Journal of Forestry Research (2024) 35:13
https://doi.org/10.1007/s11676-023-01668-5

ORIGINAL PAPER

Rising utilization of stable isotopes in tree rings for climate change and forest ecology

Ru Huang[1] · Chenxi Xu[2,3] · Jussi Grießinger[4] · Xiaoyu Feng[5,6] · Haifeng Zhu[5] · Achim Bräuning[4]

Received: 27 May 2023 / Accepted: 3 September 2023

Abstract Analyses of stable isotopes (C, O, H) in tree rings are increasingly important cross-disciplinary programs. The rapid development in this field documented in an increasing number of publications requires a comprehensive review. This study includes a bibliometric analysis-based review to better understand research trends in tree ring stable isotope research. Overall, 1475 publications were selected from the Web of Science Core Collection for 1974–2023. The findings are that: (1) numbers of annual publications and citations increased since 1974. From 1974 to 1980, there were around two relevant publications per year. However, from 2020 to 2022, this rose sharply to 109 publications per year. Likewise, average article citations were less than four per year before 1990, but were around four per article per year after 2000; (2) the major subjects using tree ring stable isotopes include forestry, geosciences, and environmental sciences, contributing to 42.5% of the total during 1974–2023; (3) the top three most productive institutions are the Chinese Academy of Sciences (423), the Swiss Federal Institute for Forest, Snow and Landscape Research (227), and the University of Arizona (204). These achievements result from strong collaborations; (4) review papers, for example, (Dawson et al., Annu Rev Ecol Syst 33:507–559, 2002) and (McCarroll and Loader, Quat Sci Rev 23:771–801, 2004), are among the most cited, with more than 1000 citations; (5) tree ring stable isotope studies mainly focus on climatology and ecology, with atmospheric CO_2 one of the most popular topics. Since 2010, precipitation and drought have received increasing attention. Based on this analysis, the research stages, key findings, debated issues, limitations and directions for future research are summarized. This study serves as an important attempt to understand the progress on the use of stable isotopes in tree rings, providing scientific guidance for young researchers in this field.

Keywords Tree rings · Stable isotopes · Web of Science · Bibliometric

Project funding: This study was supported by the National Natural Science Foundation of China (Grant Number: 42007407, 42022059), the Sino-German mobility program (M-0393), the Key Research Program of the Institute of Geology and Geophysics (CAS Grant IGGCAS-201905), and the CAS Youth Interdisciplinary Team (JCTD-2021–05).

The online version is available at https://link.springer.com/.

Corresponding editor: Yu Lei.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11676-023-01668-5.

✉ Ru Huang
huangru13@mails.ucas.ac.cn

1 National Institute of Natural Hazards, Beijing 100085, People's Republic of China

2 Key Laboratory of Cenozoic Geology and Environment, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, People's Republic of China

3 CAS Center for Excellence in Life and Paleoenvironment, Beijing 100044, People's Republic of China

4 Institute of Geography, Friedrich-Alexander-University of Erlangen-Nuremberg, 91058 Erlangen, Germany

5 State Key Laboratory of Tibetan Plateau Earth System, Environment and Resources (TPESER), Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China

6 University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

Published online: 07 December 2023

Introduction

The importance of forests cannot be overemphasized in terms of their critical role in the global carbon, energy, and hydrological cycles. However, many forests are facing increasing stress (such as droughts, heatwaves) and may be highly affected or even decline under the impacts of global climate change (Mou et al. 2019; Senf et al. 2020; Hammond et al. 2022; Hartmann et al. 2022). To better forecast how forests may change under different climate conditions, it will be beneficial to obtain the historical picture of physiological and ecological processes affecting forests under different climate conditions. Investigations using stable isotopes in tree rings are one of the most valuable tools to meet such demands (Gessler et al. 2018; Shestakova and Martínez-Sancho 2021).

