Global Root Traits Research during 2000–2021: A Bibliometric Analysis

Hui Li [1], Muji Siri [1], Baojie Wang [1], Yixuan He [1], Cheng Liu [1], Changliang Feng [1] and Kesi Liu [1,2,*]

[1] College of Grass Science and Technology, China Agricultural University, NO. 2 Yuanmingyuan West Road, Haidian District, Beijing 100193, China
[2] National Field Station of Grassland Ecosystem, Guyuan 076550, China
* Correspondence: kliu@cau.edu.cn

Abstract: Root traits have an important impact on plant growth, which reflects the adaptation of plants to nutrients. This paper describes the focus and progress of root traits research and provides references for future research. Based on the Web of Science online database, articles related to root traits from 2000–2021 were evaluated using bibliometric methods. The results showed that the study of root traits has been growing steadily in the last two decades. Wang Yan is the author with the highest number of published papers, the most citations and the highest H-index. The top three published countries are the USA, China and India. The top three institutions are the University of Western Australia, China Agricultural University and Nanjing Agricultural University. *Plant and Soil*, *Frontiers in Plant Science* and *PLoS One* have the highest number of published articles. In terms of co-occurrence of keyword analysis, growth, soil and plant diversity are highly correlated with root traits. It was found that cooperation between authors, institutions and countries are not close enough and that z global network of cooperation has not yet been formed. Therefore, worldwide cooperation should be strengthened to promote resource sharing and the openness of relevant mechanisms.

Keywords: root traits; bibliometric; publication outputs; research progress; network analysis; web of science

1. Introduction

The underground roots of plants play an essential role in plant growth and production performance and affect ecosystem functions [1,2]. Roots enable plants to find nutrients and water in the environment and firmly fix themselves in the soil [3]. Thus, plants have evolved a series of underground strategies (i.e., root traits) to efficiently acquire these resources and respond to their spatial and temporal availability during long-term adaptation [4]. Root traits are an important indicator in reflecting the response of plants to change in environmental conditions and the impact on ecosystem processes [5,6]. In recent years, the field of root functional ecology and ecological physiology have attracted extensive attention and the research combined with all aspects of plant roots is also increasing rapidly [7].

The root system is a continuous body composed of root nodes and its anatomical, morphological, physiological and mechanical properties are different [8,9]. Different root segments or groups of segments vary in root traits and their contribution to ecosystem functions [10]. Root characteristics mainly include architectural, morphological, physiological and biotic traits, which have potential effects on ecosystem processes [1]. The general idea behind the trait-based framework is that changes in root traits across individual plant species, communities and ecosystems capture changes in a series of ecosystem processes. The traits of root structure mainly determine the spatial form of the root system of a single plant; common structural features include root depth, root length density, root volume and root branching; morphological traits refer to the characteristics of a single root, including root diameter, specific root length (SRL), specific root surface area (SSA), root tissue density, root dry matter content, etc.; root physiological traits include nutrient absorption, root

respiration and root exudate release; and root biotic traits include the direct interaction between roots and soil organisms affecting nutrient capture, such as the interaction with mycorrhizal fungi, rhizobia (legumes), pathogens and so on [1].

The traits of root configuration are related to the competitive effects and responses of the two plants. Semchenko et al. [11] found that the species most suitable for tolerating competition had deep roots, low SRL and minimal branching. Plant morphological traits can affect the total root length and root surface area and control the size of the interaction area between roots and soil and mycorrhizal fungi, to help plants obtain and absorb nutrients [12–14]. For example, a reduction in root diameter is considered a feature that improves plant water uptake and productivity under drought conditions [15]. Under dry conditions, the root diameter of woody and herbaceous plants are smaller diameter fine roots and greater SRL [16–18]. Plants with a high root elongation rate (RER) can quickly capture water in unutilized soil [19–21]. Studies have also pointed out that root physiological traits, especially root exudates, play an important role in affecting soil nutrient availability. For example, plants can improve the utilization of phosphorus by secreting root exudates rich in organic acids [4] and release other kinds of root exudates to enhance the mineralization of organic matter and improve the availability of soil nutrients [22]. Besides, some specific traits of roots are also closely related to ecosystem restoration [23,24]. Therefore, an effective understanding of root traits may be important for learning about the competitive effects of species and the process of long-term adaptation of plants [4,25].

Some scholars have made a detailed review of the research progress in the field of root traits, but lack analysis and evaluation of the research trend and focus on root traits from the perspective of bibliometrics analysis. To better understand the research status of root traits, this paper adopts the method of scientometrics, which is helpful in displaying hot research topics and their evolution in this field and prospects for future research directions to fill the knowledge gap in this field. This paper used the Web of Science core collection database as the data source to retrieve the root traits of relevant papers from 2000 to 2021 and published and adopted bibliometric analysis to systematically reveal research trends, focuses and problems existing in this field, providing reference and inspiration for future related research.

