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From correlation to mechanism: A bibliometric analysis of dendrochronological research evolution on tree growth responses to climate change

Qi Li [a], Jinbao Li [b,c], Tsun Fung Au [d,e,*,1], Teng Li [a,**,1]

[a] School of Geography and Remote Sensing, Guangzhou University, Guangzhou 510006, China
[b] Department of Geography, University of Hong Kong, Hong Kong SAR 999077, China
[c] HKU Shenzhen Institute of Research and Innovation, Shenzhen 518057, China
[d] Institute for Global Change Biology, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, United States
[e] Department of Ecology and Evolutionary Biology, University of Michigan, Ann Arbor, MI, United States

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ABSTRACT

The impact of climate change on tree radial growth is a central issue in global change ecology, for which dendrochronology provides crucial long-term data. Here, we conducted a bibliometric and visual analysis of dendrochronological research on tree growth responses to climate change based on 2199 articles from the Web of Science database (2000–2024). The objective is to systematically delineate the developmental landscape of this vibrant, methodologically advancing, and emerging field. The analysis reveals a significant increase in annual publications, driven by technological innovations, enhanced data-sharing mechanisms, and extensive international collaborations, with China, the United States, and European nations constituting the core research contributors. The research focus has profoundly evolved from early climate reconstruction to a detailed deconstruction of the multi-scale "climate-driven–physiological response–ecosystem functioning" mechanisms underlying tree responses. While the antagonistic interplay between the CO_2 fertilization effect and extreme climate stress remains a persistent hotspot, recent research frontiers have increasingly centered on tree adaptation mechanisms under extreme climate events, spatial heterogeneity in responses, and forest resistance and resilience. Crucially, technological advancements and the integration of multidimensional indicators are propelling the field from describing correlations towards investigating the fundamental causal mechanisms by which climate change impacts tree growth. This study systematically elucidates the climate response mechanisms and dynamic trends of tree growth under climate change and analyzes the evolutionary pathways of research hotspots. Its findings offer scientific data to support the formulation of differentiated forest management strategies and the optimization of regional climate policies.

1. Introduction

Forests play a crucial role in the global carbon cycle by absorbing and storing substantial amounts of carbon dioxide, thereby mitigating climate change (Forzieri et al., 2022; Mo et al., 2023; Zhao et al., 2022). Additionally, they provide fundamental ecosystem services, including water storage and biodiversity conservation (Hua et al., 2022; Pan et al., 2011). Climate change is anticipated to impact forest structure and functions worldwide, altering tree growth patterns by impacting key environmental factors such as temperature, precipitation, and atmospheric carbon dioxide levels. Global warming promotes tree growth in cold and humid regions (Gao et al., 2022; Pau et al., 2022), due to rising spring temperatures and CO_2 fertilization effects (Dow et al., 2022; Ruehr et al., 2023). These changes affect physiological processes of tree growth, including photosynthesis and nutrient uptake (Anderson-Teixeira et al., 2022; Babst et al., 2019; Vacek et al., 2023), which affects the stability of forest ecosystems. Furthermore, climate change has led to more frequent and intense drought events, posing a

* Corresponding author at: Institute for Global Change Biology, School for Environment and Sustainability, University of Michigan, Ann Arbor, MI, United States.
** Corresponding author.
E-mail addresses: tomau123@connect.hku.hk (T.F. Au), liteng@gzhu.edu.cn (T. Li).
[1] These authors contributed equally as corresponding authors.

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serious threat to the survival and growth of trees (DeSoto et al., 2020; Hartmann et al., 2022; Zuidema et al., 2022). More frequent heat waves also diminish the resilience of trees to drought events, rendering forest ecosystems more vulnerable (Anderegg et al., 2015).

Dendrochronology, leveraging tree annual growth as natural archives of climate change, has long been used in paleoclimate reconstruction (Cook and Kairiukstis, 1990; Fritts, 1976). However, in the light of escalating global climate change impacts on forest ecosystems, the application and focus of dendrochronology have expanded with increasing emphasis on the intricate mechanisms governing tree growth responses to contemporary climate change. Methodological innovations, particularly the integrated use of stable isotopes and multi-proxy approaches, have driven this evolution from descriptive analyses to in-depth investigations of physiological-ecological mechanisms (Choi et al., 2023; Kostić et al., 2022; Pan et al., 2024; Van Der Sleen et al., 2017). Current research in the field increasingly concentrates on the impacts of extreme climate events, tree adaptation mechanisms, regional response heterogeneity, and the complex interplay between CO_2 fertilization effects and climate stressors (Bert et al., 2022; Jandova et al., 2025; Jia et al., 2022; Qin et al., 2023; Vitasse et al., 2019). With its unique long-term records and increasingly sophisticated analytical techniques, dendrochronology has become a central research tool for deeply analyzing the impacts of climate change on tree growth and assessing the response and adaptation potential of forest ecosystems. Given the dynamic development, evolving research perspectives, and increasing interdisciplinary integration demonstrated by the field over the past two decades, mapping its knowledge domain, identifying core themes, and recognizing emerging frontiers with a systematically bibliometric analysis is crucial for deepening understanding and guiding future research directions.

The primary objective of bibliometric analysis is to statistically evaluate literature data from scholarly publications to identify hotspots and trends within a specific research field (Liu et al., 2022; Pei et al., 2022; Wang and Su, 2020). This analytical method enables researchers to comprehend research activities and developmental trajectories by quantifying the number of publications, citations, and interrelations among studies (Drago et al., 2023; Song et al., 2023; Yu and He, 2020). Furthermore, bibliometrics not only monitors the advancement of scientific research on particular topics but also highlights influential academic institutions, authors, and journals (Ahmad and Slots, 2021). Consequently, bibliometrics is instrumental in identifying emerging research areas, innovative research models, and global academic collaboration networks.

Previous bibliometric studies of tree rings have predominantly investigated the evolution of dendrochronology, tree-ring isotope research, dendrohydrology, and dendrogeomorphology (Bovi et al., 2022; Feng et al., 2024; Huang et al., 2024; Islam et al., 2024). These studies, while focused on distinct sub-fields, collectively highlight a core scientific pursuit: using tree rings to understand environmental change. Among the various environmental drivers, climate stands out as the most fundamental factor influencing tree growth on a global scale. However, a systematic bibliometric analysis of dendrochronological research specifically addressing the impacts of climate change on tree growth remains lacking. This study aims to explore the dendrochronological research on the effects of climate change on tree growth, focusing on the following questions: (1) How have collaborative networks and their geographical distribution advanced the research on dendrochronology concerning climate change impacts on tree growth? (2) What are the key characteristics and disciplinary foundations of this research field, and how have methodological and conceptual advancements influenced its development? (3) How have the main research themes and foci within dendrochronological studies of climate change impacts on tree growth evolved over time? (4) What are the current and emerging research hotspots, and what paradigm shifts are occurring in dendrochronology concerning climate change impacts on tree growth?