Since the end of the twentieth century, stable isotopes (herein focused only on C, O, H) in tree rings have been increasingly applied in different fields such as forest ecology and (paleo) climatology. More specifically, studies focusing on tree ring stable isotopes are indicative of net primary productivity (Belmecheri et al. 2014; Levesque et al. 2019), tree vitality and forest health (Cherubini et al. 2021), as well as water sources (Wang et al. 2021a, b; Huang et al. 2022; Zhao et al. 2023a). Voelker et al. (2019) reported that stable carbon isotopes in tree rings indicated that fire suppression had compromised the drought resilience of mixed-conifer forests and increased their vulnerability to biotic disturbances.

In addition, several ~ 1000-year tree ring isotope-inferred precipitation/temperature reconstructions have been produced worldwide (e.g., Feng and Epstein 1994; Treydte et al. 2006, 2009; Wang et al. 2013; Grießinger et al. 2017; Nakatsuka et al. 2020; Büntgen et al. 2021; Yang et al. 2021; An et al. 2022). With such enhanced progress, Siegwolf et al. (2022) published "Stable isotopes in tree rings: inferring physiological, climatic and environmental responses", which reviews current advances in tree ring stable isotope research. Such rapid developments in tree ring isotope science necessitates a state-of-the-art bibliometric review.

Bibliometric analysis, a scientific computer-assisted review methodology, is the statistical analyses of books, articles, and other publications (Ai et al. 2022). It is also referred to as "research on research", providing a qualitative description of trends based on a bibliometric analysis. Such methods are increasingly used in hydrology (Ning et al. 2019), climatology (Huang et al. 2020; Fu and Waltman 2022), geomorphology (Zhang and Chen 2020; Bovi et al. 2022), ecology (Chen et al. 2022), forestry (Polinko and Coupland 2021), and plant science (Adamo et al. 2021). Despite the substantial progress being made by tree ring isotope research, only few studies have used bibliometric methods to identify research trends in this field.

The aim of this study is to explore data on research outputs of stable isotopes in tree rings from the Web of Science (WOS) literature database, unveiling the global research status and hot spots in this field. The research stages, key findings, debated issues, and limitations for tree ring isotopes are also outlined. The results of this study can be a guide on tree ring stable isotope research.

Materials and methods

Data source

The Web of Science Core Collection was selected as our data source for bibliometric analysis, given its wide application in ecology (Song and Zhao 2013; Wang et al. 2022a), forestry (Polinko and Coupland 2021) and hydrology (Cao et al. 2021).

To capture the relevant literature as comprehensively as possible, two search terms were used: "tree ring* AND isotop*" and "tree ring* AND (stable isotop* OR Delta O-18 OR Delta C-13 OR delta H-2 OR Delta D)" (Note: the wildcard isotop* matches both "isotopic" and "isotope"). The number of publications from these two retrieval terms was 2251 and 1921, respectively. Fields like author, title, journal, cited frequency, abstract, address, affiliation, publication type, author keywords, keywords plus, Web of Science category and references in each record were downloaded for analysis. The web search covered the period from 1900 to 2023, and the final data retrieval was performed on January 17, 2023. After all the records were initially screened and merged, and repeated data deleted, 2393 records were left. Subsequently, all records were manually screened to select the relevant records. Finally, after two thorough manual screenings, only 1,475 records were selected for further analysis. Stable carbon, oxygen, and hydrogen isotopes in tree rings were focused on in this study depsite of the fact that there is an increasing number of publications using other isotopes in tree rings (e.g., nitrogen, Silva et al. 2016; Wang et al. 2022b). Other metal isotopes or non-stable isotopes (^{14}C) are also excluded in this study.

Data analysis

Biblioshiny in the bibliometrix package in the statistical environment R (Aria and Cuccurullo 2017; R Core Team 2023) revealed the temporal patterns of annual publications, citations, subjects, sources, authors, institutions, countries, key articles, research hotspots (indicated by keywords plus) for tree ring stable isotope studies. Biblioshiny is a shiny APP offering a web-interface for bibliometrix (Aria and Cuccurullo 2017). The detailed outline of this study is shown in Fig. 1.