2. Materials and Methods

2.1. Data Collection

The Web of Science (WoS) is the largest, most authoritative and most comprehensive academic information resource library in the world, covering most disciplines. In this study, the SCI-E database and the core database of the WoS were used as the data sources to retrieve the research articles on root traits published from 2000 to 2021. Root architectural traits, physiological root traits, root morphological traits, and root biotic traits were used as keywords and TS ("root traits *" OR "root architectural traits *" OR "physiological root traits *" OR "root morphological traits *" OR "root biotic traits *") was used as a query formula. The result files were exported as a text file containing" full record and citation data " for bibliometric analysis. Through search and selection, a total of 16,233 papers were obtained and the publication information (e.g., publication year, institution, author, journal, country and keywords) was quantitatively analyzed. We defined which country an article is from by its corresponding author's country.

2.2. Data Analysis

Bibliometrics is a bibliometrics analysis package based on R, which has powerful functions such as analysis of scientific literature, citation network analysis and visualization [26]. After extracting the information from 16,233 papers, the author, country information and cooperative relationship were analyzed by using a Bibliometric package. VOSviewer is a powerful software program that can build and visualize the literature measurement network [27], cluster analysis of the information for main research institutions and keywords and draw the cooperative relationship network diagram between main research institutions

and the co-occurrence network diagram of the main keywords. Two kinds of bibliometric analysis software have been widely used in bibliometric research [28]. Through frequency and co-occurrence analysis of keywords, the emphases and trends of current root trait research were analyzed.

The impact factor and the H index are important evaluation parameters in bibliometric analysis. The impact factor is an important index that reflects the influence of journals, the quality of papers and the academic level of researchers [29]. H index not only accurately measures the academic achievements of different authors in specific fields, but also reflects the strength of a country in specific fields [30,31]. Therefore, the higher the H index, the greater the academic influence. This paper adopts the impact factor and the H index to reflect the academic influence of the author and the country. The journal impact factors were obtained by querying the Journal Citation Report published by Clarivate Analytics in 2020 and using the Bibliometrix package to calculate the H-index. Q1 and Q2 indicate the difference in impact factors of journals using Journal Citation Reports (JCR).

3. Results and Discussion

3.1. Quantity of Articles and Citations

The number of publications on root traits showed a steady upward trend as a whole from 2000 to 2021, except for 2006 and 2012, when it decreased by 1% and 0.8%, respectively, compared with the prior year (Figure 1). This shows that research on root traits has gradually attracted the attention of relevant scholars. Among these publication years, there were six years of growth rates in excess of 20%: 2005 (34.98%), 2011 (27.13%), 2019 (22.38%), 2008 (20.77%), 2004 (20.54%) and 2001 (20.45%).
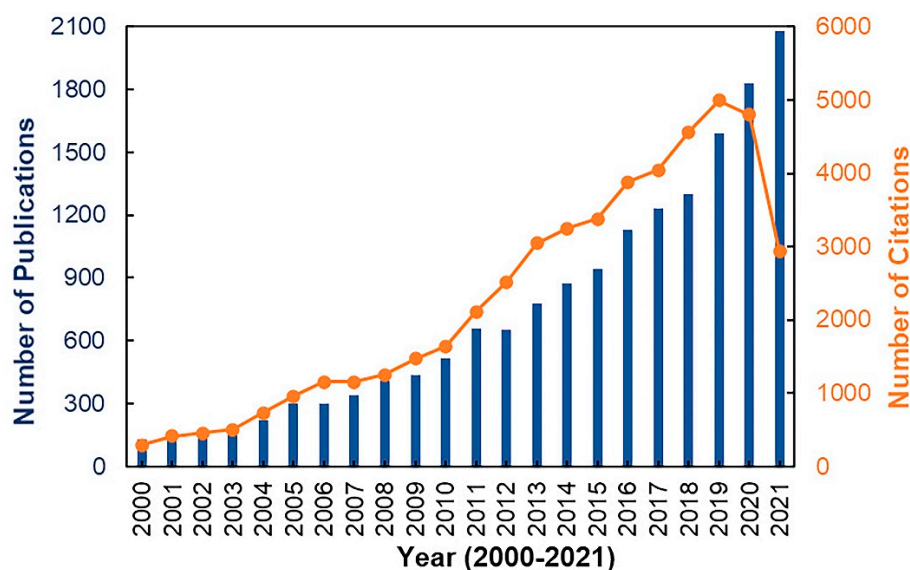

Figure 1. Trends in the number of articles and citations identified by Web of Science (WOS) that are related to root traits from 2000 to 2021.

The total number of citations was 49,542 from 2000 to 2021 and the average number of citations per publication was 3.05. The number of citations of published articles on root traits increased from 2000 to 2019 and then decreased (Figure 1). The largest number of citations was 4996 in 2019. Since 2020, the average citation frequency per paper has decreased, the main reason for this being the short time until publication and the large number of papers, that have caused a decrease in the average citation frequency. At present, the increasing number of citations indicates that the research on root traits has become one of the hot spots in the field of botany and ecology and its research value will gradually attract people's attention.