2. Data and methods

2.1. Data collection

Literature data were obtained from the Science Citation Index Expanded (SCI-EXPANDED) within the Web of Science (WoS) citation database. WoS is the most widely used database in bibliometrics and encompasses a substantial number of high-quality scientific journals (Budler et al., 2021). A total of 2199 relevant papers were collected from 2000 to 2024 (Fig. 1). To comprehensively capture research outputs in this field, the following search formula was employed: ((TS=("tree ring*" OR "dendrochronology" OR "growth rings" OR "ring width") AND TS= ("tree growth" OR "radial growth" OR "annual growth" OR "stem growth" OR "wood formation") AND TS= ("climate change" OR "warming" OR "atmospheric CO_2")) AND PY= (2000–2024) AND DT= (Article)) AND LA= (English), retrieved on June 10, 2025. Prior to importing the data into VOSviewer for analysis, the data underwent manual normalization, which included disambiguating author names, merging synonymous keywords, and standardizing institutional affiliations, to ensure a uniform format and reduce bias in the following data analysis (Zhang et al., 2024).

2.2. Research methods

In this paper, bibliometric and visualization analyses were conducted using VOSviewer and CiteSpace. VOSviewer is a software tool designed for visualizing and analyzing bibliometric networks, assisting researchers in identifying key trends, authors, and their collaborations (Eck and Waltman, 2014; Wu et al., 2024; Zandifaez et al., 2024). The software can manage large datasets, making it suitable for research visualization across various fields. CiteSpace is a robust bibliometric tool that maps knowledge domains, analyzes co-citation networks, and identifies significant trends and influential research in diverse areas (Chen et al., 2010). It enables researchers to visualize the evolution of research topics, recognize emerging trends, and gain insights into collaborations and institutional contributions across different regions (Chen, 2006).

The bibliometric methods employed bibliographic coupling and co-citation analysis. Literature coupling analysis assesses the strength of the linkage between two papers by comparing the number of identical references they share. A higher linkage strength indicates a closer research focus between the two papers. Co-citation is achieved when two distinct literactures are simultaneously co-cited by a third document (van Eck and Waltman, 2010). Furthermore, co-citation analysis in VOSviewer underscores the recognition of the expertise and authority of specific literature, journals, or authors within the field (Asghar et al., 2024). This method reveals the intellectual connections and foundational knowledge that underpin current research, as it identifies highly influential works, authors, or journals that contemporary scholars frequently draw upon together. To further clarify the research landscape of this specific sub-field within dendrochronology, we employed the dual-map overlay of journals, visualized keyword dynamics using an Alluvial Diagram in bibliometrics, and conducted keyword burst detection. The Alluvial Diagram connects high-frequency keywords across different time periods through horizontally flowing ribbons, intuitively illustrating the evolutionary paths, thematic inheritance, and emerging directions of research hotspots in this field (Paul and Roy, 2023; Rojas-Sanchez et al., 2023). Burst detection facilitates the identification of terms and keywords that exhibit a sharp increase in frequency over a short period, thereby revealing shifts in research hotspots (Wu et al., 2021).

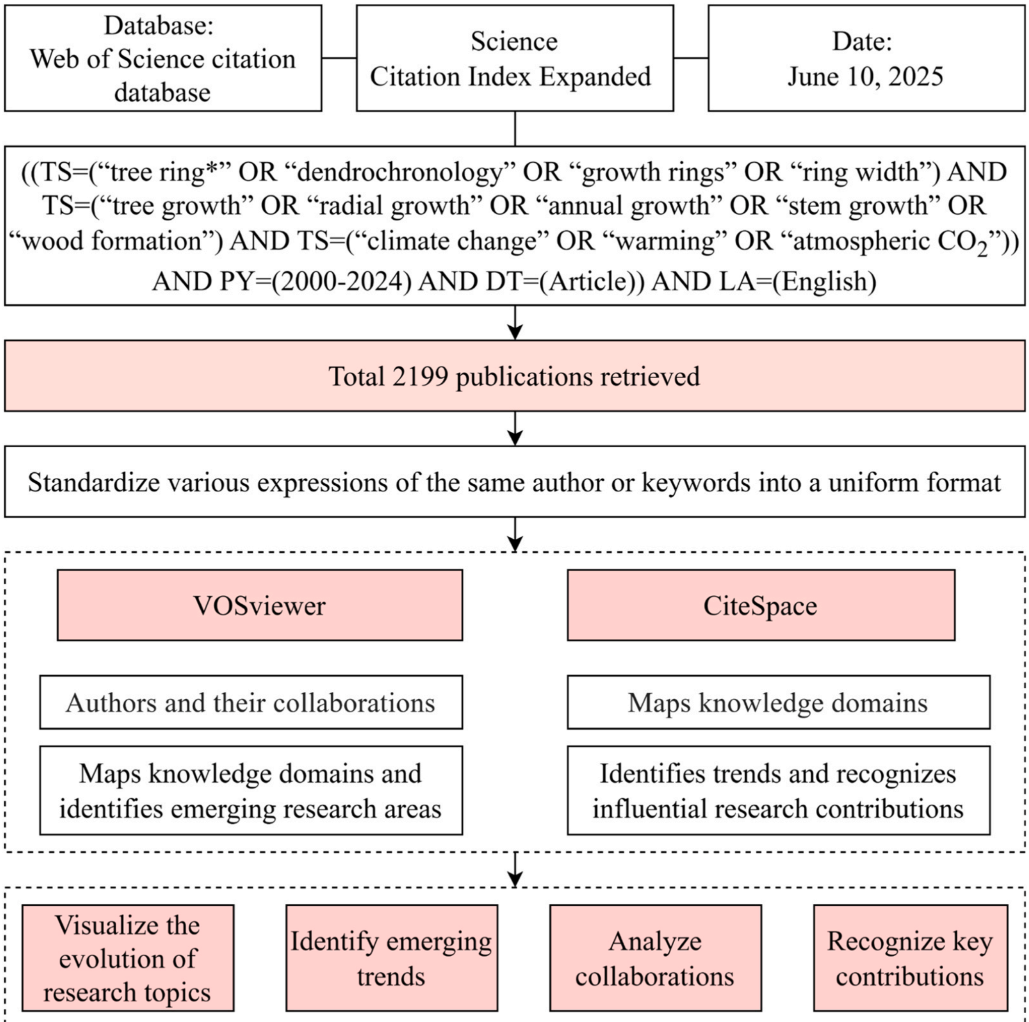


Fig. 1. Flowchart of the bibliometric analysis methodology for dendrochronological studies on climate change impacts. The search strategy employed in the Web of Science database used the following fields: TS (Topic, searching in title, abstract, and keywords), PY (Publication Year), DT (Document Type), and LA (Language).

3. Results and discussion

3.1. Distribution pattern of publications

The number of publications has increased from 11 in 2000–241 in 2024 (Fig. 2a), demonstrating an overall growth trend. The decline in research publications from 2022 to 2023 was primarily influenced by the pandemic, as dendrochronological research typically requires an extended lead time from data preparation, including sampling, processing, and dating, to the publication of results (Cook and Kairiukstis, 1990; Feng et al., 2024). Additionally, standardized processes ensure the accuracy of dendrochronological data, while R packages and the sharing of such data (International Tree-Ring Data Bank, ITRDB) facilitate the reproducibility, validation, and reuse of research findings (Zang and Biondi, 2015). The data accessibility is one of the reasons why dendrochronological research on climate change's impact on tree growth has flourished.

3.2. Main research regions and countries

In terms of the intensity of international cooperation, the United States, Germany, Switzerland, Spain, China, and Canada are the primary contributors (Fig. 2b). Across the entire dataset, a total of 103 countries have contributed to publications in this field, highlighting a broad global engagement in research on tree growth responses to climate change. The United States and Germany engages in cooperation with a diverse range of countries, while Switzerland primarily collaborates with nations that produce a high volume of publications.

