with the USA as the core, including Japan, India, etc.; and Group Four refers to a group of countries with France as the core, including Austria, Senegal, Italy, Botswana, etc. (Figure 3). Cooperation and exchange help to improve the research level and academic influence of countries, and countries with strong academic influence gain increasing levels of scientific research cooperation. This promotes the development of SON research.

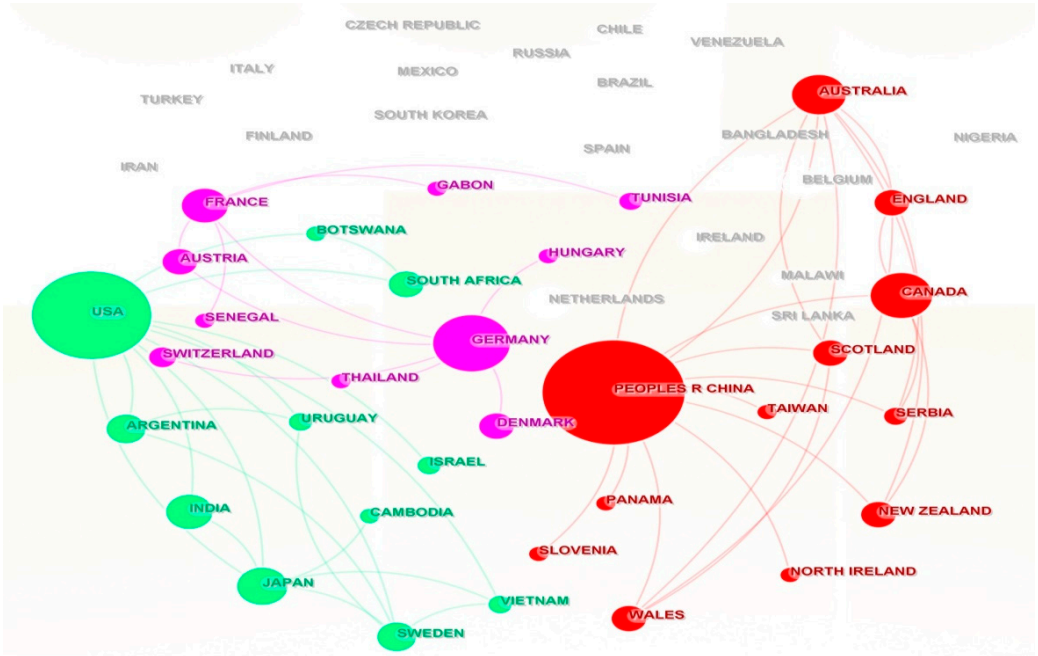

Figure 3. Knowledge map of cooperative countries during 2000–2022. Notes: Nodes represent countries. The size of a node is proportional to the number of papers produced by the country. The links represent the collaborative relationship between different countries and institutions.

Institutions whose publication frequency of SON research was greater than 20 were defined as high-frequency publication institutions. Statistical analysis of the scientific research output of the institution with a high frequency of publication (taking the SCI articles on SON research as the index) can clearly present the development process and research results of the SON research of the institution. The Chinese Academy of Sciences topped the list with 172 papers, followed by the United States Department of Agriculture (78 papers) (Figure 4). At the top of the list are the Helmholtz Association, Northwest A F University China, Chinese Academy Of Agricultural Sciences, Shenyang Institute Of Applied Ecology, Ministry Of Agriculture Rural Affairs, Institute Of Soil Science Cas, Chinese Acad Ag, Consejo Superior De Investigaciones Cientificas Csic, Northwest A F Univ, Udice French Research Universities, United States Department of Agriculture Ars, Wageningen University Research, Wuhan Botanical Garden Cas, Agri Food Canada, Agriculture Agri Food Canada, and other internationally renowned scientific research institutions. These research institutions have a strong research force and outstanding international influence in SON research. The relatively tight network structure also indicates that there is a relatively close relationship between research institutions.

On the whole, China's SON research field has a certain influence in the world. There is more SCI literature related to SON research topics, involving 115 countries and regions. Cooperation and exchange contribute to improving the research level and academic influence of the countries and institutions. Compared with other institutions, the Chinese Academy of Sciences published the most relevant articles and ranked first. However, further analysis found that its centrality was relatively small (0.05) (Figure 4), which indicated that its international cooperation and exchange are relatively weak and should be further enhanced.

