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Review

Charting the Research Terrain for Large Old Trees: Findings from a Quantitative Bibliometric Examination in the Twenty-First Century

Chunping Xie [1,*], Chang Liu [2], Dawei Liu [3] and C. Y. Jim [4,*]

1 Tropical Biodiversity and Bioresource Utilization Laboratory, Qiongtai Normal University, Haikou 571127, China
2 Nanjing Institute for Comprehensive Utilization of Wild Plants, China Co-ops, Nanjing 211111, China; lion22sky@163.com
3 Faculty of Criminal Science and Technology, Nanjing Police University, Nanjing 210023, China; dwliu@nfpc.edu.cn
4 Department of Social Sciences and Policy Studies, Education University of Hong Kong, Hong Kong, China
* Correspondence: xcp@mail.qtnu.edu.cn (C.X.); cyjim@eduhk.hk (C.Y.J.)

Abstract: Despite their relatively small numbers, large old trees play disproportionately important roles in global biodiversity and ecosystem functions. There is a lack of systematic reviews and quantitative analyses of the accumulated literature. Understanding the research context and evolution could pump prime research and conservation endeavors. Using the comprehensive Web of Science, we applied VOSviewer (1.6.19) and CiteSpace (6.1R2) bibliometric software to examine the large old tree research field in 2000–2022. The queries of the bibliographic database generated quantitative–visual depictions in the form of knowledge maps. The nodes denote research intensity, and inter-node linkages denote the pathways and frequencies of collaborative activities. The research outputs differed significantly in terms of regions, countries, institutions, high-citation articles, productive researchers, hot topics, and research frontiers. Conspicuous spatial disparities were displayed, with the U.S.A., China, and Australia leading in publication counts and a cluster of European countries making considerable collective contributions. The research collaboration demonstrated a dichotomy: European countries networked more by geographical propinquity, and the top three countries connected by long-distance leap-frog jumps. The entrenched discrepancies between the endowed developed domains vis-à-vis the deprived developing domains were clearly expressed. The research productivity progressed through three stages: initial, growth, and flourishing. The leading institutions, researchers, and highly cited papers were recognized. The keyword analysis pinpointed diverse research hotspots: growth dynamics, conservation and management, ecological functions, and environmental response. This study informs recommendations for future research directions and cooperation on longevity mechanisms, evolutionary adaptation, dynamic monitoring, and temporal–spatial patterns. The integrated application of GIS, machine learning, and big data technologies could strengthen research capability.

Keywords: large old trees (LOT); research hotspot; research frontier; bibliometrics; VOSviewer

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1. Introduction

Large old trees (LOT) denote a condensed representation of the fusion of nature and culture. They accommodate imprints of evolution, competition, co-existence, and abiotic and biotic changes in their environs. While preserving a record of the changing regional ecological environment, they witness the vicissitudes of history and interactions with neighboring human communities [1]. LOT contribute significantly to various ecosystem services. These include biodiversity conservation, micro-habitat provision, carbon sequestration, nutrient cycling, soil and water conservation, and microclimate regulation [2].

Besides ecological functions, they offer profound cultural value, embodying unique cultural connotations, religious significance, collective ethnic memory, and human landscape resources (Figure 1) [3,4]. Therefore, their presence is valuable for preserving natural heritage, contributing to cultural continuity, and enhancing ecosystem stability.

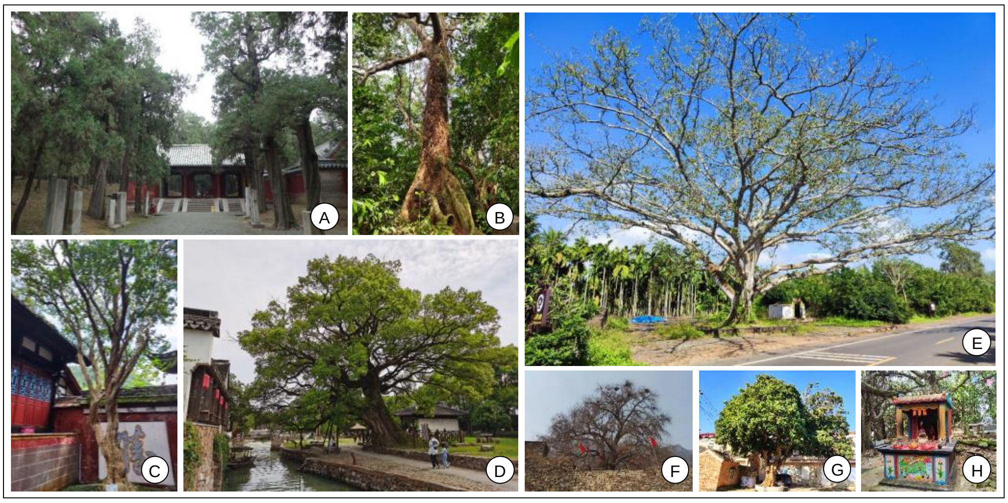

Figure 1. Large old trees in various habitats in China. (**A**) Family cemetery; (**B**,**E**–**H**) Rural area; (**C**) Temple; (**D**) Scenic Area; (**H**) Religious shrine companion LOT.

Conserving LOT can protect ecology and biodiversity and preserve our ancestors' spiritual homeland and nostalgic living landmarks for future generations [5]. However, due to various factors such as environmental pollution, climate change, natural and anthropogenic disasters, and pests and diseases, the survival of LOT is critically challenged [6,7]. A notable body of knowledge has accumulated with rising research endeavors in recent years. It is deemed opportune to objectively analyze the research findings and trends. A systematic literature review can enhance understanding of the moving research focus and limitations. The outcomes could inform continued studies, conservation, and the management of a precious but declining resource.

Bibliometrics is an emerging research approach that applies mathematical and statistical techniques to analyze the scientific literature's vast and complex information contents [8]. The method has been increasingly employed to explore the development trend of disciplines and specific fields. Associated with continually expanding research scope, it encompasses theoretical and methodological explorations and extensive applied research [9]. A notable advantage is its ability to efficiently and objectively quantify scientific information and discover the inherent patterns and directions of knowledge development [10]. Regarding metric evaluation, bibliometrics can analyze the academic output and impact of researchers, institutions, countries, or journals. Typical quantitative indicators include publication counts, citation frequencies, and impact factors [11].

In tracking the research frontiers, bibliometrics can identify the development direction by analyzing the evolution trend of topical or high-frequency words [12]. Knowledge map construction and analysis can decipher the knowledge interaction, crossover, and co-evolutionary trajectory between disciplines [13]. In addition, the technique can realize intelligence monitoring and early warnings, revealing potential development trends or major unexpected events in a certain field [14]. Therefore, bibliometrics has been widely applied to scientific information management, decision analysis, and competitive intelligence fields. Its capability to quickly and efficiently discover regularities in knowledge realms has a promising application appeal.