There exists a geographic pattern in international cooperation efforts (Fig. 2c). Europe has the highest number of publications (2422 papers), followed by Asia (889 papers) and North America (859 papers). Among the primary publishers in Asia and North America, China (635 papers) and the United States (541 papers) are the leading contributors in this field, respectively. In contrast, Europe exhibit a greater diversity in publication pattern, with Germany, Switzerland, Spain, France, the United Kingdom, and the Czech Republic all making substantial contributions to the overall publication count. Dendrochronological research in Africa remains relatively underdeveloped, although numerous tree species with datable annual rings exist on the North Africa and sub-Saharan Africa (Farahat and Gärtner, 2024; Ngoma et al., 2017; Trouet et al., 2010; Gebrekirstos et al., 2008; Therrell et al., 2007).

Although publication patterns in this area vary across continents, the intensity of international cooperation is not confined to geographical proximity. China exhibits a high level of collaboration with the United States (113papers) and Canada (55papers), which are also major recipients of cooperation from Australia. Sweden, Finland, and Russia maintain close collaborative ties. Additionally, collaborative networks in Europe, particularly in Switzerland, the United Kingdom, France, Germany, Italy, the Netherlands, and the Czech Republic, significantly contribute to research in this field. Furthermore, Spain engages in

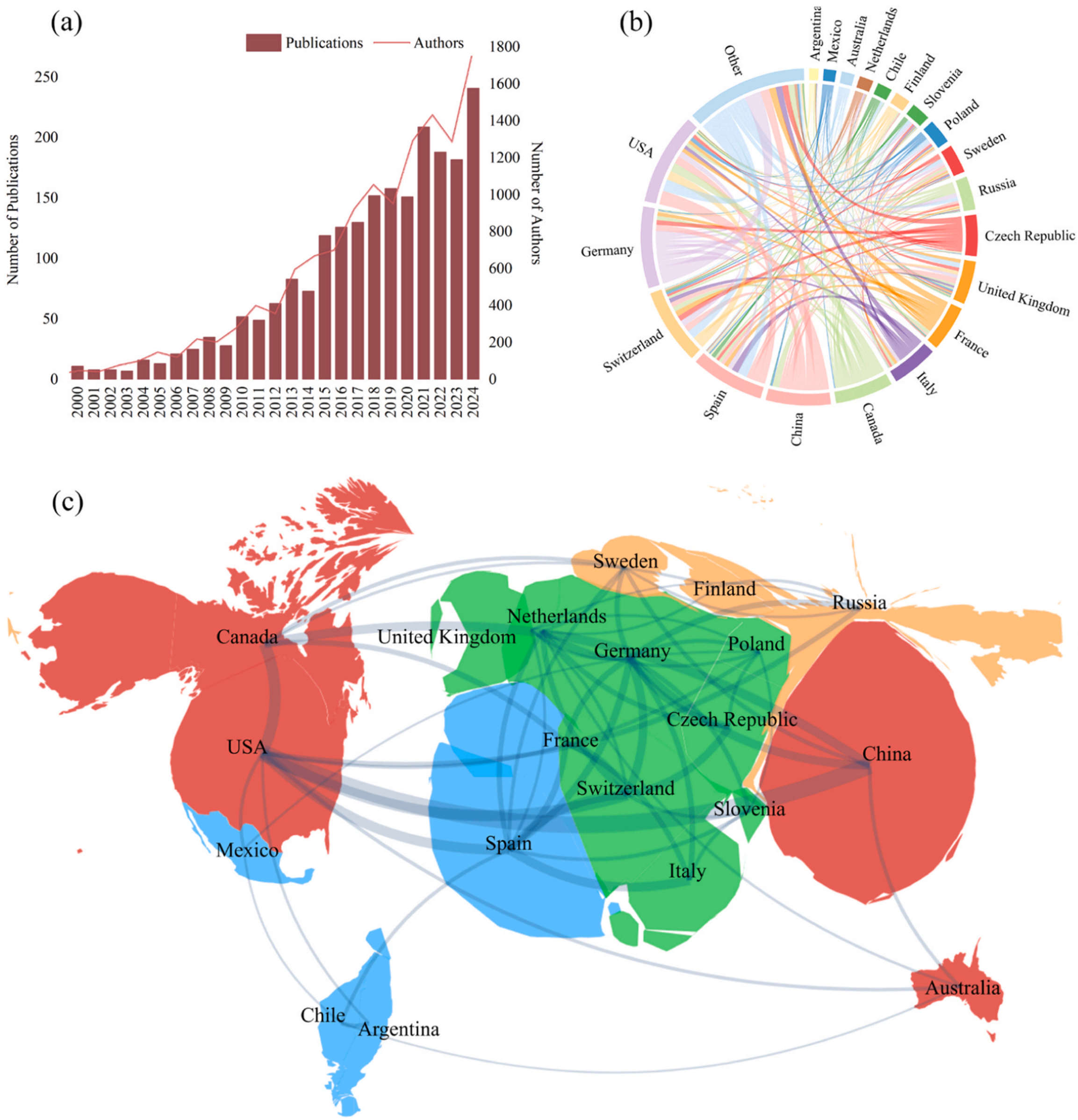


Fig. 2. Publication trends and international collaboration. (a) Number of publications and authors from 2000 to 2024. (b) Cooperation between contributed countries. Chord length indicates the collaboration strength. Line thickness correlates with the intensity of the closeness. (c) Geographical visualization of international collaboration among the top 20 publishing countries. The area of each country is adjusted based on the number of publications. Similar cooperation relationships and research themes are represented by the same color.

relatively close cooperation with Mexico, Brazil, and Argentina in South America.

3.3. Networks of authors and institutions

The top 5 institutions by publication count are as follows: the Chinese Academy of Sciences (CAS), the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), the Spanish National Research Council (CSIC), the University of Arizona, the Siberian Federal University (SFU) (Fig. 3a). In terms of citations, the CAS leads with 8406 citations, followed by the WSL with 8013 citations, the CSIC with 4746 citations, and the University of Arizona with 4620 citations. These four institutions are recognized as authorities in dendrochronological studies related to climate change and tree growth, boasting significantly more citations than the fifth-ranked institution, which has 2653 citations, as well as the others.

Dendrochronology and climate change research have benefited from the collaborative efforts of numerous scholars, who have elucidated the complex responses of forest ecosystems to environmental changes and reconstructed long-term regional climate variations through interdisciplinary approaches (Fig. 3b). Collaboration among authors typically focuses on specific topics. It is relatively common for authors from the same research organization or closely affiliated organizations to collaborate. Authors belonging to the same cluster at a given time tend to investigate similar subjects. A central theme within this field is the response of forests to drought and climate warming. For example, Camarero, the field's most cited researcher, has significantly contributed to dendrochronology and climate change research by using tree-ring data to explicate forest ecosystem responses to climate change, especially drought (Camarero et al., 2015, 2011; Camarero and Gutiérrez, 2004). Gazol et al. (2018) also investigated the mechanisms by which extreme drought leads to tree mortality, proposing an early warning system. Moreover, dendrochronology has also proven invaluable in regional paleoclimate reconstruction. For example, Yang et al.