Since 2000, research on root traits has been increasing year by year, which we believe is due to the continuous development of scientific and technological means. The development of molecular techniques has also made it possible to distinguish the root systems of different species in the subsurface, which is an important reason to promote research on root traits.

3.2. Analysis of Publication Journals

The 16,233 papers studied were published in 1987 different journals, with 67 journals containing more than 50 papers. The top 20 journals published 4459 papers, accounting for 27.47% of the total (Table 1). Most of the published journals focus on crop plants, soil and ecology, which confirms the important role of root traits in these aspects. The journal with the largest number of published papers was *Plant and Soil*, with a total of 529 published papers, accounting for 3.26% of the total number of papers. The following journals were *Frontiers in Plant Science* and *PLoS One* with 472 and 383 papers, respectively, accounting for 2.91% and 2.36% of the total number of papers. Considering journal impact factors, *New Phytologist* has the highest impact factor among these publications, at 10.152. Next are *Plant Physiology* and *Journal of Experimental Botany* with impact factors of 8.34 and 6.992, respectively. Among all the top 20 journals that published the most articles, most of them belonged to Q1, except for *PLoS One, Euphytica, Crop Science* and *Functional Plant Biology*, which belonged to Q2.

Table 1. Top 20 journals by the number of articles published from 2000 to 2021.

Ranking	Source Journal	Number of Articles	2020 Impact Factor	% of 16,233	Quartile in Category
1	Plant and Soil	529	4.192	3.26	Q1
2	Frontiers in Plant Science	472	5.754	2.91	Q1
3	PLoS One	383	3.24	2.36	Q2
4	New Phytologist	272	10.152	1.68	Q1
5	Euphytica	257	1.895	1.58	Q2
6	Theoretical and Applied Genetics	236	5.699	1.45	Q1
7	Crop Science	231	2.319	1.42	Q2
8	Journal of Experimental Botany	217	6.992	1.34	Q1
9	Agronomy-Basel	215	3.417	1.32	Q1
10	Science Reports	200	4.38	1.23	Q1
11	Field Crops Research	188	5.224	1.16	Q1
12	Journal of Ecology	164	6.256	1.01	Q1
13	Annals of Botany	161	4.357	0.99	Q1
14	Plants-Basel	146	3.935	0.9	Q1
15	Plant Physiology	145	8.34	0.89	Q1
16	Scientia Horticulturae	145	3.463	0.89	Q1
17	Environmental and Experimental Botany	129	5.545	0.79	Q1
18	BMC Plant Biology	127	4.215	0.78	Q1
19	Functional Ecology	123	5.608	0.76	Q1
20	Functional Plant Biology	119	3.101	0.73	Q2

It can be seen from the number of published journals that the research on root traits has received extensive attention, especially in the field of plants, because the root is one of the most important organs for plant development and growth.

Published articles from different journals show that root functional traits also have an important role in linking plants and communities and can string together above-and

below-ground plant parts as a way to explain community species competition, survival and ecosystem productivity [4,25].

3.3. Anaysis of Authors, Institutions and Countries

A total of 51,916 authors published 16,233 papers, with an average of 3.20 authors per paper. Among them, 49 authors published more than 50 papers, accounting for 0.09% of the total, 634 authors published more than 10 papers, accounting for 1.22% and 39,780 authors published only one paper, accounting for 76.62% of the total number of authors.

The author who published the most papers was Wang Yan (172 papers), followed by Zhang Yajun (162 papers) and Wang Xinxin (155 papers) (Table 2). The author with the highest H index was also Wang Yan, followed by Wang Jun (136 papers) and Li Hongbo (88 papers). The author with the most citations was Wang Yan, whose papers had been cited 3307 times, 19.23 times citations per paper on average. Wang Jun (136 papers) and Li Yan (154 papers) followed, whose papers had been cited 2754 and 2706 times, with 20.25 and 17.57 times citations per paper on average.

Table 2. The top 20 authors by number of articles published from 2000 to 2021.