The bibliometric software VOSviewer was developed by Nees Jan van Eck and Ludo Waltman of the Science and Technology Research Center of Leiden University [15]. VOSviewer has powerful knowledge map construction, visualization, and analysis functions. Researchers can import scientific literature, patents, and other data into the software for full-text analysis. The software extracts keywords and establishes their co-occurrence relationships, allowing the construction of a knowledge web between project markers. Concerning visualization, it intuitively displays the knowledge structure as a network diagram. It uses the color and size of nodes to represent importance and the inter-node distance to denote the degree of association. This interactive visualization network intuitively displays the complex internal structure of knowledge [16].

The knowledge map can help researchers identify hotspots, changes in the knowledge structure, and institution and personnel collaboration relationships. These elaborate analytical outcomes support research plan formulation and foster new knowledge discovery [17]. Therefore, the greatest value of VOSviewer is its integration of knowledge map construction, visualization, and analysis [18]. It is not difficult to operate and does not require programming skills, allowing fast discovery of structures, clusters, and trends inherent in a given knowledge sphere. It offers scholars a practical, rigorous, and powerful bibliometric analysis tool. Similar bibliometric software such as CiteSpace can achieve most VOSviewer functions [8,17,19]. CiteSpace is a powerful informetric analysis and visualization tool that allows researchers to understand the patterns and dynamics in scholarly publications and citations within a field of study and their evolution over time [20]. Its visual representations and metrics can uncover key concepts, contributors, and developmental trajectories in a knowledge domain [17,21].

LOT research mostly focuses on species diversity, tree physiology, and ecological functions [2]. Clarifying the background and evolution of LOT studies can provide researchers with a comprehensive snapshot of the field's current state and future trends. However, a comprehensive and systematic review based on the quantitative approach is lacking. The bibliometrics method has rarely been applied to review LOT studies. This study investigated research hotspots and development tendencies. Using the Science Citation Index Expanded (SCIE) database in the Web of Science (WoS) core collection, we conducted bibliometric analysis on journal articles related to LOT using VOSviewer. We aimed to discover the research development structure and trend.

This study's primary goals addressed the following challenges by analyzing LOT literature published in 2000–2022 using bibliometric tools: (1) What are the literature's output profiles and citation characteristics? (2) What are the most influential papers using the literature co-citation network? (3) Which authors, institutions, countries, or journals have significantly contributed to the research field? (4) How are collaboration patterns structured, and how do they evolve? (5) What are the hot subjects and frontiers in the research field in the study period?

2. Materials and Methods

To a large extent, the literature search data sources directly determine the bibliometric analysis's validity and accuracy. WoS, a comprehensive information retrieval platform developed by Clarivate Analytics, is one of the world's largest and most prestigious journal citation databases [22]. It covers six citation indexes, including natural, social, and arts and humanities. It embraces over 10 billion searchable cited references spanning across 250 disciplines. WoS's uniqueness lies in indexing all metadata of each research output, including the cited and citing references, thus establishing the multiple connections between the indexed research and the broader academic literature [23]. This extensive citation network can help researchers discover the most cutting-edge and important results in specific research fields; break down barriers between journals, publishers, and database platforms; and foster the development of high-level research. Using the SCIE in WoS, we established the retrieval field "title" and the retrieval words "large old tree", "veteran tree", "heritage tree", "old tree", "old-valuable tree", "champion tree", "venerable tree", "ancient tree", or "venerable tree". The retrieval period spanned from 1 January 2000 to 31 December 2022. After the language "English" was selected, 789 relevant references were retrieved.

As the size of old trees denotes an ecosystem- and species-specific phenomenon, it can be challenging to define them in absolute terms. For example, a large Australian or African savanna tree will be much smaller than a large redwood (*Sequoia sempervirens*) in California. Likewise, different tree species in the same habitat will have different maximum dimensions and lifespans in relation to biological potential. Even among researchers working in cognate ecosystem types, the definitions of large ancient trees might differ and remain fluid, contingent on the nature of the study targets and research requirements [2]. Due to this flexibility, we made decisions based on the study objects and keywords embodied in the literature rather than trying to dwell on a definitive meaning of LOT. In addition, we found that nearly all LOT are connected to the cardinal "long-living" or "large size" criteria, albeit in relative terms depending on the context. As a result, we believe that the harvested publications in this study could encompass LOT consistently.

The retrieved literature data were saved in text format and analyzed by VOSviewer 1.6.19 [16]. The software plotted knowledge maps: co-authorship, co-institutional, and co-country. In the maps, a node's circle size represented publication counts; the inter-node distance denoted the collaboration strength between authors, institutions, and countries, with a short distance indicating strong collaboration [24]. The co-occurrence of keywords in the literature was plotted on a keyword clustering knowledge map. Each node represents a keyword, with the circle size representing its occurrence count. The inter-node distance denotes a keyword's co-occurrence frequency, with a short distance indicating a high frequency [21]. The retrieved annual publication data, including journals, publication counts, and author institutions, were statistically analyzed using Excel and depicted in charts. The burst detection algorithms of CiteSpace 6.1.3 were employed to discover the research frontiers [20].

3. Results and Discussion

3.1. Distribution Pattern of Publications

The changes in the number of publications are the main indicator of the development trend of a field over a period. These data can be used to evaluate the stage and development dynamics of the field, as well as predict the future trend [25]. This study initially obtained 789 references from the WoS Core Collection. We performed an item-by-item screening using a manual method and software to select research articles, literature reviews, editorial materials, and letters to the editor. Finally, 388 pieces closely related to the study theme were included for subsequent analysis. The time series of the number of articles published in 2000–2022 can be classified into three stages (Figure 2). (1) The initial stage (2000–2010) had less than 20 publications per year and an average of 9 per year, ranging from only 7 in 2000 to 15 in 2005. During this stage, more attention was paid to the population dynamics and tree physiology of old-growth forest trees, such as Douglas fir [26] and old-growth temperate and boreal forests [27]. (2) The growth stage (2011–2018) experienced a notable increase in publications, with an average of nearly 20 per year, ranging from 14 in 2014 and 2016 to 24 in 2011 and 2015. The main scope was regionally focused studies of the resource distribution, survival status, ecological habits, and environmental relevance of LOT [7,28,29]. Many excellent studies were published in top journals, such as *Science*, *Biological Conservation*, and *Conservation Letters*. (3) The flourishing stage (2019–2022) witnessed 130 papers published in four years, accounting for nearly one-third of the total research outputs in the whole study period, at an average of 33 papers per year. Besides continuing previous studies, this stage was marked by large-scale geographical studies. It covered specific issues such as carbon sequestration, climate impacts, genetic diversity, and the emergence of new topics [30–32]. The research literature is projected to grow continually, with Chinese scholars showing a particular interest [1,30,33].