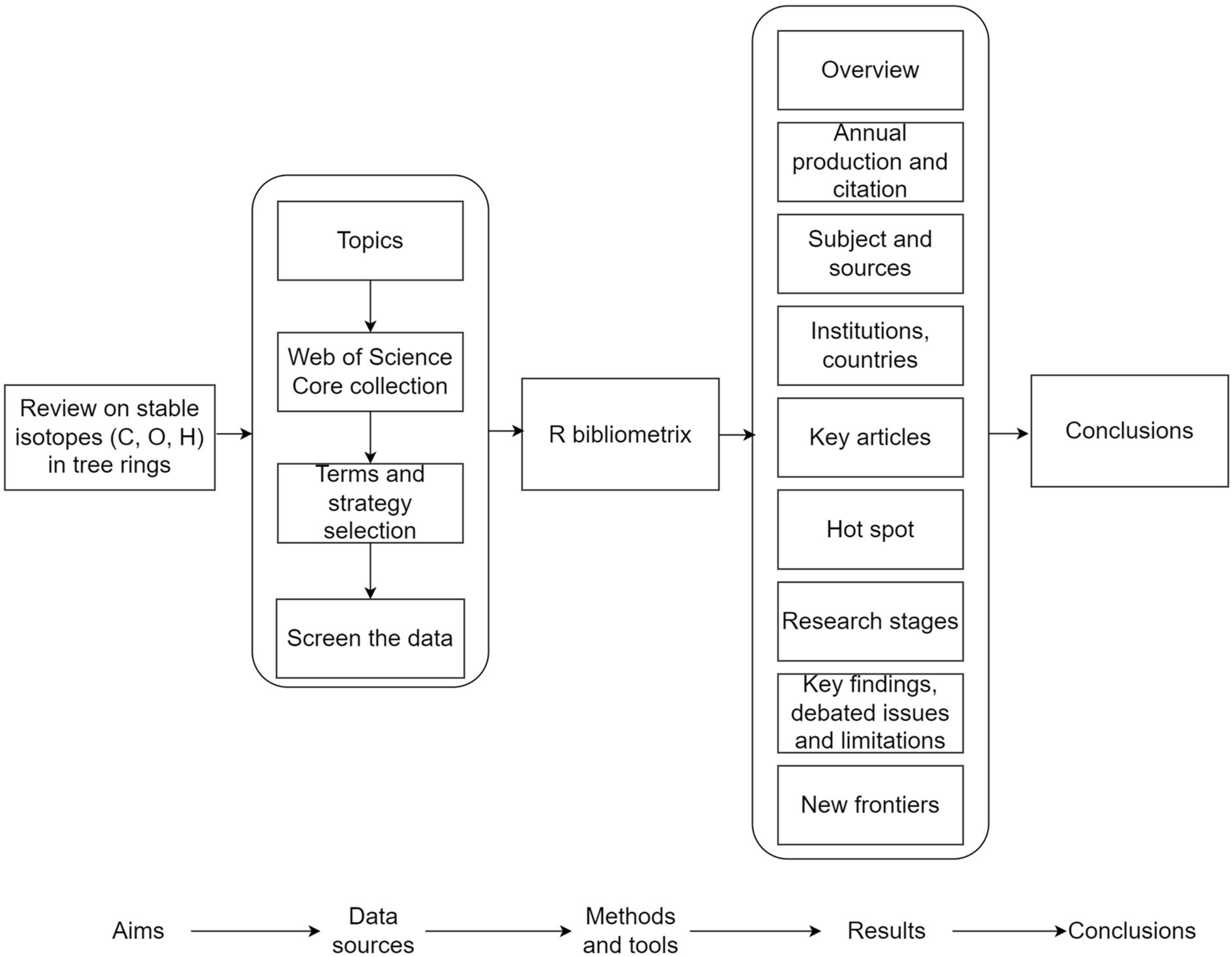

Fig. 1 Workflow diagram

The Web of Science provides two types of keywords when possible: author keywords, selected by the author and submitted with the manuscript to the journal, and keywords plus assigned by the Web of Science. Herein, 'keywords plus' instead of the authors' keywords is used to explore the research hotspots. Detailed reasons are provided in the supporting materials.