Ranking	Author	Number of Articles	% of 16,233	H Index	TC	TC/N
1	Wang Yan	172	1.06	28	3307	19.23
2	Zhang Yajun	162	0.998	26	2061	12.72
3	Wang Xinxin	155	0.955	23	1977	12.75
4	Li Yan	154	0.949	26	2706	17.57
5	Zhang Xiao	144	0.887	24	1959	13.6
6	Li Xianglin	141	0.869	25	2536	17.99
7	Wang Jun	136	0.838	27	2754	20.25
8	Zhang Jing	134	0.825	26	2372	17.7
9	Li Jia	132	0.813	24	2385	18.07
10	Li Zizhao	120	0.739	24	2569	21.41
11	Wang Houmiao	115	0.708	24	2206	19.18
12	Liu Ying	114	0.702	24	2317	20.32
13	Zhang Hao	114	0.702	26	2232	19.58
14	Wang Zhi	110	0.678	22	2073	18.85
15	Liu Jia	91	0.561	20	1602	17.6
16	Zhang Zhi	90	0.554	16	1023	11.37
17	Chen Yinglong	89	0.548	21	1445	16.24
18	Li Hongbo	88	0.542	27	2103	23.9
19	Wang Li	88	0.542	20	1268	14.41
20	Kumar Arvind	86	0.53	19	1553	18.06

A total of 11,179 scientific research institutions or universities participated in the publication of 16,233 articles on root traits from 2000 to 2021. The top 20 institutions published 6667 articles, accounting for 41.07% of the total. Among the top 20 affiliations by the number of papers published, University of Western Australia (630 papers) had the largest number of published papers on root traits, followed by China Agricultural University (451 papers) and Nanjing Agricultural University (390 papers), respectively (Figure 2).

The top 20 corresponding authors published 13,721 articles on root traits, accounting for 84.53% of the total. Authors from China and USA each published more than 2000 articles. As for articles containing Chinese authors as corresponding authors, there were 2926, 2060 completed by Chinese authors alone and 866 completed in cooperation with other country's authors (Figure 3). For articles from USA authors as corresponding authors, there were 2638, 1867 were completed by the USA alone and 771 completed in cooperation. According to the author collaboration network diagram divided by the number of published papers, there are 23 clustering results among authors (Figure 4), of which the most representative

is the red, green, blue, yellow and purple clustering network, accounting for 39.3% of the total number of authors. Combining the total number of authors involved in published articles on root traits and whether they have collaborated with researchers from other countries, although some authors or studies have been more collaborative and discussed, effective collaboration among researchers in a truly global sense has not yet been achieved. It has been found through many studies that current collaboration is still only in a certain small-scale research area, thus leading to limited use of some research results. Therefore, this metric review argues for increasing the close cooperation among global root researchers in various fields and accelerating the sharing of research results.
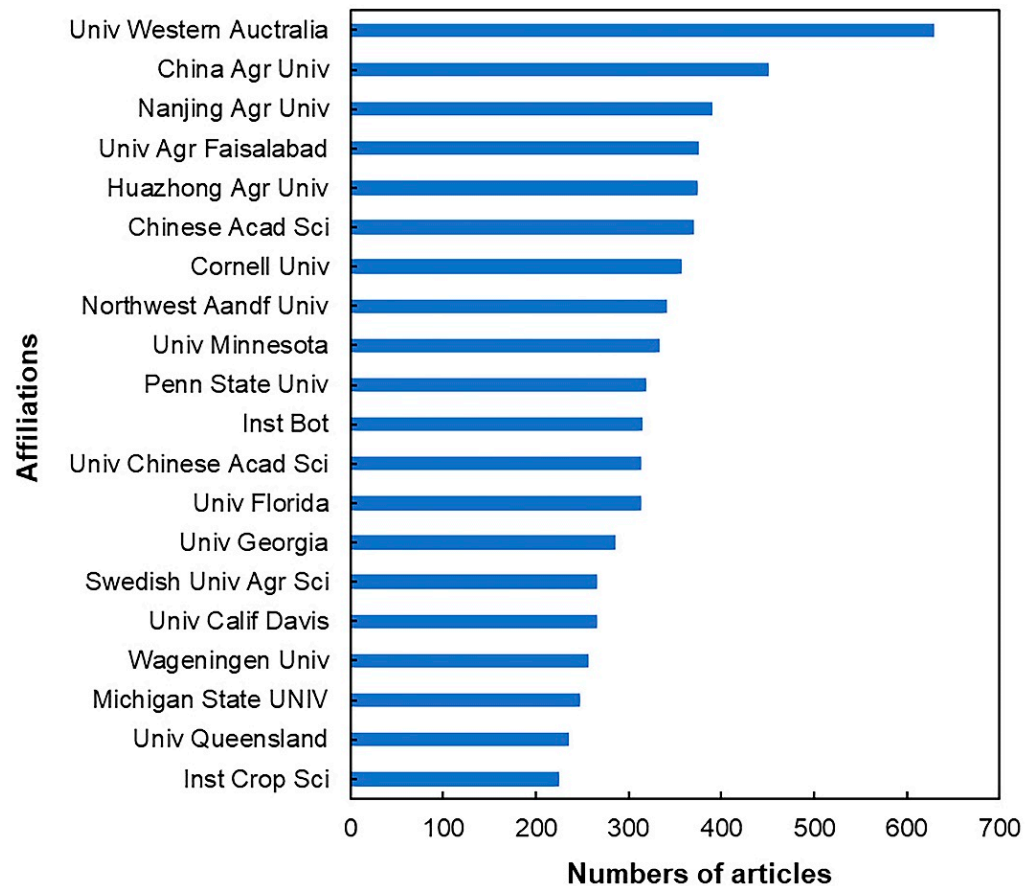

Figure 2. The top 20 affiliations by number of articles published from 2000 to 2021.