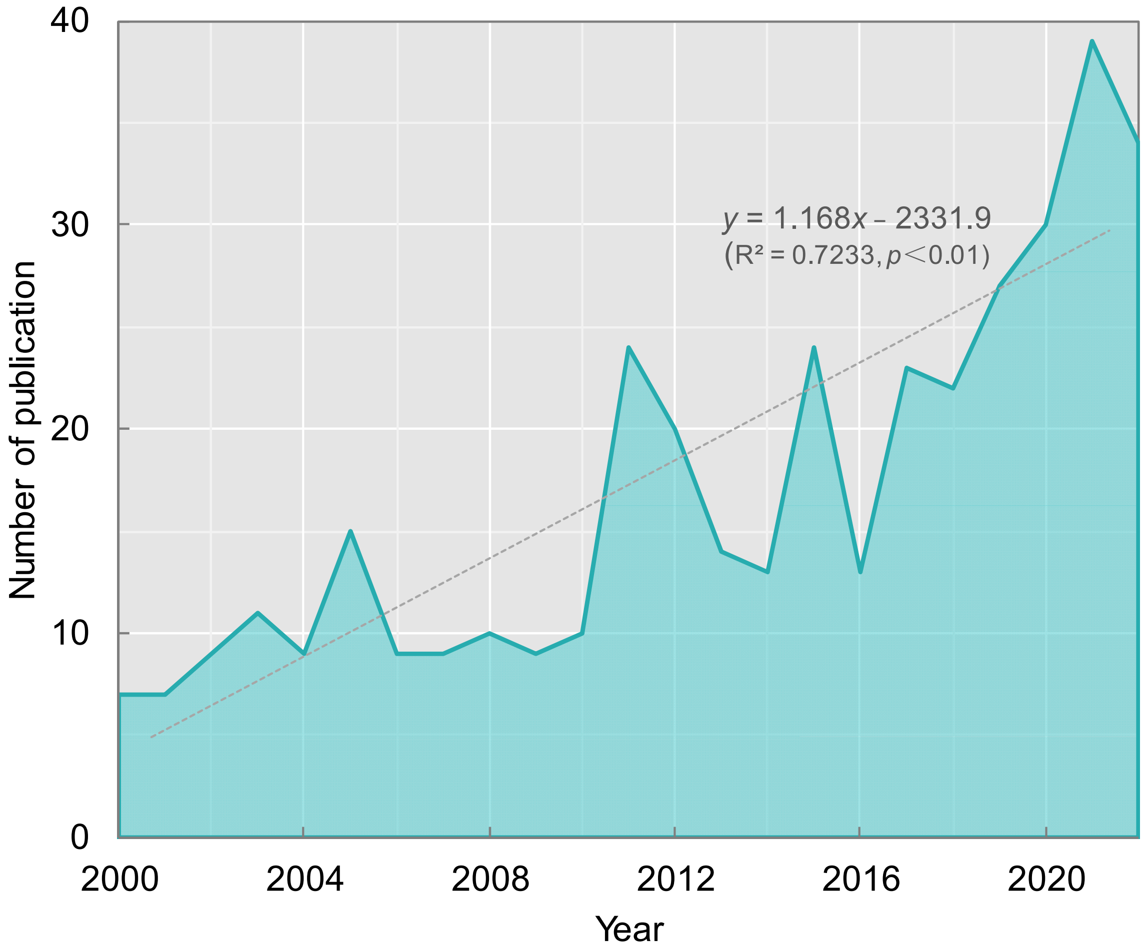

Figure 2. Time-series variations and regression trend line of publication outputs on LOT research in 2000–2022 using the WoS core collection database.

3.2. Main Research Regions and Countries

The number of publications by country on LOT can reflect the attention accorded by each country. The node size, connection strength, and other values in the co-occurrence map (Figure 3) can depict the collaborative relationship between countries, furnishing hints and guidance to develop international cooperation [8]. The node size represents the number of articles published by a country. Node connections show the magnitude of linkages between countries. The link strength indicates the connection effect of a node in relation to the entire network. A high total link strength highlights the key nodes in the network [34]. The national collaboration network can reveal the distribution of research strength in the research field. Countries with more publications have implied relatively strong research capabilities. When adopting a total link strength of >18 as the threshold, except for a few developing countries, such as China, Peru, and Ecuador, most are developed countries, such as the U.S.A., Australia, England, Germany, Spain, France, and Canada (Table 1). Regarding publication counts, the U.S.A., China, and Australia contributed the most, with 124, 77, and 30 articles, respectively. Moreover, these three countries have the highest citations, exceeding 1000. Although Canada published only 22 articles, its number of citations, at 1012, is close to that of Australia.

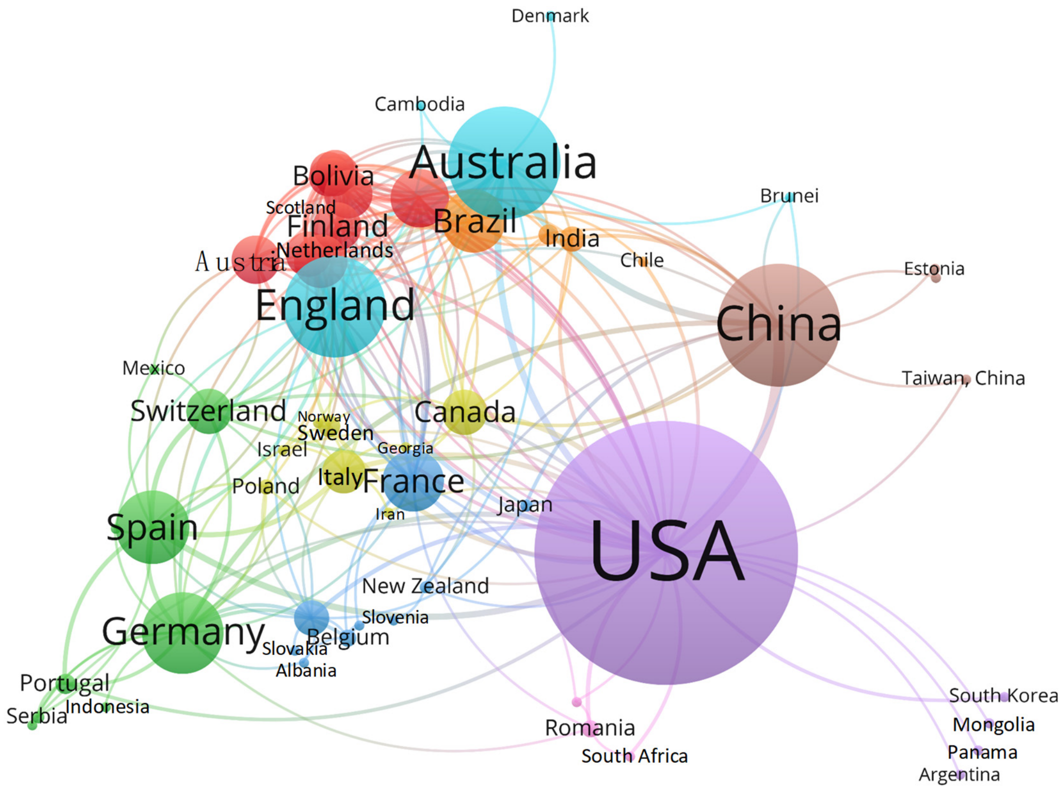

Figure 3. The research collaboration network of countries in 2000–2022 using the WoS core collection database. Many countries with only 1–2 publications are not displayed.