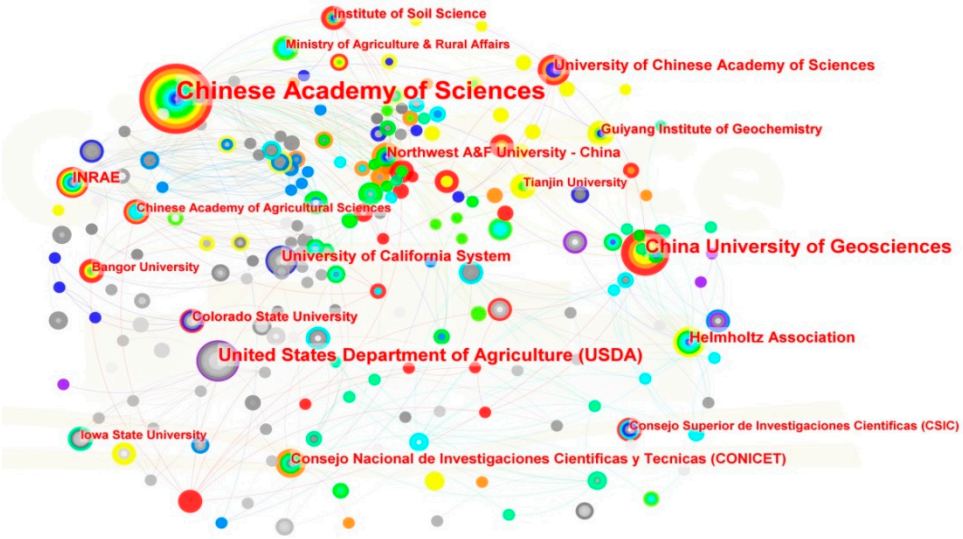

Figure 4. Knowledge map of cooperative institutions during 2000–2022. Nodes represent institutions. The size of a node is proportional to the number of papers produced by the institution. The links represent the collaborative relationship between different institutions. The color of the rings and links corresponds to the year. The concentric circles indicate high centrality (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

3.5. Research Hotspots

The title of a study provides a summary of the main content of the article [51]. The reader usually first understands the narrative theme of the article through the title. When searching, scientific researchers will also look for subject words from the title and divide the professional scope so as to find the target literature [52]. Therefore, we used Citespace software to carry out the co-word analysis of 906 SCI article title extraction topics in the WoS database, and we used VOS-viewer software to carry out visualization. Figure 5 shows that climate change, biomass, diversity, and land were the main topics covered in SON research over the last 20 years. The keywords forest, species, tropical, China, soil, carbon, biomass, diversity, and land use were classified into the following nine categories to represent research hotspots through cluster analysis (Figure 5). Cluster 1 represents the largest cluster with 33 keywords, mainly including keywords such as cropping systems, nitrification, climate, fertilizer, plant growth, enzyme activity, humic substances, stable isotope, organic nitrogen, etc. [53–56]. Cluster 2 had 27 items, referring to keywords such as soil properties, amino acid, cropping system, biochemical attributes, soil erodibility, karst groundwater, particulate organic matter, microorganisms, temperature sensitivity, etc. [57–60]. Cluster 3 had 25 terms, which included keywords such as agricultural soils, nitrogen mineralization, grassland, phosphorus, agricultural abandonment, arbuscular mycorrhizal fungi, components, amino acid enantiomers, etc. Cluster 4 had 21 items, which included keywords such as carbon sequestration, microbial community, fresh water, agricultural soils, nitrogen mineralization, grassland, etc. Cluster 5 had 20 items, mainly including keywords such as stable isotopes, amino acids, groundwater, climate change, contamination, soil fractions, etc. Cluster 6 had 18 items, mainly including keywords such as forest community, dual isotopes, litter decomposition, atter nitrogen, soil organic nitrogen, denitrification, mineralization, etc. [61–63]. This category contained the most keywords. Cluster 7 had 16 items, mainly including keywords such as phosphorus, agricultural abandonment, arbuscular mycorrhizal fungi, components, amino acid enantiomers, etc. [64–67]. Cluster 8 had 15 items, mainly including keywords such as organic nitrogen, biodiversity, nitrate sources, carbon sequestration, microbial community, fresh water, agricultural soils, nitrogen mineralization, grassland, phosphorus, etc. Cluster 9 had 11 items, mainly including keywords such as organic matter, water groundwater microbial biomass,

stable isotopes, amino acids, groundwater, climate change, contamination, soil fractions, cropping systems, nitrification, climate, fertilizer plant growth, enzyme activity, humic substances, stable isotope, organic nitrogen, etc. [43,67–70].