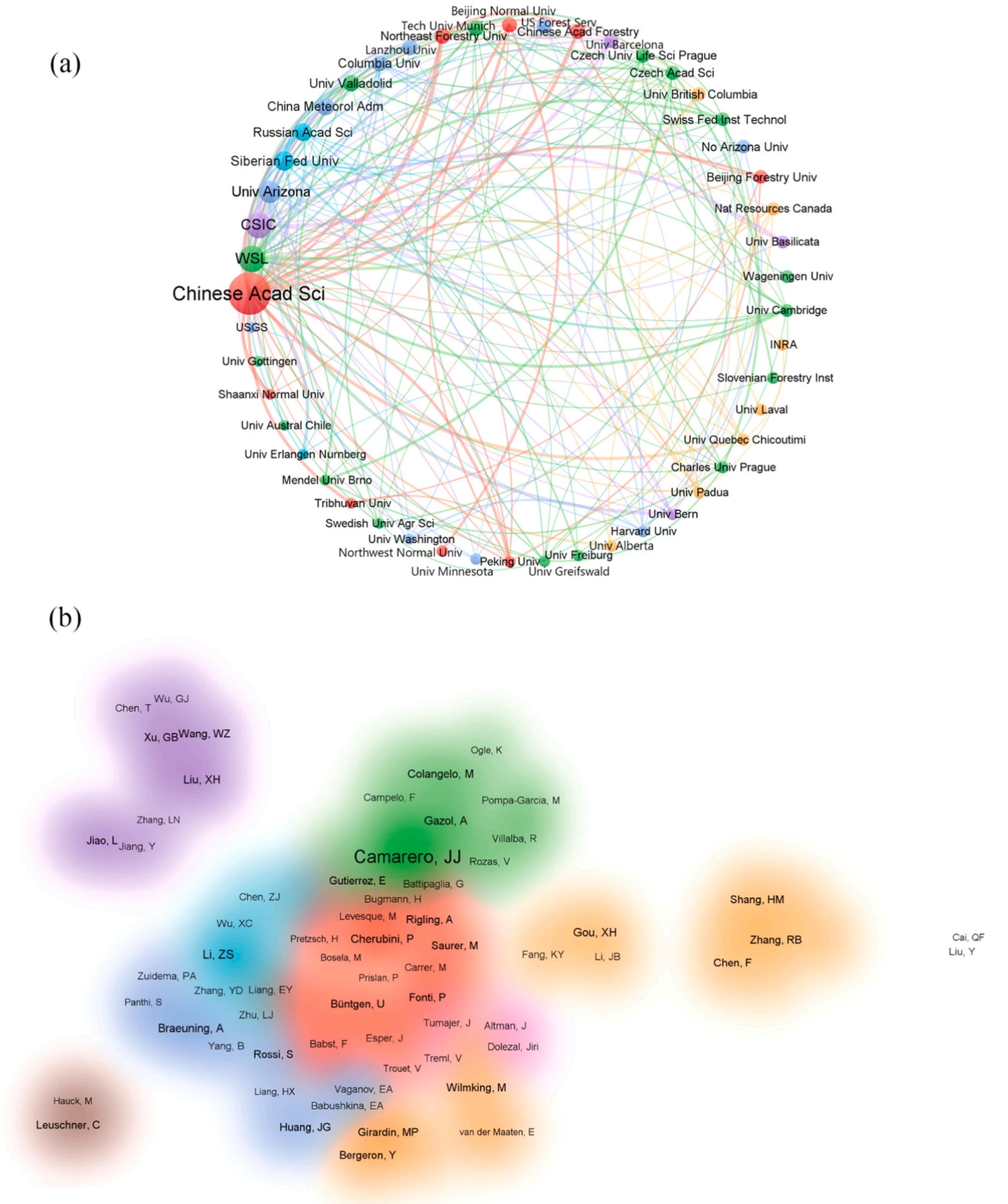


Fig. 3. Co-authorship analysis between (a) institutions and (b) authors. The circle size and font size represent the volume of publications. Similar cooperation relationships and research themes are represented by the same color. The thickness of the line (a) and the distance between clusters (b) are related to the intensity of closeness.

(2002) focused on Asian paleoclimate research, particularly on the Tibetan Plateau, revealing temperature changes over the past two millennia, thereby providing insights into regional climate change.

In addition, significant differences exist between institutions regarding research interests. Due to the extensive nature of international collaborations and the flexibility of the subject matter, authors working closely together may also originate from diverse research areas. Scholars have significantly advanced dendrochronology and climate change research by investigating forest responses, refining tree-ring methodologies, reconstructing paleoclimates, and analyzing alpine ecological dynamics(Dow et al., 2022; Schwarz et al., 2020; Gou et al., 2007; Wilmking et al., 2004). Their collective work provides a robust scientific foundation for understanding the impacts of global climate change on natural ecosystems.

3.4. Analysis of publication sources

The dual-map overlay clearly illustrates that the process from the citing side to the cited side is a “confluence” process, emphasizing the interdisciplinary nature of climate change and tree growth (Fig. 4a). From the perspective of disciplinary development, climate change and tree growth fall within the fields of “ECOLOGY, EARTH, MARINE,” with “EARTH, GEOLOGY, GEOPHYSICS” and “PLANT, ECOLOGY, ZOOLOGY” serving as foundational disciplines, which have citation frequencies of 4299 and 6627, respectively, and standardized citation frequency values of 3.4 and 5.4.

Despite the presence of numerous comprehensive journals that cover multiple fields or possess distinct specialties, the foci of journals in the field of dendrochronology concerning climate change and tree growth