Table 1. Overview of main countries' research publications on large old trees in 2000–2022 using the WoS core collection database.

Country	Publications	Citations	Total Link Strength	Country	Publications	Citations	Total Link Strength
U.S.A.	124	5445	103	Ecuador	2	114	23
China	77	1649	48	Peru	3	80	21
Australia	30	1345	44	Austria	6	122	19
England	18	875	40	Finland	11	342	19
Germany	23	590	32	Scotland	3	48	19
Spain	16	883	29	Canada	23	1012	18
Brazil	9	141	25	Netherlands	4	87	18
France	9	124	24	Switzerland	10	354	18

The colors and proximity of country nodes indicate the closeness of their relationships (Figure 3). The map does not display many countries with only 1–2 publications and limited research capacity. Whereas the U.S.A. is overwhelmingly dominant, the European countries collectively demonstrate a strong presence, with more contributions from England and Germany than from other jurisdictions. Most connections in the U.S.A. are associated with Europe. Despite the considerable geographical distance, the rather prominent Australia is well connected with Europe, especially England, rather than the closer Asian countries. China is the only Asian country with notable representation, yet most of its linkages are outside Asia and extend to distant lands. China also plays a leading role in the realm of developing countries.

Regarding grouping, countries such as Germany, Spain, Switzerland, and Portugal have closer ties, forming a spatial research cluster. Austria liaises more closely with Finland, the Netherlands, Scotland, and other countries. Such distribution patterns signify that geographical propinquity in Europe has driven the propensity for international collaboration. Additionally, Europe's political, social, and cultural affinities are conducive to research cooperation. However, the map also shows that China, U.S.A., and Australia are geographically remote. Nevertheless, their node connections are relatively strong, indicating a different spatial pattern of cross-regional teamwork through a leap-frog mode jumping across the oceans.

With the continual strengthening in identifying and protecting biodiversity conservation hotspots, regional- and global-scale research partnerships in the LOT field are expected to grow. However, such new developments will continue to be realized mainly in the endowed developed countries. Besides China, which may be considered a transitional economy, most deprived developing countries will continue to have minimal participation. To redress this entrenched dichotomy, global climate change, and the rapid loss of biodiversity, countries could proactively strengthen collaboration in research and practice. The knowledge maps provide hints to fill the gaps.

3.3. Key Research Institutions

The contribution of individual research institutions is evaluated by the authors' affiliation. The collaborative network of research institutions can indicate the distribution of research strength in the field (Figure 4). Research institutions with more publications and stronger connectivity have better capabilities. In Figure 4, the circles represent research institutions, and the circle size indicates the publication count. The connections signify cooperative relationships, with the thickness and length of connections showing the strength of cooperative relationships. The nodes and links with the same colors indicate a cluster with close internal relationships. For example, in China, the Beijing Forestry University, Chinese Academy of Forestry Sciences, and Nanjing Forestry University have closer cooperation, indicating affiliation to the same research administration system. The relationships between Boston University, Colorado State University, and Oregon State University in the U.S.A. are closer. They also reflect a certain degree of geographical propinquity.

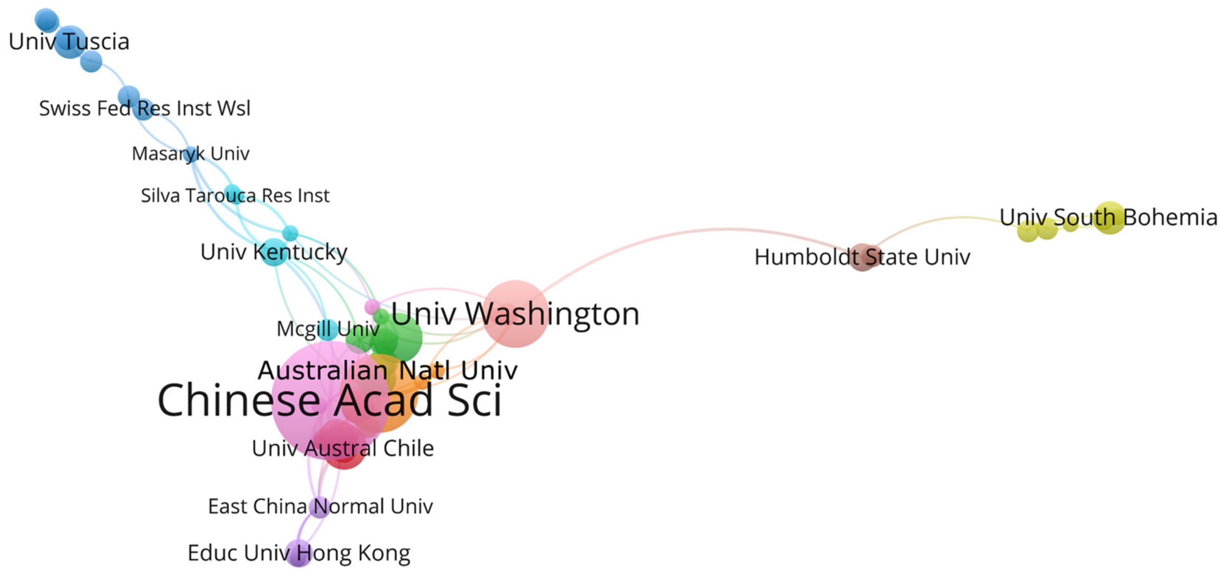

Figure 4. Cooperation between research institutions in 2000–2022 using the WoS core collection database.

Based on the number of publications (Table 2), the top three institutions are the Chinese Academy of Sciences, the Australian National University, and the University of Washington, with 21, 14, and 12 articles, respectively. These three institutions also dominate citations. Besides the Chinese Academy of Sciences, four institutions in China are also on the list: East China Normal University, Education University of Hong Kong, Zhejiang University, and Chongqing University. Although their publication counts are small, their international academic influence is gradually rising, reflected by a total link strength of eight to nine. Overall, the institutions of the U.S.A., Australia, and China are notably stronger than those of other countries.

Table 2. Main research institutions ranked by citations of publications in 2000–2022 using the WoS core collection database.