The graph of the cooperation network of the top 30 countries by volume of publications shows three kinds of clustering results among countries (Figure 5). Countries with larger nodes have more cooperative relationships with more countries and their degree of centrality and importance in the cooperative network is more significant. The USA is the center of the cooperative network for root traits research, with four major partners, namely China, Germany, Canada and Brazil. In addition to the USA, China and Germany also had good root traits research and carried out close cooperation and exchanges with other countries in the world. The thick line connections between the USA and other countries show that the USA has produced a large number of articles on international cooperation in the study of root traits. In addition to the USA, other major countries in the world have also expanded their cooperation networks. It was confirmed that the cooperation between developed countries guided the research direction of root traits, which also meant that international cooperation promoted the development of root traits research.
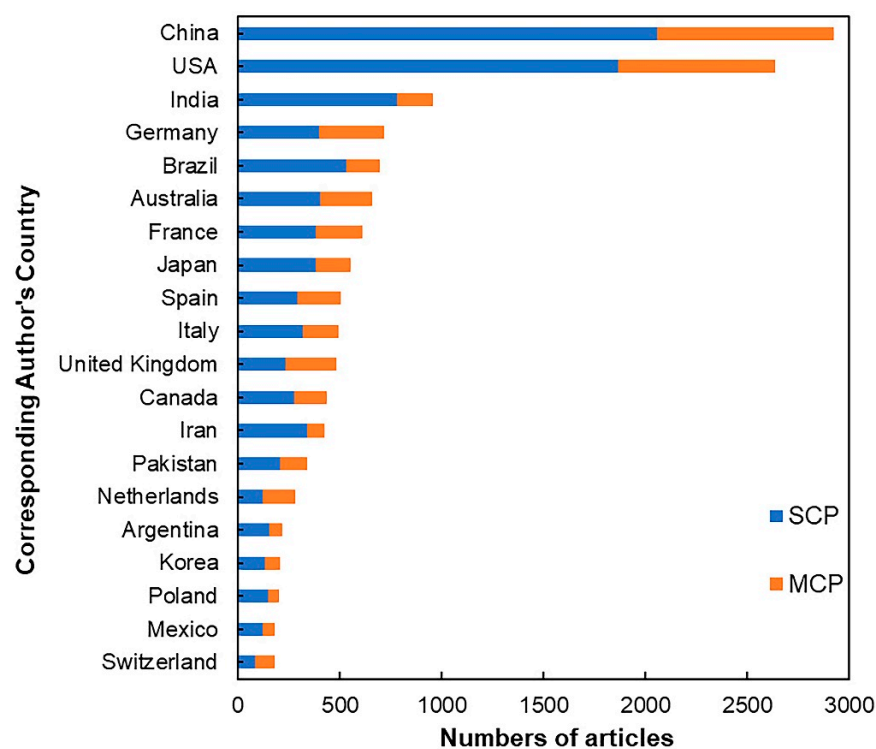
Figure 3. The top 20 corresponding author's countries by the number of articles published from 2000 to 2021. SCP: Single Country Publications; MCP: Multiple Country Publications.
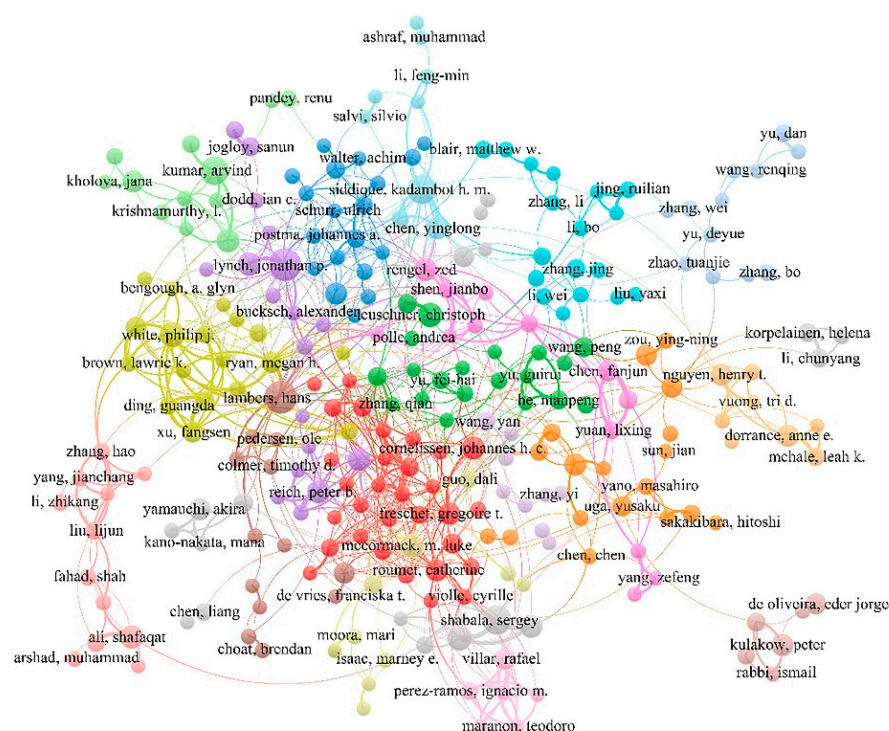