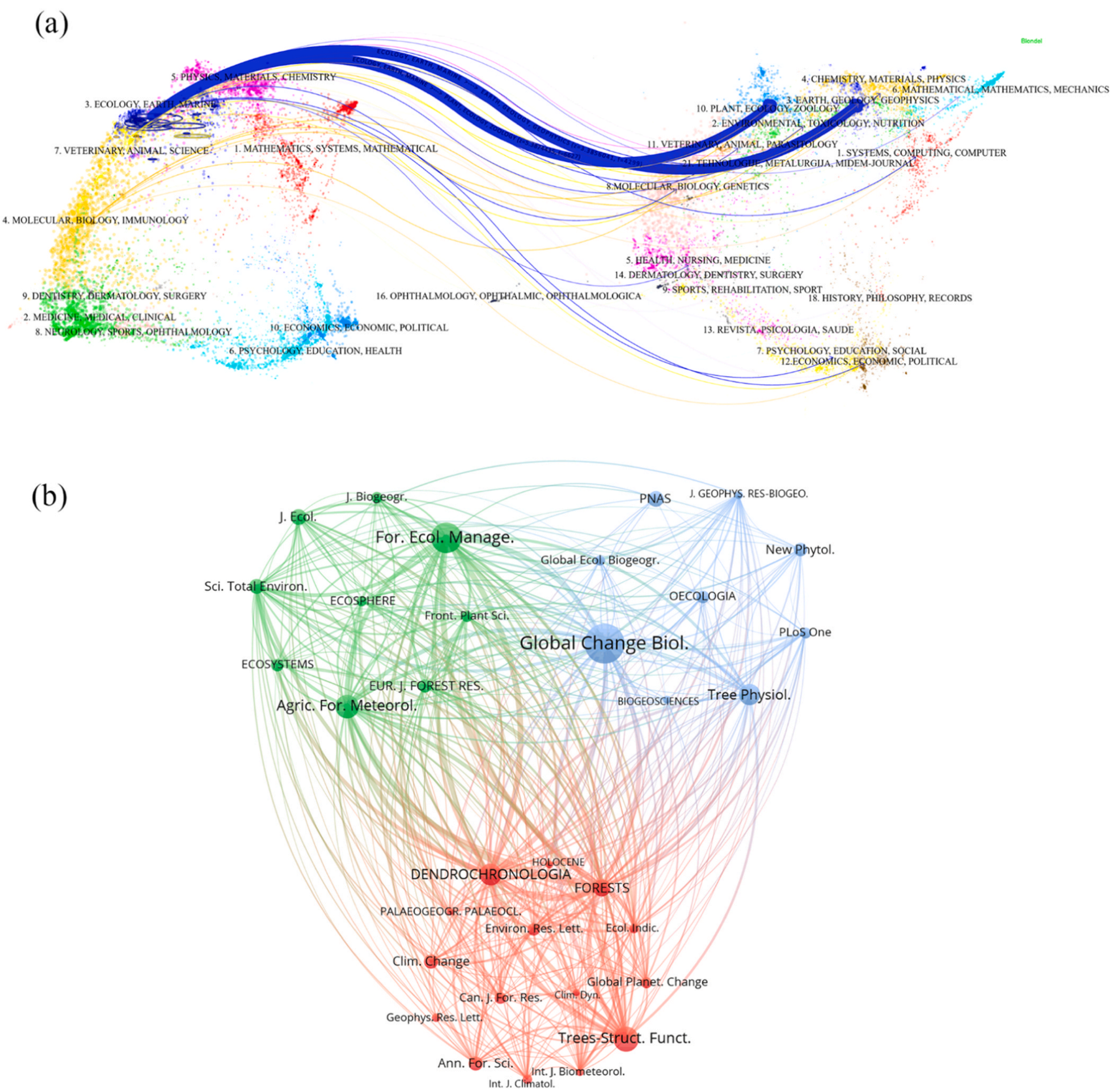


Fig. 4. (a) Double-map overlay analysis and (b) bibliographic coupling of sources. In panel (a), the left side illustrates the disciplinary fields of the journals cited by the analyzed publications, while the right side displays the disciplinary fields of the journals where the analyzed publications were published. In panel (b), the circle size and font size represent the number of citations, and similar research themes are represented by the same color.

can be categorized into three main groups among the 35 journals examined: Cluster 1, which encompasses forestry (red); Cluster 2, which includes ecology and environmental sciences (green); and Cluster 3, which combines forestry and environmental sciences (blue) (Fig. 4b). Within these clusters, forestry emphasizes tree growth dynamics and forest management; ecology investigates the impacts of climate change on forest ecosystems and the adaptation of tree species; and environmental science examines forest carbon sinks and the effects of climate change, such as the increasing frequency of drought events.

The articles included in this study were published in more than 200 distinct journals, with the journal *Dendrochronologia* ranking first in terms of the number of articles published, followed by *Forests* (Table 1). Table 1 lists the top 10 active journals, of which *Forest Ecology and Management* belongs to the field of forest ecology while the remaining nine are categorized under ecology and environmental sciences. Among these, the journal *Global Change Biology* has the highest number of cited articles, followed by *Forest Ecology and Management*.

3.5. Co-citation analysis

The foundation of dendrochronology was first laid by systematically introducing theoretical framework and methodologies for historical climate reconstruction and exploring data validation, enhancing the reliability of reconstructions (Fritts, 1976) (Fig. 5). Building upon this, critical innovations in data processing addressed specific challenges in creating reliable climate proxies, which are fundamental to assessing the impact of climate on tree growth (Cook and Kairiukstis, 1990).

Dendrochronology, as a rigorous and systematic discipline, has greatly benefited from computational advancements. The COFECHA program (Holmes, 1983) represented a significant early contribution, facilitating cross-dating procedures and remaining a standard tool in dendrochronological research. ARSTAN (Cook and Holmes, 1986), through effective detrending procedures, enables researchers to more clearly analyze the relationship between tree growth and climate. DENDROCLIM (Biondi and Waikul, 2004), incorporating a sliding correlation analysis function, has enabled researchers to investigate the intricate relationships between tree growth and climate. Furthermore, the dplR package (Bunn, 2008), implemented in R, enhances data processing and analysis efficiency while promoting research transparency and reproducibility. More recently, the treeclim package in R (Zang and Biondi, 2015) has gained popularity due to its balance of user-friendliness and powerful tree-ring analysis capabilities.

The co-citation analysis (Fig. 5b) illustrates the foundational methodologies and seminal works that have significantly shaped the study of tree growth response to climate change. Numerous researchers have advanced dendrochronology by developing methodologies and frameworks that enhance understanding of climate change impacts on tree growth. The spline detrending method (Cook and Peters, 1981) effectively removes biological growth signals, particularly in trees from humid regions. The Unbiased Tree-Ring Index (UTRI) (Cook and Peters, 1997) further enhances the reliability of tree-ring data for climate reconstructions and ecological studies. Effective Climate Factors (ECTFs) (Wigley et al., 1984) have improved the accuracy of climate reconstructions based on tree-ring data. A review of stable isotopes (McCarroll and Loader, 2004) provides a comprehensive framework for integrating isotopic data into tree-ring research and is widely cited. Research on "growth differentiation" in northern forests (D'Arrigo et al., 2008) has deepened our understanding of the effects of climate warming on tree growth.

Table 1
The main ten journals.

Sources title	Publications	Citations	IF 2024	JCR quartile 2024
Dendrochronologia	183	2972	2.3	Q2
Forests	176	1867	2.5	Q2
Forest Ecology and Management	170	5434	3.7	Q1
Trees-Structure and Function	111	3611	2.1	Q2
Global Change Biology	109	9054	12	Q1
Agricultural and Forest Meteorology	106	3314	5.7	Q1
Science of the Total Environment	63	1373	8.0	Q1
Tree Physiology	48	2524	3.7	Q1
European Journal of Forest Research	37	1049	2.7	Q1
Frontiers in Plant Science	35	768	4.8	Q1

Note: IF = Impact Factor, JCR = Journal Citation Reports

Contributions from other disciplines have significantly enriched dendrochronological research by providing novel perspectives, more robust assessment criteria, and higher-resolution climate data. A global meta-analysis of tree mortality due to drought and heat stress (Allen et al., 2010) underscores the vulnerability of forest ecosystems to climate change. The Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al., 2010) provides a more nuanced assessment of drought severity under global warming scenarios by integrating evapotranspiration. The CRU TS v4 dataset (Harris et al., 2020), characterized by its global coverage, high temporal resolution, improved interpolation techniques, and enhanced data provenance and geospatial quality control, is extensively used in dendroclimatological studies examining climate change impacts on tree growth. These contributions collectively highlight the interdisciplinary nature of dendrochronology by integrating advancements in analytical techniques, ecological assessments, and climate metrics, thereby enhancing our understanding of the complex interactions between tree growth and climate change. Furthermore, tree-ring climate atlases (Cook et al., 2007, 2010, 2015; Morales et al., 2020), constitute invaluable paleoclimate reconstruction resources for understanding regional drought patterns and long-term tree responses to drought. These atlases, spanning centuries to millennia, provide crucial evidence for conducting paleoclimate research and validating climate models (Caruso et al., 2024; González-Reyes et al., 2024; Stahle et al., 2020).