Institution	Publications	Citations	Total Link Strength
University of Washington	12	857	12
Australian National University	14	840	18
Chinese Academy of Sciences	21	730	21
Oregon State University	9	590	9
Boston University	3	555	8
Colorado State University	5	414	10
Mendel University Brno	3	271	9
University of Kentucky	5	131	11
East China Normal University	4	108	9
Education University of Hong Kong	5	69	9
Zhejiang University	4	65	8
Bard College at Simon's Rock	3	53	8
Chongqing University	3	53	8
Masaryk University	3	47	8

3.4. Main Researchers

According to the formula $N = 0.749(N_{\max})^{1/2}$ yielding $N = 2.9$ (rounded to the nearest whole number, 3) [8], we define authors with three or more publications in the 2000–2022 study period as core researchers in the field. Table 3 lists authors with more than eight publications. The top three are D.B. Lindenmayer, C.Y. Jim, and Y. Ji, with 15, 14, and 11 articles, respectively. Lindenmayer's research is dedicated to LOT ecology and habitat value [2,7,29]. His work has significantly improved ecological understanding and conservation practices for LOT globally. Jim has been committed to protecting and researching LOT in China since the 1990s [1], especially in South China [28,35,36]. He has developed unique insights into the spatial distribution of heritage trees. Four of the eight authors on the list are from China, implying the increasing contributions of Chinese scholars.

Table 3. Main researchers with more than eight publications in 2000–2022 using the WoS core collection database.

Author	Number	Institution
Lindenmayer, D.B.	15	Australian National University
Jim, C.Y.	14	Education University of Hong Kong and University of Hong Kong
Ji, Y.	11	Chinese Academy of Sciences
Wang, X.	9	Chinese Academy of Sciences
Franklin, Jerry F.	9	University of Washington
Yamamoto, Shin-Ichi	8	Okayama University
Nishimura, N.	8	Nagoya Sangyo University
Lin, F.	8	Chinese Academy of Sciences

Co-citation analysis is an important indicator computed by VOSviewer to reveal the relationships between publications, authors, and journals. The more two items are cited together, the closer they are positioned in the co-citation network, indicating stronger content associations. These data provide an effective way to map the knowledge domains and identify influential contributors. The font size of the node is determined by its weight; the larger the node, the more frequently the article is cited. The connections between nodes symbolize the authors' collaborative relationships. VOSviewer divided the selected authors into five clusters (Figure 5).

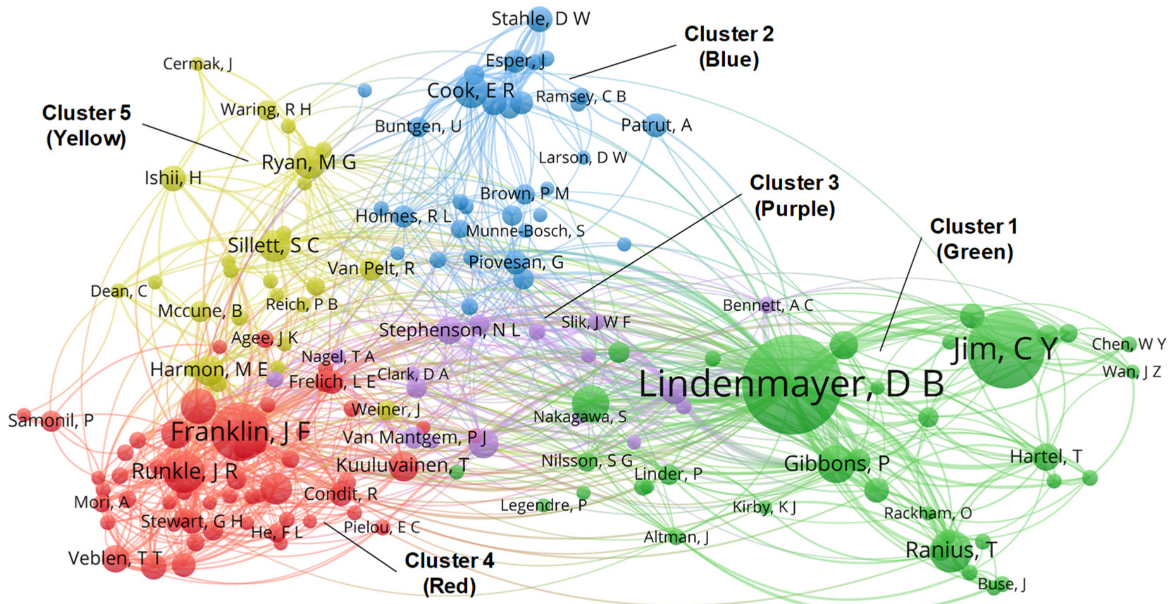

Figure 5. The author co-citation knowledge map for 2000–2022 divided into five clusters using the WoS core collection database.

Cluster 1 (green) includes key scholars such as D.B. Lindenmayer, C.Y. Jim, and T. Ranius, who are mainly committed to research on LOT ecology, management, conservation, and biodiversity [2,7,28,29,35]. Cluster 2 (blue) includes D.W. Stahle, K.R. Briffa, A. Patrut, and others, mainly committed to dendrochronology to assess changes in the climatic environment [37]. Cluster 3 (purple) includes J.A. Lutz, N.L. Stephenson, W.F. Laurance, and others who are mainly committed to monitoring the growth of LOT and proposing corresponding management and protection measures through their spatial relationships and growth status in natural habitats [38]. Cluster 4 (red) includes J.F. Franklin, J.R. Runkle, C.G. Lorimer, and others, mainly committed to forest ecological research, especially the survival dynamics of LOT [39]. Cluster 5 (yellow) includes M.G. Ryan, S.C. Sillett, M.E. Harmon, and others, mainly committed to the physiological study of LOT, such as their photosynthesis, water transport, carbon fixation, and productivity [26]. However, in this division, some scholars work across the clusters, such as W.F. Laurance, who is also related to scholars in Cluster 1. The scholars' research on LOT was extensive, with close and notable cooperation.

3.5. Highly Cited Publications

Examining highly cited publications and citation patterns provides useful insights into the development, trends, and key contributors in a research field over time. It provides the context for metrics-based evaluation and identifies influential past and future research directions. The top 20 most cited publications in the field of LOT and related information in 2000–2022 are summarized in Table 4. The most cited paper (505 times), "Components of tree resilience: effects of successive low-growth episodes in old ponderosa pine forests", was published in *Oikos* in 2011 (Table 4). Based on tree ring analyses, the authors argued that recent increases in forest mortality due to climatic trends might be related to thresholds of individual resilience components rather than an overall loss of resilience over time. The study pointed to a promising research direction with significant implications for forest management [40]. Other publications related to forest management were written by V. Rozas [41], J. Esper [42], and E. Fichtler [43].