Figure 4. The network map of co-authorship analysis of authors between 2000 and 2021. The size of nodes indicates the number of published articles, the connection thickness between nodes indicates the degree of cooperation between authors and the color of different nodes indicates different clustering results.
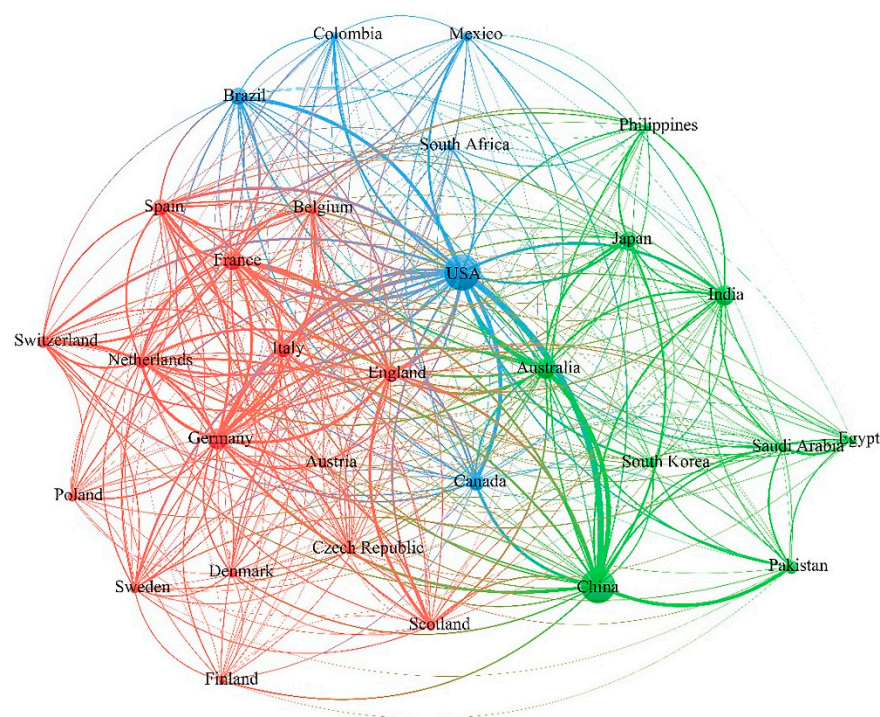
Figure 5. Core international collaboration network map of the top 30 countries from 2000 to 2021. The size of nodes indicates the number of published articles, the connection thickness between nodes indicates the degree of cooperation between authors and the color of different nodes indicates different clustering results.

A total of 142 countries have carried out research on root traits. The countries with the largest number of published papers are mainly located in North America, Oceania and Europe (Figure 6). USA (12,075 publications) was the most productive country and the second-contributing country was China (11,819 publications). Compared with the USA and China, the number of publications in the remaining 10 countries is relatively small. For example, there are 3300 publications in India, 3267 publications in Germany and 3073 publications in Australia.
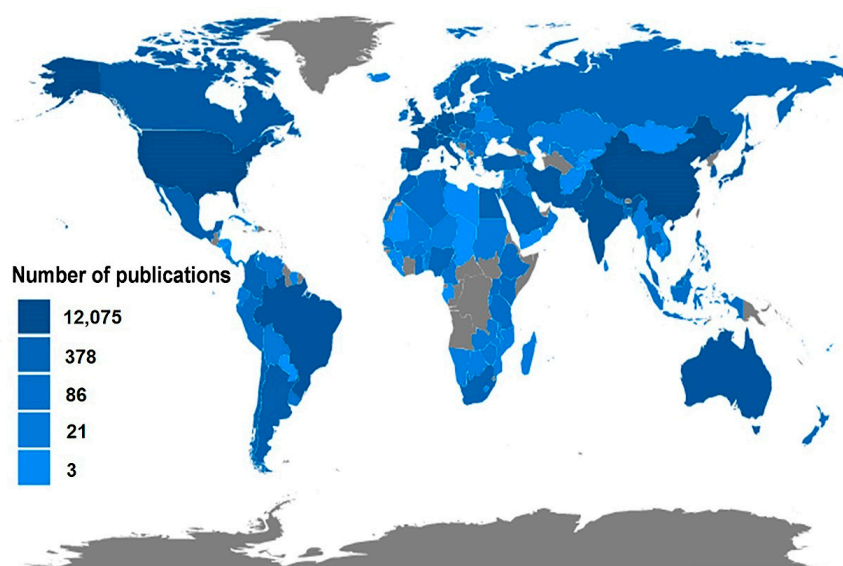

Figure 6. The distribution map of the number of publications of countries between 2000 and 2021.