3.6. Evolution of research

The study of dendrochronology in response to climate change has undergone a significant evolution (Fig. 6). Initially focused on the generalized negative impacts of climate change (Bigler et al., 2006; Liu et al., 2013; Wang et al., 2012; Wilmking et al., 2004), it has gradually shifted towards a multi-scale analysis of the ecological mechanisms underlying environmental stresses, emphasizing the role of regional heterogeneity in regulating the adaptive capacity of trees (Kostić et al., 2022; Qin et al., 2023). Early research concentrated on identifying key climate drivers and their effects on tree growth. Using traditional indicators such as tree-ring width and density, scholars systematically verified the influence of temperature and precipitation variability on radial growth, revealing divergent response strategies among tree species (D'Arrigo et al., 2008; Huang et al., 2010). This laid the groundwork for a quantitative analysis of climate-growth relationships, although it primarily focused on the linear correlation between single environmental factors and morphological indicators of trees.

With advancements in research and technology, stable carbon isotopes have become increasingly prevalent in forest ecology, shifting the focus towards the ecophysiological mechanisms associated with extreme climatic events (Vitali et al., 2024; Zeng et al., 2024). The asymmetric effects of such events, particularly drought, have emerged as a central theme, with researchers uncovering resource trade-off strategies of trees under stress through physiological indicators like water use efficiency and carbon allocation patterns (Liu et al., 2019; Wieser et al., 2018). Moreover, the research scale has expanded from individual trees to entire ecosystems, integrating remote sensing data and process modeling to elucidate the sensitivity of forest carbon sink functions to

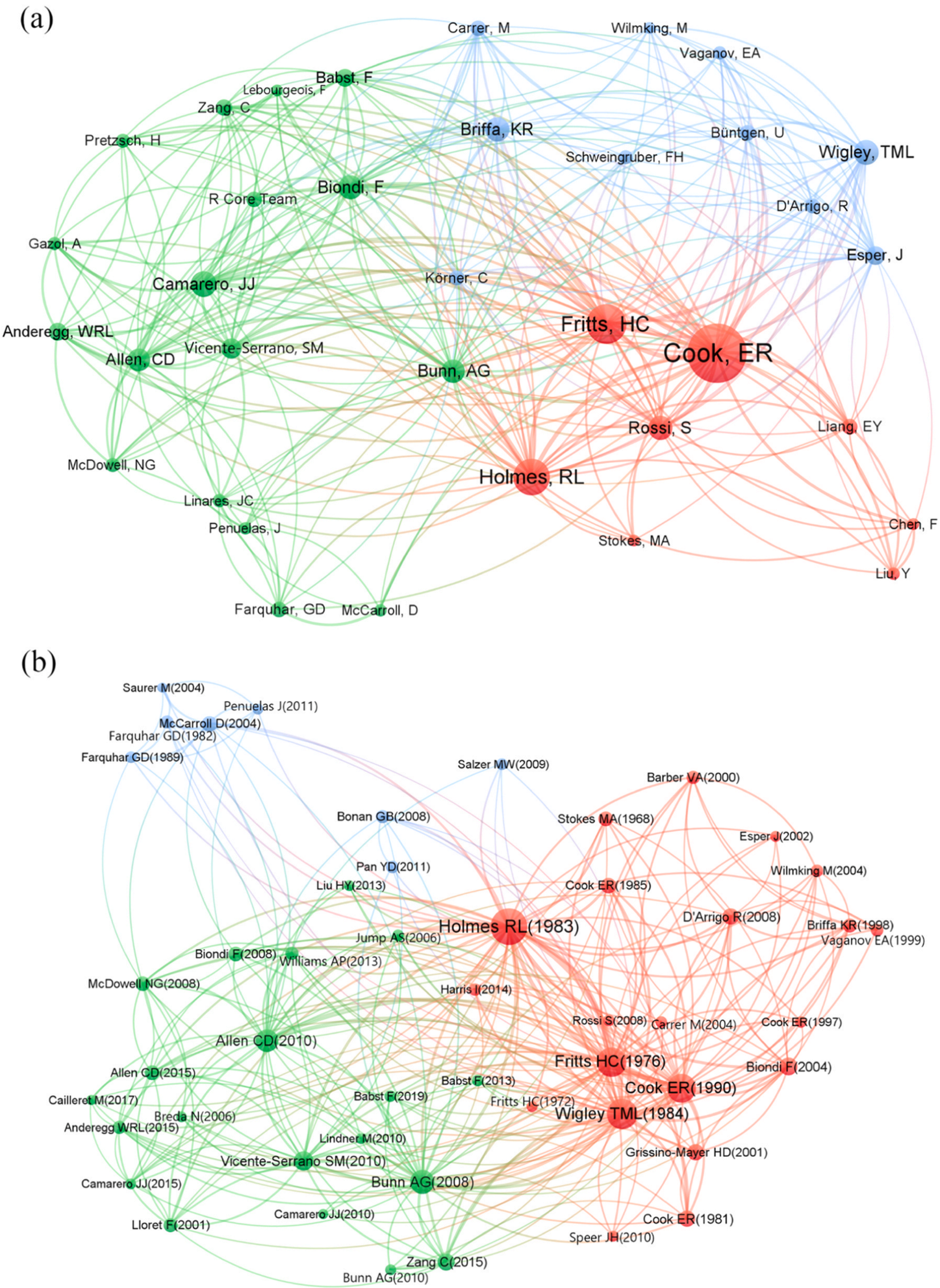


Fig. 5. Co-citation of cited (a) authors and cited references (b). The circle size and font size represent the number of citations. Similar research themes are represented by the same color.

climate fluctuations and resilience thresholds (Boyd et al., 2019; Pernicová et al., 2024; Xu et al., 2022). Scholars are also increasingly examining the responses of trees to climate change across different regions, the impacts on transition zones such as timberlines, and the broader phenomenon of divergence (Saurer et al., 2014; Trahan and Schubert, 2016). These studies not only aims to enhance the accuracy of historical climate reconstructions but also seeks to quantify the adaptive potential of trees under future warming scenarios, thereby providing spatially heterogeneous decision-making support for forest resilience management (Shestakova and Martínez-Sancho, 2021; Van Mantgem