Table 4. Top 20 cited publications based on the WoS core collection database in 2000–2022.

Rank	Year	Author	Journal	First Institution and Country	Topic	Citations
1	2011	Lloret, F. et al.	*Oikos*	Ecological and Forestry Applications Research Centre, Spain	Dendrochronology	505
2	2000	Briffa, K.R.	*Quaternary Science Reviews*	University of East Anglia, England	Dendrochronology	453
3	2012	Lindenmayer, D.B. et al.	*Science*	Australian National University, Australia	Conservation and management	414
4	2000	He, F.L. et al.	*Journal of Ecology*	Pacific Forestry Centre, Canada	Population dynamics	292
5	2007	Cermak, J. et al.	*Tree Physiology*	Mendel University in Brno, Czech Republic	Physiology	260
6	2000	Ranius, T. et al.	*Biological Conservation*	Lund University, Sweden	Biodiversity	230
7	2002	McDowell, N.G. et al.	*Tree Physiology*	Oregon State University, U.S.A.	Physiology	210
8	2014	Lindenmayer, D.B. et al.	*Conservation Letters*	Australian National University, Australia	Conservation and management	209
9	2017	Lindenmayer, D.B. et al.	*Biological Reviews*	Australian National University, Australia	Review	205
10	2009	Haneca, K. et al.	*Journal of Archaeological Science*	Flanders Heritage Institute, Belgium	Review	186
11	2010	Sillett, S.C. et al.	*Forest Ecology and Management*	Humboldt State University, U.S.A.	Silviculture	145
12	2003	McDowell, N. et al.	*Plant Cell and Environment*	Oregon State University, U.S.A.	Conservation and management	144
13	2001	Lorimer, C.G. et al.	*Journal of Ecology*	University of Wisconsin, U.S.A.	Population dynamics	144
14	2002	Phillips, N. et al.	*Tree Physiology*	Boston University, U.S.A.	Physiology	137
15	2003	Fichtler, E. et al.	*Biotropica*	University of Gottingen, Germany	Physiology	133
16	2008	Esper, J. et al.	*Forest Ecology and Management*	Swiss Federal Research Institute WSL, Switzerland	Dendrochronology	125
17	2014	Blicharska, M. et al.	*Conservation Biology*	Swedish University of Agricultural Sciences, Sweden	Conservation and management	105
18	2009	Johnson, S.E. et al.	*Tree Physiology*	Pennsylvania State University, U.S.A.	Physiology	101
19	2013	Luo, Y. et al.	*Nature Communications*	Lakehead University, Canada	Population dynamics	101
20	2005	Rozas, V.	*Annals of Forest Science*	University of Oviedo, Spain	Dendrochronology	96

The papers "Annual climate variability in the Holocene: Interpreting the message of ancient trees" and "Global decline in large old trees" were cited 453 and 292 times, respectively, ranking second and fourth most cited. The first work reviewed some recent dendroclimatic research related to global change. In determining the significance of twentieth-century global warming, evidence from dendroclimatology supports the assumption that the last 100 years have been exceptionally warm compared to the previous two millennia [37]. The second work found that LOT populations are quickly disappearing in many parts of the world, threatening ecological stability and biodiversity; hence, they demand urgent protection [7].

In the 20 publications, seven main subjects can be distilled: conservation and management, population dynamics, biodiversity, dendrochronology, physiology, silviculture, and review. Among them, five, four, and four articles cover the most studied themes of physiology, population dynamics, and dendrochronology, respectively. (Table 4). By journal, *Tree Physiology* has the most publications at four, followed by *Forest Ecology and Management* and *Journal of Ecology* with two each. Regarding journal type, most are top journals in the fields of forestry, ecology, and botany. In the distribution by country of the first author, European and North American (especially the U.S.A.) are the majority.

3.6. Hot Topics of Large Old Tree Research

3.6.1. Research Hot Topics

Keywords can represent the core and essence of a paper's research scope and focus [17]. The high-frequency occurrence of keywords in a bibliometric database can reflect the main research themes of a subject area. Such data can determine the development focus of a subject area, research hotspots, and research frontiers. Keyword co-occurrence mapping in VOSviewer provides an insightful visual representation of the structure and evolution of research fields [16]. By analyzing how frequently keywords appear together in publications, VOSviewer reveals relationships between research topics based on proximity and connectivity [15]. The emergence and fading of keyword clusters spotlight rising and declining concepts over time. The node size signifies the importance of topics based on keyword frequency and co-occurrence. This method yields an intuitive, unbiased bird's-eye view of a research domain that synthesizes and quantifies the significance of concepts from textual contents [9]. Compared to reading many abstracts, a keyword co-occurrence map efficiently communicates the synoptic intellectual landscape. It enables researchers to identify central themes versus peripheral ideas and track the dynamic changes in a field [24]. Its ability to filter and drill down makes it a powerful technique for deep bibliometric exploration. This study set the minimum threshold of word frequency statistics in VOSviewer at nine. The top 100 high-frequency keywords were chosen to annotate keyword co-occurrence in LOT research (Figure 6).

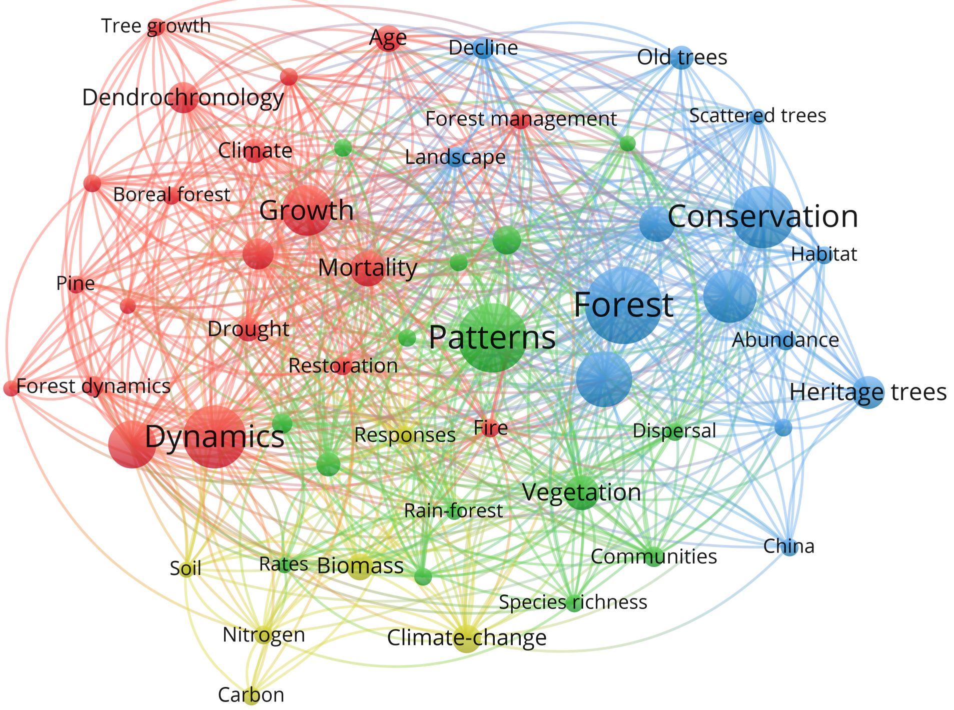

Figure 6. View of keyword co-occurrence tags of large old tree research in 2000–2022 using the WoS core collection database.