3.4. Analysis of Keywords

The occurrence frequency of the top 50 keywords in the articles on root traits published between 2000 and 2021 showed a significant difference (Figure 7). The total occurring frequencies of these 50 keywords were 33,191, of which 8 keywords were more than 1000, such as "growth" (3141), "traits" (1741), "plants" (1253), "tolerance" (1244), "responses" (1158), "yield" (1099), "soil" (1053) and "diversity" (1006). These eight keywords accounted for 35.24% of the total frequency. These 50 keywords showed the hotspots in the study of root traits, mostly focusing on plant growth, the relationship between traits and yield, the interaction between soil and traits, the response of traits to community diversity, and so on.
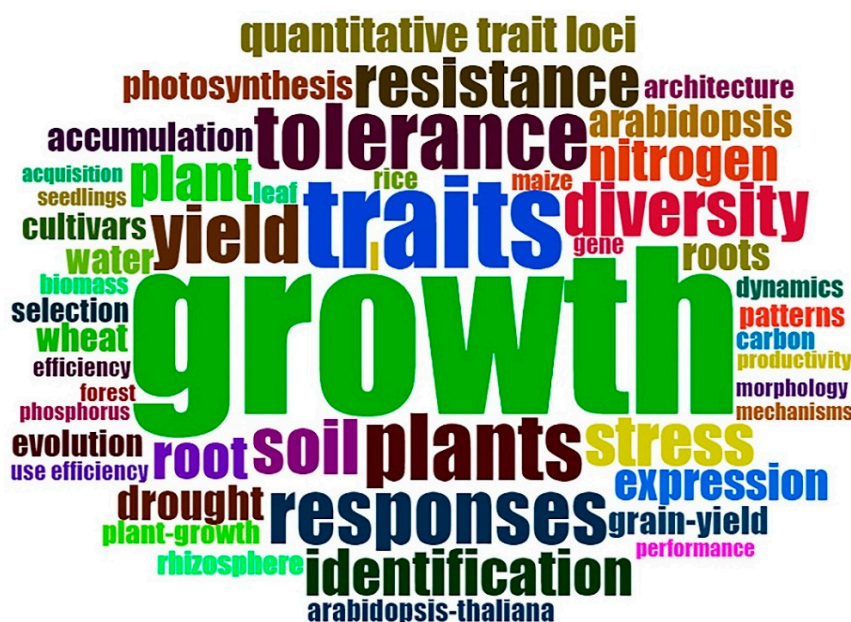

Figure 7. The top 50 keywords mentioned in root traits research from 2000 to 2021.