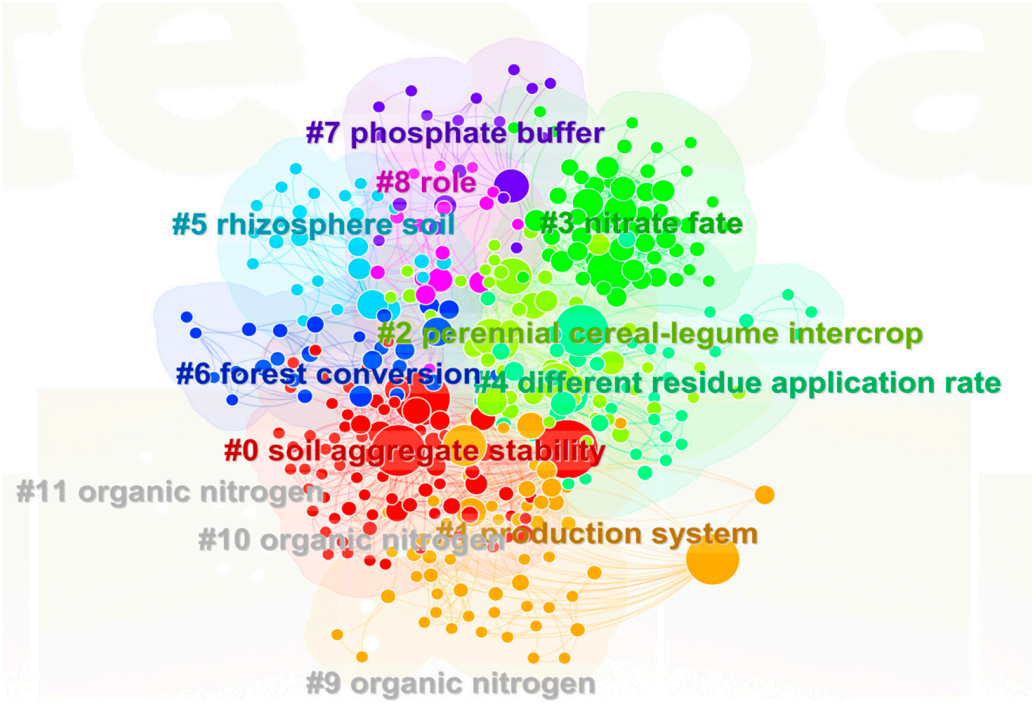

Figure 5. Knowledge map of keywords during 2000–2022. Notes: Colors indicate the cluster in which each keyword was related the most. The size of a node is proportional to the literature number of the subject category. Lines represent the co-occurrence link strength among terms.

The research topic of a publication is highly concise as reflected in the keywords. Generally, the frequency of keywords reflects the research hotspots of specific fields. Furthermore, the emerging trends are often represented by bursting keywords, which increase sharply in frequency and can be used as indicators to help us investigate research frontiers and predict research trends [71]. Therefore, we use burst detection as an effective analytical method to find the keywords that have resulted in special attention from the relevant scientific communities in a certain period of time [72]. The knowledge map of keywords during 2000 to 2022 is shown in Figure 6, and the trend topics were analyzed according to the annual frequency of keywords. The results showed that research on SON was in an initial stage before 2010 (Figure 6). The frequency of keywords, such as humic substances, cropping systems, and soil organic, was lower. However, many research findings were published during this period. The frequency of keywords significantly changed from 2010 to 2019, and the main research interests focused on microbial biomass and turnover with soil, especially for nitrogen mineralization and acid. Stable isotopes, denitrification, nitrate, groundwater, contamination, and others were hot topics from 2019 to 2022. Domestic and foreign scholars have carried out a great deal of research on soil organic nitrogen components [73], mainly in relation to fertilization, irrigation, soil type, and land use. At present, the characteristics of soil organic nitrogen and surface water organic nitrogen, soil organic nitrogen maintenance in farmland, and organic nitrogen pollution in small watersheds under forest conversion have become research hotspots.