Additionally, the synonym terms were merged into one to better understand the trend of tree ring isotope studies ("Friedrich Alexander Univ", "Friedrich Alexander Univ Erlangen Nuremberg", "Friedrich Alexander Univ Erlangen Nurnberg", "Friedrich Alexander Univ Erlangen Nurnberg FAU", "Friedrich Alexander Univers Erlangen Nuremberg" were replaced with "Univ Erlangen Nurnberg"). Other major synonyms are summarized in Table S1.

All data analysis and the resulting plots were applied in the statistical environment R (R Core Team 2023).

Results and discussion

Overview of publication outputs

A total of 1475 papers from 249 sources (journals, books and other materials) were published during 1974–2023. There were 3485 authors in these studies, and only 44 published single–authored papers. On average, 5.1 authors contributed to every document. Half of the 1475 papers (50.9%) included international co–authors (at least from two countries). In addition, the average publication age in our dataset was 10.3 years, with 35.6 citations for every analyzed document.

Publications and citation trends

Both the annual number of publications and citations show an overall increase (Fig. 2, 1974–1980: two publications per

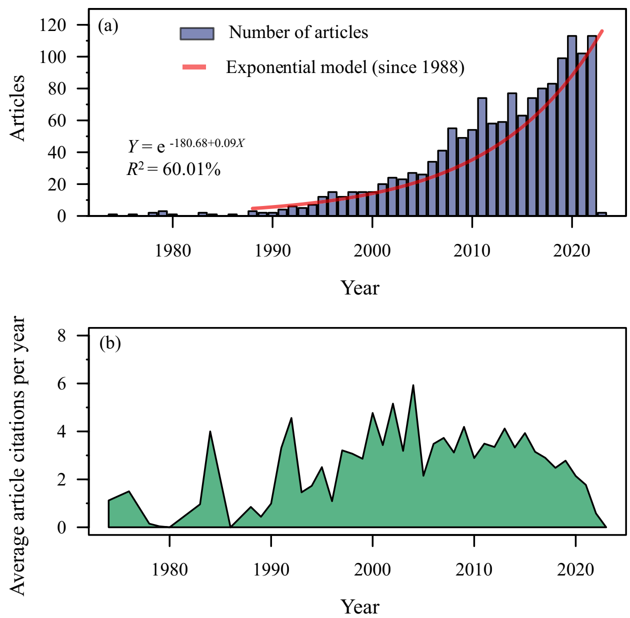

Fig. 2 Long-term trends of tree ring stable isotope publications from 1974 to 2023: (a) annual number of publications and (b) average article citations per year

year; 2020–2022: 109 publications per year; less than four average article citations before 1990; around four average article citations per year after 2000). Before 1990, there were only 17 publications related to tree ring stable isotopes. Two years with more than 20, and 100 publications were observed in 2000 and 2020, respectively. Annual publications increased from 1 in 1974 to 113 in 2022, leading to an average annual increase of 1.4% and 1475 accumulated publications. The number of publications per year have increased more than seven times from 2000 (15) to 2020 (113). Since 2000, the annual number of publications has exhibited a stable increase.

Average article citations were less than four per year before 1990. After 2000, average article citations increased to around four per year. Average article citations per year increased before 2016, however, a decrease occurred after 2016. Such a decrease in citations might be attributed to the time lag of two to three years after publication, which allows papers to accumulate sufficient citations (Belter 2015). Collectively, this demonstrates that the field of stable isotopes in tree rings developed rapidly with remarkable outputs over the past decades.