In the cluster analysis and keyword co-occurrence network graph analysis, the most significant relationships between "growth" and "traits", "tolerance", "plant" and "yield", respectively, were found for keywords that appeared more than 20 times (Figure 8). The results showed that these four keyword groups had the highest frequency of co-occurrence and the strongest relevance and most studies focused on these topics. Keywords such as "nitrogen", "carbon", "soil", "diversity" and "drought" also occupied an important position in the co-occurrence network. There are six clustering networks in the main keyword co-occurrence network (Figure 8), in which the red clustering network containing traits and the green clustering network containing yield are located at the core of the co-occurrence network, covering the most keywords. There are clusters around crop traits and performance (green), general physiology (blue), soil communities and processes (yellow) and linking root traits to other plant traits and ecosystem functioning (red)**.** The clustering results revealed that current research is mainly conducted on the correlations between root traits and plant growth, nutrition utilization, biodiversity, global change and ecosystem functions. Thus, root traits have a close relationship with root growth and with the development of all aspects of populations, communities and ecosystems. Researchers have also found that root growth and spatial distribution, which are closely associated with root traits, are not only limited by nutrients but also by stimulation or inhibition among root traits of other species in the community [32–36], such as root secretions [37,38], inter-root biota, etc. [39,40]. It is also related to the heterogeneity of environmental resources, such as the uneven distribution of nutrients and water [41–43].
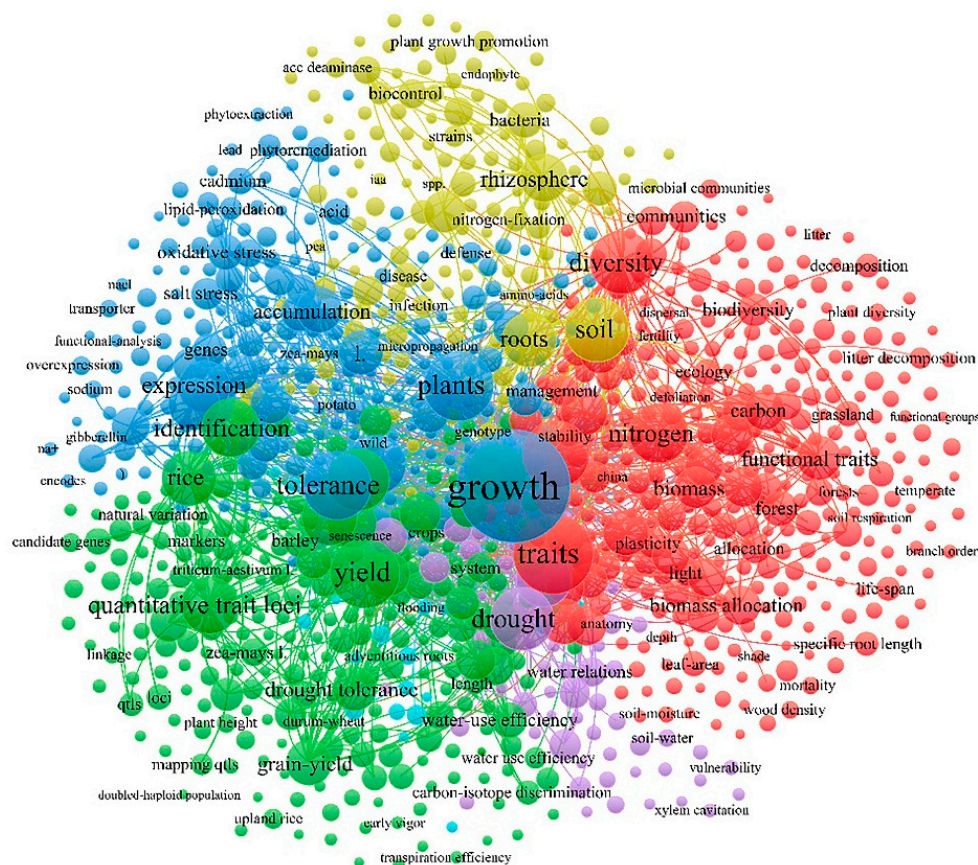
Figure 8. The main keywords of network co-occurrence come from articles. The size of the node indicates the frequency of keyword use. The connection between two nodes indicates the simultaneous relationship between two keywords. The thickness of the connection between the two nodes indicates the co-occurrence frequency of the two groups of keywords. Different node colors represent different clustering results.

In conclusion, it is found that understanding root function and its impact on plant growth, ecosystem processes and function through root traits are hot and difficult points in the current research on root ecology [44].

Through the discussion in this paper, we found that, although the research on root traits is developing rapidly, some issues are still worth exploring. First, on a small scale, the research on some specific root traits should be deepened because root traits are highly variable and plastic [25,45,46], easily influenced by environmental factors [4,47] and may have a greater potential for community function, which needs to be explored, at the same time; in addition, the research on root traits related to soil structure, nutrient heterogeneity, etc., should be strengthened [41–43]. Root traits are directly or indirectly related to some microorganisms in the soil and their interactions can have different effects on community resource allocation and productivity [48].

Then there is the large scale of the overall study. Firstly, collaboration among authors, institutions and countries should be strengthened to promote the sharing of research, information and resources. Therefore, it is more important to deepen the cooperation among root researchers from different regions and countries, to promote the sharing of relevant results and to achieve more efficient scientific exchange. Second, better methods of sampling and analyzing root traits should be investigated to aid researchers in their research. Thirdly, a multi-angle, multi-level or multi-scale study on root traits should be conducted to facilitate the related mechanism disclosure.

4. Conclusions

In the past two decades, research on root traits has gradually increased and has developed to varying degrees all over the world. The results of bibliometrics analysis showed, that since 2000, the annual yield of root traits has increased steadily and was in a state of stable development, indicating the necessity and broad research prospect of root traits. For authors, the author with the most published papers was Wang Yan and the author with the most citations and the highest H index was also Wang Yan. The publication journals *Plant and Soil, Frontiers in Plant Science, PLoS One* and *New Phytologist* ranked as the top four based on the number of published articles. As for institutions with some published papers, the University of Western Australia, China Agricultural University and Nanjing Agricultural University ranked in the top three. In terms of publishing countries, the United States and China are the two countries with the most publications. The USA is the most influential country in terms of its total number of citations. China ranks second in the number of published papers but still lags behind other developed countries in terms of academic influence. For cooperation among major countries, institutions and authors, the cooperation and exchange are not close enough and a global cooperation network has not yet been formed. Within the articles, root traits, growth, tolerance, soil and diversity were frequently mentioned keywords. It indicated that the current research on root traits was mainly in the fields of woody, herbaceous and crops, focusing on how plant root traits respond to environmental changes under different environmental conditions.

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