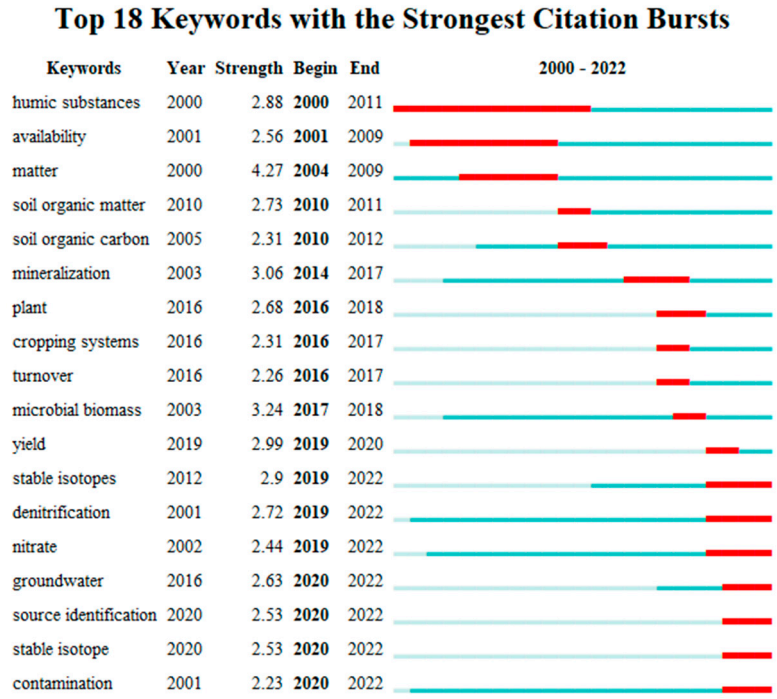

Figure 6. Knowledge map of keywords during 2000–2022. Colors indicate that each keyword was related in the different years. The red bar means that the keyword is related to the most in those years.

4. Conclusions

The critical functions of SON in biogeochemical cycles and plant–soil–microbe interactions in forest ecosystems have attracted global attention. This study, taking "Web of Science" as the sample data source, conducted a bibliometric analysis on the global research overview of SON with information related to journals, top cited publications, authors, institutions, countries, hot issues, and research trends over the past 20 years, and it provides a unique snapshot of the SON knowledge domain.

Our study indicates that SON research has entered a mature development period, with significant increases in researcher output from 2000 to 2022. Moreover, the number of scholars involved in SON research is simultaneously increasing. Many scholars have focused on SON research in forest conversion, cropping systems, bio-chemical attributes, soil erodibility, water groundwater, plantation management, and so on. The most productive institutions and authors in this subject area are in the USA and China, with the Chinese Academy of Sciences being the key institution performing such research. *Soil Biology and Biochemistry*, *Science of the Total Environment*, and *Biogeochemistry* are the leading international journals that have played a key role in the evolution of the field and have laid a solid foundation for future research. Future topics may include the characteristics and maintenance of SON in farmland and SON migration in small watersheds under forest conversion.

Although the current study has provided a comprehensive view of soil organic nitrogen research from a large database and has made some contributions to the field, like previous bibliometric analyses, it also has some limitations. First, to avoid getting irrelevant search responses, we analyzed publications within strict limitations in this study. Although the Web of Science database contains the widest scope of studies, some countries have their own language databases. In order to obtain more accurate results when searching for articles, this work may be improved in the future by including cross-comparison studies among country-specific databases. Second, although we identified the main research hotspots and their evolution, more detailed information on each research hotspot is still needed. Finally, it should be pointed out that bibliometric tools have their own functional limitations, though they have been used for many bibliometric research studies. However,

with the advance of science and technology, promising potential new tools, such as machine learning, could enhance the accuracy of information extraction. On the whole, the findings of this paper are based on objective data and are stable and reliable.

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