Subject and sources characteristics

Forestry, geosciences multidisciplinary, and environmental sciences are the major areas for the application of tree ring stable isotope studies (Fig. 3a), accounting for 42.5% of all subjects during 1974–2023. Contributions from different fields changed during differing periods. Before 2000, around 61.1% of related papers were on geosciences multidisciplinary, geochemistry and geophysics, ecology, meteorology or atmospheric sciences, and forestry. Since 2000, contributions from forestry and environmental sciences have increased, while those from geosciences multidisciplinary have decreased. The percentage of articles in geosciences multidisciplinary kept relatively stable during different periods. The increasing contributions from forestry and environmental sciences likely result from an emphasis from the public and society.

Studies of tree ring stable isotopes overall have appeared in 249 sources (journals, books, other materials). The number of sources remained stable at 45 from 1974 to 1999, and from 2000 to 2004. After 2004, the number of sources increased steadily, reaching 119 in 2015–2019. Additionally, the journals, *Tree Physiology* (96), *Trees-Structure and Function* (54), and *Dendrochronologia* (52) were the most popular for researchers to publish their results. These three journals contributed 13.7% of the total sources. Publications in these journals showed a clear increase since 2000 (Fig. 3b). This indicates that stable isotopes in tree rings were widely employed to investigate ecological/physiological processes in forestry research.

Institutions and countries

Most productive institutions and countries

The top 10 institutions in terms of overall number of publications are provided in Table 1. The Chinese Academy of Sciences (CAS) dominates with 423 publications, mainly from the Northwest Institute of Eco-environment and Resources (114), formerly the Cold and Arid Regions Environmental and Engineering Research Institute, and the Institute of Earth Environment (82). CAS is followed by the Swiss Federal Institute of Forest Snow and Landscape Research (WSL, 227) and the University of Arizona (204). The large number of publications by these institutions clearly indicate their influence in the field.

Different countries have different dominant roles based on the number of publications by several authors, the number of publications by corresponding author, total citations, and the average article citations (Fig. 4). The USA leads in number of publications (1327, Fig. 4a), the number of publications by corresponding author (285, Fig. 4b), and total citations (14,114, Fig. 4c). China is second with regards to the number of publications (1012, Fig. 4a), and the number of documents by corresponding author (197, Fig. 4b). However, the total citations (2640) and average article citations (13.4) for China were behind the UK (total citations: 6475, average article citations: 62.3), Germany (total citations: 5856, average article citations: 38), Switzerland (total citations: 5515,