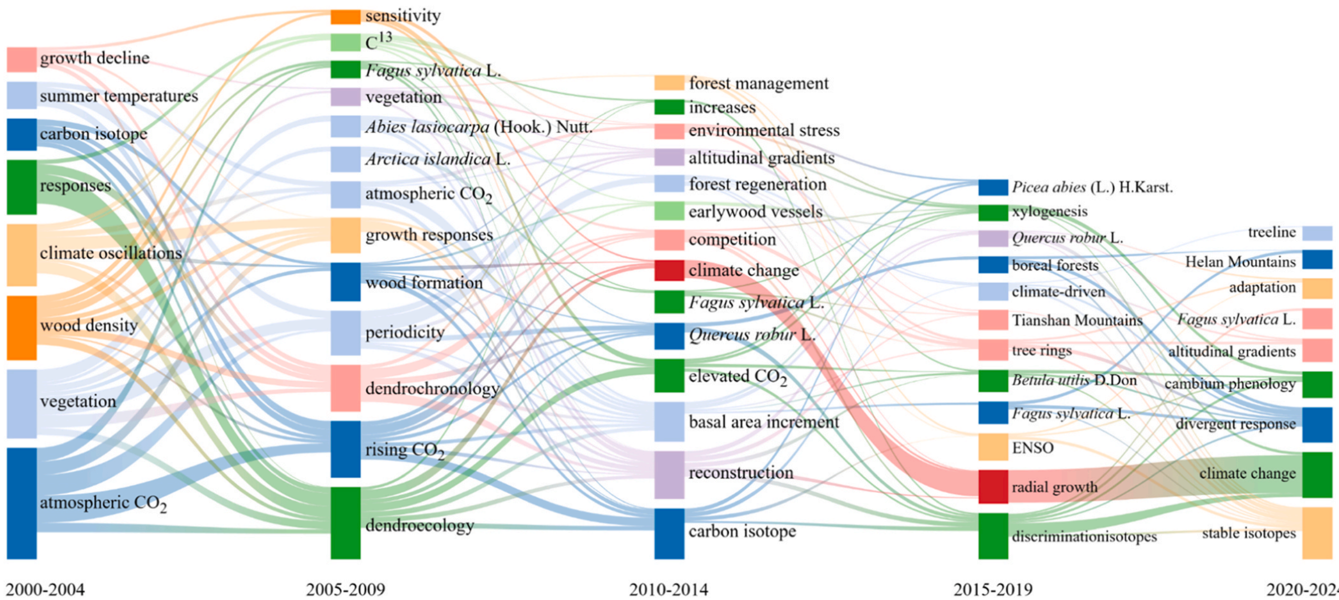
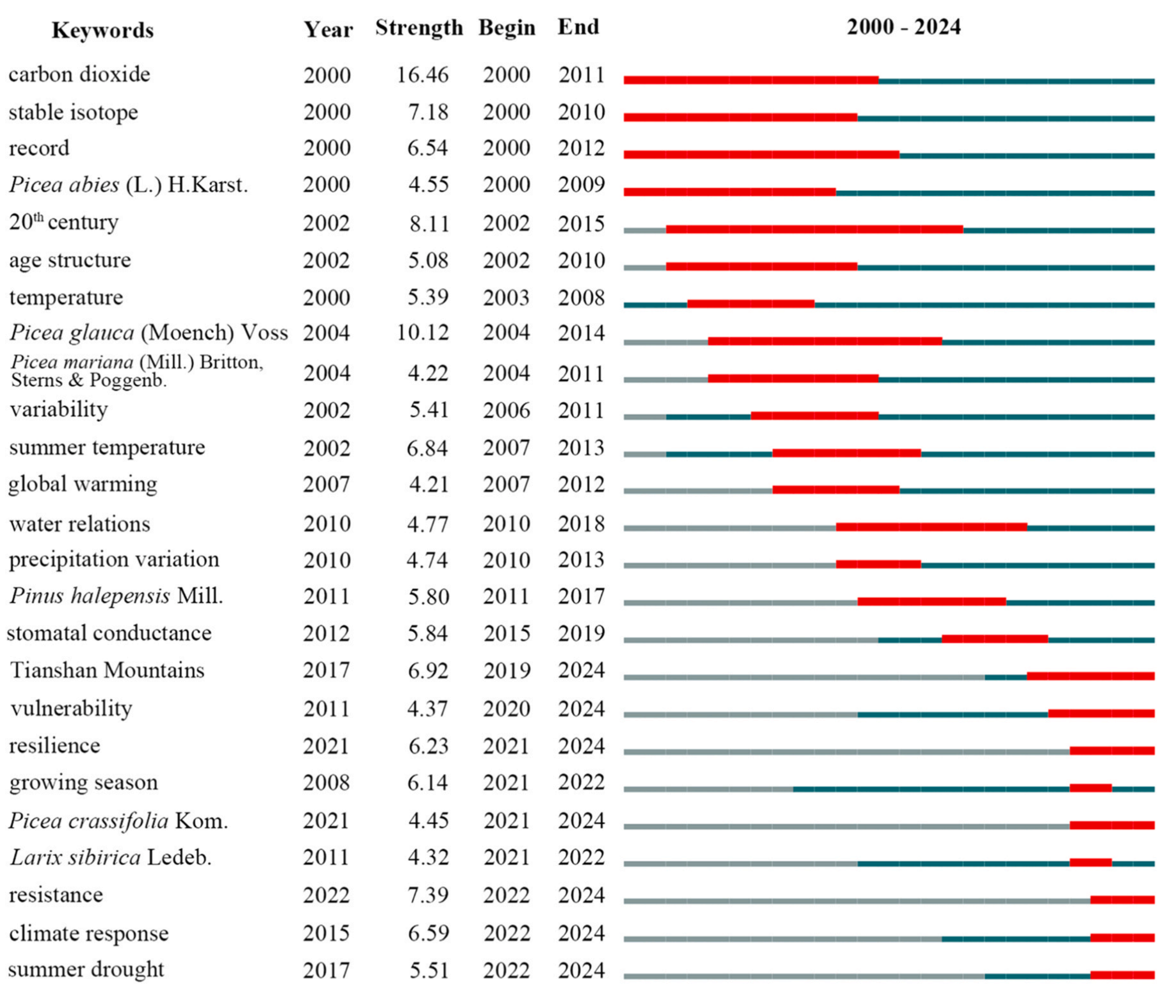


Fig. 6. Thematic evolution of research keywords across time periods. The size of the nodes represents the frequency of keyword occurrences. Similar research themes are represented by the same color.



Keywords	Year	Strength	Begin	End	2000 - 2024
carbon dioxide	2000	16.46	2000	2011	
stable isotope	2000	7.18	2000	2010	
record	2000	6.54	2000	2012	
Picea abies (L.) H.Karst.	2000	4.55	2000	2009	
20th century	2002	8.11	2002	2015	
age structure	2002	5.08	2002	2010	
temperature	2000	5.39	2003	2008	
Picea glauca (Moench) Voss	2004	10.12	2004	2014	
Picea mariana (Mill.) Britton, Sterns & Poggenb.	2004	4.22	2004	2011	
variability	2002	5.41	2006	2011	
summer temperature	2002	6.84	2007	2013	
global warming	2007	4.21	2007	2012	
water relations	2010	4.77	2010	2018	
precipitation variation	2010	4.74	2010	2013	
Pinus halepensis Mill.	2011	5.80	2011	2017	
stomatal conductance	2012	5.84	2015	2019	
Tianshan Mountains	2017	6.92	2019	2024	
vulnerability	2011	4.37	2020	2024	
resilience	2021	6.23	2021	2024	
growing season	2008	6.14	2021	2022	
Picea crassifolia Kom.	2021	4.45	2021	2024	
Larix sibirica Ledeb.	2011	4.32	2021	2022	
resistance	2022	7.39	2022	2024	
climate response	2015	6.59	2022	2024	
summer drought	2017	5.51	2022	2024	

Fig. 7. Top 25 keywords with the strongest citation bursts. The blue line indicates the time period of keyword emergence, while the red line denotes the years of significant changes in keyword frequency.

et al., 2020).