In Figure 6, the circle size represents the keyword occurrence frequency. The length and thickness of lines between circles denote their strength of association, with shorter and thicker lines denoting a stronger association. Circles of the same color have higher topical relatedness, while connected circles of different colors indicate some associations. Figure 6 displays four major keyword clusters. The keywords at the center of clusters carry the highest weight, representing research focus on 'conservation', 'forest', 'patterns', 'dynamics', 'growth', 'dendrochronology', 'biomass', 'response', and 'climate'. We grouped them into four principal themes and analyzed them as follows:

(1) The red cluster: The high-frequency keywords mainly include dynamics, growth, disturbance, mortality, dendrochronology, regeneration, age, climate, drought, forest dynamics, forest management, fire, and restoration. Dendrochronological tree ring analysis yields growth dynamics over centuries in response to climate, drought cycles, disturbance events, and changing environmental conditions [43]. Studying the tree age structure and mortality patterns provides insights into forest succession, recruitment, and regeneration processes [25]. A major research focus is examining how disturbances like fire, wind, pests, and pathogens shape forest development and tree demographics over an extended timescale [2,7]. Understanding the drivers of tree longevity, such as genetics, competitive interactions, and stress resistance, has implications for conservation [32,44,45]. Quantifying aboveground biomass and carbon sequestration in old trees is crucial for assessing their ecosystem services [46]. Overall, the research aims to elucidate the complex interactions between old tree growth, climate, disturbance regimes, and forest structural development to guide restoration and sustainable management under changing climatic conditions. Integrating dendroecological methods, demography, successional theory, and climate adaptation will further advance old tree research [41,47].

(2) The green cluster: This cluster contains high-frequency keywords such as patterns, vegetation, coarse woody debris, competition, communities, succession, dispersal mechanisms, old-growth forest, recruitment, and species richness. Studying old-growth forests can uncover the ecological patterns and processes developed over centuries [39]. Field studies analyze vegetation dynamics, species richness, and spatial distribution patterns to elucidate how tree communities assemble, interact, and change through succession. Investigating dispersal limitations and recruitment mechanisms provides insights into the unusual LOT demographics [48]. Quantifying the accumulation and decay of coarse woody debris reveals nutrient cycling dynamics and successional pathways [49]. Additionally, examining competitive interactions between dominant tree species sheds light on canopy structure and species co-existence [50]. Succession models project compositional and structural forest changes over decades. Comparative work identifies differences in ecological patterns and processes between old-growth and secondary forests [51]. Elucidating old-growth systems' complex, slowly changing ecology can inform sustainable forest management to balance timber production and biodiversity goals [52]. An integrative approach, combining empirical studies, controlled experiments, and modeling, can yield new insights into these complex ecosystems and their legacy effects on forest development.

(3) The blue cluster: The high-frequency keywords mainly include conservation, diversity, biodiversity, management, heritage tree, decline, abundance, landscape, forest, habitat, and large old tree. The research aims to support the conservation and sustainable management of old trees by assessing their abundance, distribution, and diversity across forest ecosystems and landscapes to identify hotspots and declines [7,30]. In addition, quantifying diverse habitat associations helps to locate and protect large, old, hollow-bearing trees [53]. Furthermore, analyzing the causes of mortality informs the stewardship of vulnerable heritage trees [39]. Developing selective harvesting practices maintains the continuity of old trees within managed forests. Restoration efforts focus on facilitating the recruitment and recovery of old-growth-associated species [54]. Climate change adaptation research examines enhancing resilience among remnant old trees and facilitating migration [40,48]. By elucidating the multifaceted roles of LOT in ecosystems, from supporting wildlife, storing carbon, and influencing stand structure to providing cultural value, the

research highlights the importance of integrative approaches to studying, valuing, and sustaining old trees [2,3,6,37]. Overall, such approaches continue to advance and optimize conservation outcomes.

(4) The yellow cluster: The high-frequency words mainly include climate change, biomass, nitrogen, responses, carbon, and soil. The research examines how old trees respond to climate change and influence ecosystem processes, such as quantifying the aboveground biomass in LOT to provide insights into forest carbon sequestration potential [47,55–57]. Additionally, analyzing nitrogen concentrations and resorption in foliage reveals nutrient cycling dynamics. Soil studies under old tree canopies elucidate carbon storage patterns and microbial community structure [31]. Moreover, dendrochronological methods examine age-related growth changes and climatic responses over centuries. Manipulative experiments assess vulnerability to drought, warming, and elevated CO_2 in LOT [41,58,59]. Understanding adaptive capacity, acclimation, and resilience to climate change can enhance efforts to conserve old-growth forests. Furthermore, comparisons of young and old stands help quantify age-based differences in productivity, carbon storage, and response to climate [42]. Such research can improve climate change projections and guide mitigation strategies based on the capabilities of long-lived trees. Ultimately, an integrated approach combining empirical data, experiments, and modeling continues to reveal the complex climate–ecosystem interactions mediated by LOT.

3.6.2. Research Frontiers

Burst words are keywords rapidly growing in use frequency over a period. They can identify emerging trends and their development intensity in the field [60]. Emerging trends and mutations demonstrated in the scientific literature can be associated with internal and external causes. Typical internal causes include discoveries and scientific and technological breakthroughs in the field. External causes such as topical societal issues and major news items may inspire scientists to adopt a new study perspective [19]. CiteSpace's sudden test analysis concluded that the LOT research frontiers include genetic diversity, species diversity, climate responses, and carbon accumulation.

(1) The genetic basis of longevity and stress resilience in long-lived tree species can be elucidated using the latest DNA sequencing and analysis techniques. An important research focus has developed to examine the genomic mechanisms underlying longevity and stress tolerance in long-lived tree species. The findings can enrich tree adaptation knowledge and facilitate conservation. Recent advances in DNA laboratory techniques have allowed the genome assessment of long-lived trees at an unprecedented resolution [61,62]. The genetic markers accounting for extreme longevity have been identified, improving our understanding of gene-regulated growth, carbon assimilation, and responses to abiotic stresses [63]. Comparative genomic analyses between long-lived and short-lived tree taxa have discovered genomic signatures registering adaptation to environmental pressures over centuries to millennia [44]. Targeted resequencing of stress-responsive genes has identified alleles conferring resilience to salinity, drought, and temperature extremes in LOT [64]. Epigenetic studies have characterized DNA methylation patterns and small RNA dynamics contributing to acclimation to environmental changes [65,66]. Advances in in situ sequencing permit direct analysis of genetic material in tree cores, opening new avenues for paleogenomic research [67]. Moving forward, elucidating genotype-phenotype relationships through gene functional studies, progenitor-derivative comparisons, and genome–environment associations will generate insights into the genetic basis of longevity and stress adaptation in long-lived trees. An integrative approach combining population genomics, phylogenomics, epigenetics, and functional genomics promises to inform tree conservation and climate resilience strategies vis-à-vis increasing environmental pressures.