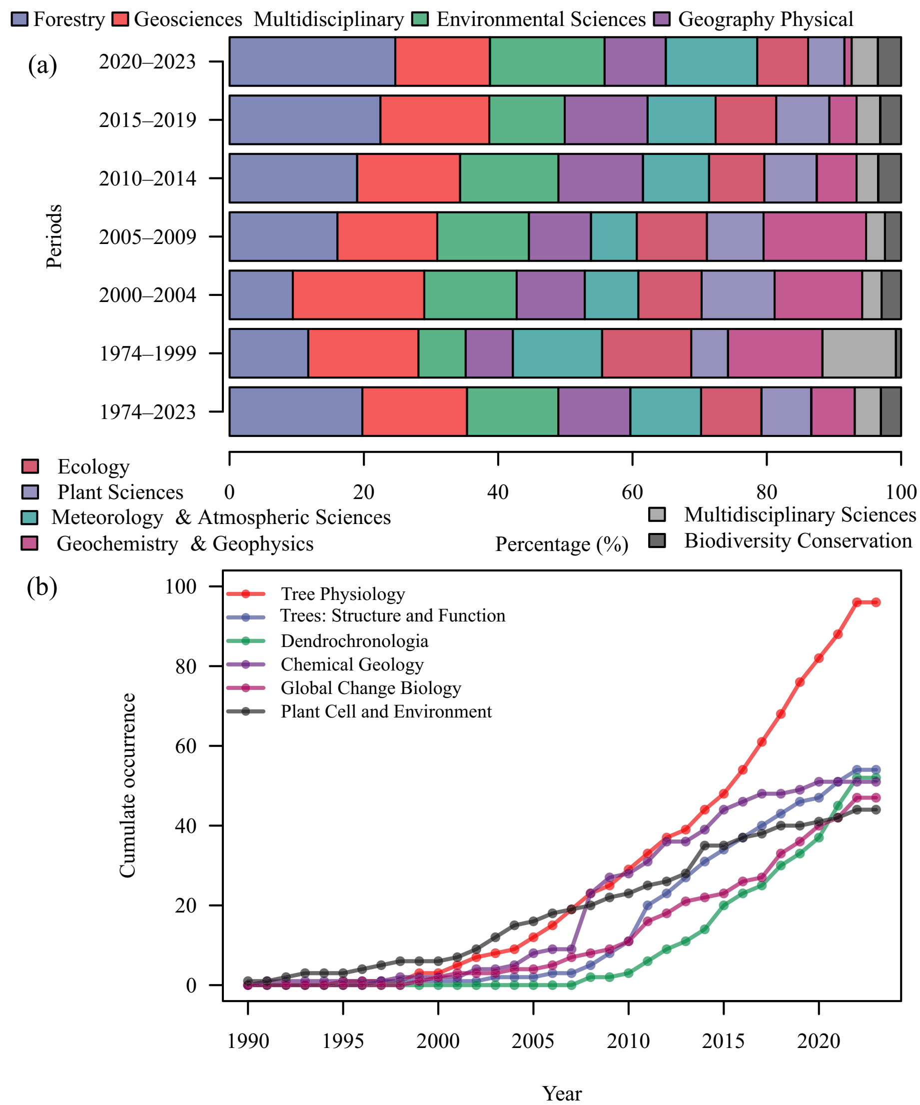

Fig. 3 **a** Percentage of major subject categories during 1974–2023,1974–1999, 2000–2004, 2005–2009, 2010–2014, 2015–2019, 2020–2023. These were selected based on the development and production of tree ring stable isotopes; **b** cumulative production for the top 6 most relevant sources related to tree ring stable isotopes

Table 1 List of the top 10 institutes derived from the analysis including affiliation, country, and number of articles

Affiliation	Country	Number of articles
Chinese Academy of Sciences	China	423
WSL	Switzerland	227
University of Arizona	USA	204
Paul Scherrer Institute	Switzerland	121
Swansea University	UK	104
University of Erlangen-Nuremberg	Germany	101
University of Bern	Switzerland	87
Hokkaido University	Japan	62
Columbia University	USA	59
University of Lleida	Spain	59

average article citations: 55.7), and Spain (total citations: 3175, average article citations: 41.2, Fig. 4c, d). Further, the UK leads in average article citations (62.3, Fig. 4d). This may result from the highly cited review papers by authors affiliated with the UK (e.g., McCarroll and Loader 2004).

Collaborations among authors, institutions, and countries

Whether authors, institutions or countries are considered, collaborative studies at national and international levels are becoming increasingly common for tree ring isotope research. The average numbers of authors, institutions, and countries revealed an upward trend since 1974 (Fig. 5). Over 2010–2023, the number was twice compared to 1974–1999 (Fig. 5). Additional collaboration network analysis revealed that the most influential institutions and countries had high numbers of collaborations (Fig. S1). The importance of