In long-term studies of climate change and tree growth through dendrochronology, atmospheric CO_2 concentration and climate change serve as the primary drivers (Succarie et al., 2020). The synergistic effects of elevated atmospheric CO_2 concentration and climate change directly influence the growth rates and ecological adaptations of trees (Huang et al., 2007; Xu et al., 2013). CO_2 can enhance tree growth through fertilization effects while simultaneously contributing to extreme climate events associated with the greenhouse effect (Peñuelas et al., 2017; Saxe et al., 2001). This paradoxical relationship has attracted considerable research interest. Researchers have quantified the water use efficiency of trees using stable carbon isotopes to accurately assess the spatial and temporal variations of drought stress (Jia et al., 2022; Lin et al., 2022; Saurer et al., 2014, 2004; Trahan and Schubert, 2016). Stable carbon isotopes ($\delta^{13}C$) are used to assess the water use efficiency (WUE) of trees (Van Der Sleen et al., 2017; Zhao et al., 2024), particularly in species with ecological indicator functions, such as *Fagus sylvatica* L. and *Picea abies* L. (Čada et al., 2016; Di Filippo et al., 2007). This approach establishes the classical research paradigm of "environmental stresses and physiological responses of trees." Given that *Fagus sylvatica* L. and *Quercus robur* L. are readily available, sensitive to climatic fluctuations, and exhibit clear annual rings (Rozas, 2001), their long-term isotope records provide crucial evidence to elucidate the antagonistic mechanisms between CO_2 fertilization effects and climatic stress (Bert et al., 2022).

3.7. Hot spots and trends

The study of dendrochronology's response to climate change began with a systematic examination of climate variability since industrialization (Büntgen et al., 2011; Kutzbach et al., 2011) (Fig. 7). Early keyword clusters focused on carbon dioxide, the 20th century, and temperature, emphasizing the reconstruction of the relationship between atmospheric CO_2 concentration and temperature variability (Cabaneiro and Fernandez, 2015; Carrer and Urbinati, 2006; Cook et al., 2003; Reynolds-Henne et al., 2007). *Picea glauca* (Moench) Voss has long been recognized as a model species in dendroclimatology because of its distinct tree-ring width variability and stable isotopic signatures. This relevance is particularly pronounced in Arctic-Boreal ecosystems, where *Picea glauca* (Moench) Voss dominates treeline ecotones and preserves threshold responses to thermal extremes (Barber et al., 2000; Norris et al., 2016; Wilmking et al., 2004). Research during this period primarily operated on a hemispheric scale. However, the intensity of carbon dioxide fluctuations declined significantly after 2011, indicating a gradual saturation of broad-scale climate reconstruction studies and creating opportunities for subsequent refinement studies.

The frequent occurrence of extreme climate events worldwide has shifted research focus toward the mechanisms of tree adaptation and the analysis of ecological crises (Cavin et al., 2013; Gazol and Julio Camarero, 2016; Vitasse et al., 2019; Zang et al., 2014). This is underscored by an intensified focus on specific, severe extreme climatic events and their implications for tree and forest ecosystem vulnerability, resistance, and recovery capabilities, reflecting growing scientific concern over the impacts of increasingly frequent and intense extreme events. Concurrently, the emergence of terms such as "age structure" and "water relations" indicates a transition in the field from climate reconstruction to the deconstruction of ecological processes. For instance, *Pinus halepensis* Mill. and *Larix sibirica* Ledeb., have become representative of regional response studies (Camarero et al., 2010; Devi et al., 2008; Dulamsuren et al., 2010; Sarris et al., 2013). Technological innovations have significantly advanced this field of research, with iterative improvements in hyperspectral imaging technology (Fernandes et al., 2013; Sun et al., 2024), combined with the application of machine learning algorithms for the automatic identification of tree ring features (García-Hidalgo et al., 2024; Kim et al., 2023; Polacek et al., 2023; Wang et al., 2024). At this stage, research interest has shifted to hotspot regions for ecological responses, such as the Tianshan Mountains.

In recent years, the research frontier has rapidly advanced toward assessing tree adaptation to climate stress. Emerging terminology reflects a clear "double R orientation," where resilience and resistance together form a quantitative framework (Au et al., 2022; Gazol et al., 2018; Sohn et al., 2016; Vicente-Serrano et al., 2020; Vitasse et al., 2019; Yi and Jackson, 2021), indicating a paradigm shift from "phenomenon description" to "threshold determination." The increasing prevalence of terms related to extreme events, such as summer drought, underscores the urgent need for predicting drought frequency (Camarero et al., 2010; Du et al., 2024; Lebourgeois et al., 2013). Notably, the cycle of emerging terminology has significantly shortened, highlighting the accelerated impact of technological advancements.

In summary, the evolution of research hotspots is driven by a dual mechanism comprising climate events and technological innovations, with the synergistic application of multidimensional indicators playing a facilitating role. Metrics such as wood density, isotopic composition, and anatomical characteristics are shifting dendrochronological studies from a focus on the climatic correlation of single annual ring widths to a high-resolution spatio-temporal dynamic analysis (Choi et al., 2023; Gessler et al., 2014; Kostić et al., 2022; Pan et al., 2024; Seibt et al., 2008). This approach employs data from diverse sources to elucidate the causal regulatory mechanisms through which climate change influences tree growth. Furthermore, integrating multi-source data and developing standardized resilience metrics are crucial to facilitate a shift from reactive "hotspot tracking" to proactive "predictive intervention" (DeSoto et al., 2020; Schwarz et al., 2020; Shi et al., 2024).

4. Conclusions

With a systematic bibliometric and visual analysis of dendrochronological literature on the impact of climate change on tree growth from 2000 to 2024, this study presents the following key conclusions:

(1) Deep interdisciplinary integration and broad development prospects:

A prominent feature of this field is its high degree of interdisciplinarity, centered on the integration of ecology and geography, and extending into diverse areas such as forestry and environmental science. In practice, scholars actively engage in cross-disciplinary collaboration with fields such as climate science, computer science, and tree physiology, both drawing from and contributing to their knowledge and techniques. This deep integration not only demonstrates the breadth of existing research but also highlights the field's significant potential for innovation and future development.

(2) A vibrant, emerging field with continuously advancing methodologies:

This relatively new interdisciplinary research domain has developed rapidly over the past two decades. It is characterized by the active adoption and refinement of advanced research methods. This progress not only builds upon the solid foundation of traditional dendrochronology but also pioneers new research perspectives and application scenarios. As the environmental impacts of climate change become increasingly evident, the field has garnered sustained attention, with ongoing model innovation and methodological iteration infusing it with persistent academic vitality.

(3) Collaborative networks as key engines driving disciplinary advancement:

The significant progress over the past two decades is largely attributable to robust, multi-level collaborative networks. These encompass international cooperation transcending geographical boundaries, close inter-institutional partnerships, and synergistic efforts by researchers on core issues. These collaborative endeavors have driven the standardization of research methods, the application and iteration of new technologies, and the continuous optimization of analytical models. Furthermore, leading scholars' systematic efforts have strengthened disciplinary rigor and cultivated emerging researchers.

(4) Research focus shifting towards extreme climate impacts and the exploration of causal mechanisms:

Facing increasingly severe ecological risks, the focus of recent research has clearly shifted towards the impacts of extreme climate events on forest ecosystems and their future dynamics. Assessing forest drought resistance and resilience in the context of climate change has become a central theme. Crucially, technological advancements, the comprehensive application of multidimensional indicators, and the synergistic analysis of multi-source data are driving a significant paradigm shift from describing correlations to elucidating the underlying causal mechanisms of tree responses to climate change.

CRediT authorship contribution statement

Teng Li: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Tsun Fung Au:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Data curation. **Jinbao Li:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Qi Li:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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