(2) Examining evolutionary adaptations and plasticity in LOT using tree rings and paleoecological analyses can provide insights into the responses to past environmental changes. Tree rings provide a powerful means of retrospectively exploring the responses of LOT to past environmental changes over centuries to millennia [68]. Dendrochrono-

logical techniques enable the reconstruction of growth patterns and climatic conditions through time using isotope analysis, ring width, density fluctuations, and anatomical traits preserved in dated tree ring series [58,69]. These approaches have unveiled the adaptive shifts, plastic responses, and resilience capacities of long-lived trees over their lifespans [45]. Comparative dendroclimatological studies of co-existing long- and short-lived species elucidate differences in drought adaptation and acclimation capacity [47,48]. Advances in paleogenomics now permit direct sequencing of DNA preserved in relict wood, opening new opportunities to study evolutionary adaptations over the millennial timescale [70]. Integrative approaches combining dendroecology, wood anatomy, ecophysiology, and population genetics can enhance our understanding of the environmental sensitivities, phenotypic plasticity, and adaptive genetic variation of LOT. Such new knowledge is critical for predicting forest responses and guiding conservation strategies in the context of rapid climate change and environmental alteration in the 21st century and beyond.

(3) Technology and big data analytics can be leveraged to efficiently inventory, monitor, and analyze large LOT datasets across broad spatial scales. Advances in remote sensing, geospatial analysis, and machine learning are revolutionizing approaches to assess and monitor LOT populations across landscapes. Airborne and satellite multispectral and LiDAR data facilitate rapid inventorying and mapping of individual ancient trees and old-growth stands based on spectral signatures, height metrics, and textural analyses [71]. These remotely sensed inputs can be integrated with field measurements, genetic data, and climatic records to construct predictive distribution and habitat suitability models to identify areas likely to harbor old trees at a broad spatial scale [1,33]. High-resolution hyperspectral and thermal imaging enables noninvasive monitoring of ecophysiological stress and resilience traits [51]. Point clouds generated from LiDAR and photogrammetry can be used to quantify morphological parameters indicating tree vigor and disturbance responses [72]. Online databases and mobile apps allow for the collaborative mapping and tracking of heritage trees by professionals and community scientists. Cloud computing and deep learning algorithms facilitate data processing to extract insights from the massive datasets on ancient trees [73]. As inventory and monitoring technologies continue to improve, leveraging big data analytics and AI will be critical to efficiently assess LOT populations, model future risks, and guide conservation planning.

(4) The development of new research on LOT geographical patterns can be supported by big data, machine learning, and GIS technology. To pursue this line of research, three problems could be overcome: (a) insufficient use of the connotation and extension of big data on LOT diversity, along with low data resolution and regularity [2]; (b) the concentration of research on diversity census [36] and the lack of innovation; and (c) inadequate understanding of the inherent value of LOT [31]. The limited application of research tools does not meet the needs of LOT conservation, especially the formulation of conservation policies. However, the in-depth application of GIS and machine learning in multiple disciplines [74], especially using species distribution models (SDMs) to predict the spatio-temporal evolution of LOT [1], is expected to resolve the bottleneck of traditional research and generate a new paradigm.

The complexity of the geographical big data of LOT and the limitations of traditional methods do not permit the analysis of many ancient trees. Therefore, the joint application of GIS and machine learning technologies promises to facilitate the discovery of new patterns and concepts from big data [75]. Even though many regions have completed a background inventory of LOT, such basic data are discrete and may contain idiosyncratic and unique elements. It is often difficult to decipher data regularity, limiting the high-level design of conservation policy. In the context of global warming and accelerated urbanization, some questions could be urgently addressed: (1) What is the geographical distribution pattern of LOT? Where are the diversity centers? (2) What are the spatio-temporal trends of LOT? (3) What are the main driving mechanisms for the observed tree patterns? (4) Where are the likely locations amenable to the preservation, enrichment, and loss of LOT in the context of environmental change? The solutions for the above questions based on GIS and machine learning technologies may bring a new dimension to conservation.

4. Conclusions

Large old trees symbolize an outstanding natural-cum-cultural heritage and a notable component of a region's biodiversity. However, with global warming and increasingly frequent, intensive, and pervasive human activities, LOT habitats and trees have been stressed and degraded. These challenges have threatened their survival and rendered tree conservation more difficult. The literature on ancient trees has expanded quickly since 2000. The findings have attracted the attention of researchers and practitioners in ecology, forestry, and cognate fields. The accumulated knowledge can inform and improve tree conservation and management and contribute to global biodiversity conservation. A systematic quantitative evaluation of the extensive research outputs could generate new insights leading to deeper understanding, new research directions, and better practices.

Based on the core Web of Science (WoS) database, this study applied bibliometric analysis software to query the large literature database on LOT from 2000 to 2022. The knowledge maps quantitively presented nodes denoting the intensity of research activities and inter-node links denoting the multiple pathways and flux volume of collaborative events. The visualized results enhance our understanding of the uneven spatial distribution of research activities by region, country, institution, and researcher. Worldwide, scholars from the U.S.A., China, and Australia are the most important contributors. The results disclosed key institutions and scholars in terms of research output and citations and the most cited articles. The conspicuous regional clustering was contrasted by the minimal number or absence of studies from a large world segment. This dichotomy echoes the entrenched disparity in the research capability of the endowed developed vis-à-vis the deprived developing realms, except for China, which may have a transitional economy. The research collaboration indicated a dualistic pattern: geographical propinquity versus long-distance leap-frog connectivity.

The analysis identified the historical trajectory of the study field, research focal points, and emergent trends. The research domain has become increasingly diverse and is spreading to new subjects. The keyword analysis pinpointed the current hot topics on growth dynamics, conservation and management, ecological functions, and environmental response. The findings provide hints to recommend the future foci of LOT research: (1) the genetic basis of the longevity mechanism; (2) evolutionary adaptation to the changing environment; (3) dynamic monitoring of individual trees and forest stands based on advanced computational and remote sensing technologies; and (4) geographical study of the tree distribution and patterns, supported by the integrated application of big data, machine learning, and GIS technologies.

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