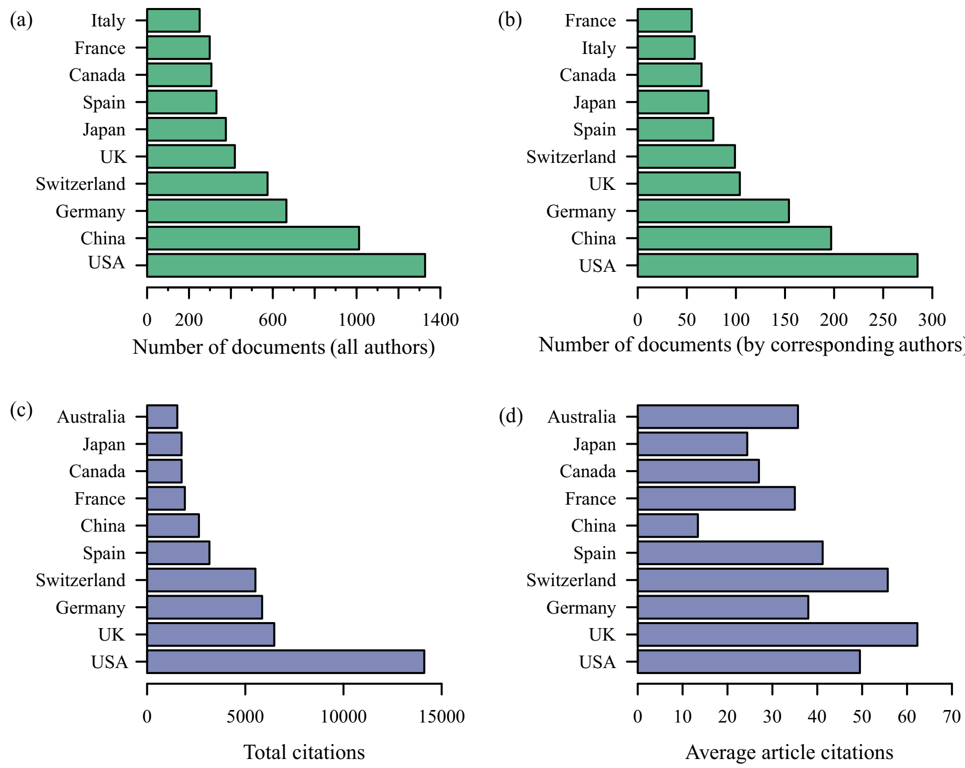

Fig. 4 Top 10 countries with publications related to tree ring stable isotopes: **a** number of documents irrespective of corresponding authors, **b** number of documents by corresponding authors, **c** total citations, **d** average article citation

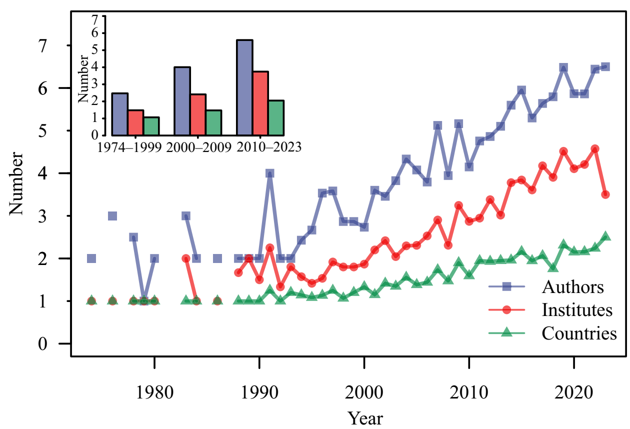

Fig. 5 Number of authors, institutions, and countries from 1974 to 2023 publishing articles on tree ring stable isotopes; the blank indicates no publication in the corresponding year. The top left inset plot shows averages for number of authors, institutions, and countries for 1974–1999, 2000–2009 and 2010–2023; these were used, considering the technology development and production on tree ring stable isotopes

cooperation is also stressed from a country comparison perspective (Jonathan 2013).

Key articles

Review papers were highly cited, the 10 most cited papers are listed in Table 2. All were published before 2010, and only one was published before 2000. Six of these ten papers were review articles, and the remaining were research articles. This suggests, specifically, that review papers have the highest potential to be highly cited. Apart from these review papers, publications related to thematic hot topics such as drought-induced forest decline (Barber et al. 2000) and original methods (Roden et al. 2000) were also attractive.

Hotspots indicated by 'keywords plus'

The terms "climatology" and "ecology" appear to be the main themes of tree ring isotope studies. Thirty 'keywords plus' are provided in the co–occurrence network and can be classified into two groups. The red zone (Cluster 1) indicates the theme "climatology", the blue zone (Cluster 2) represents the theme "ecology". It is obvious that the two clusters are significantly inter-linked (Fig. 6).

The hotspots have changed over time from 1974 to 2023 (Table 3). Atmospheric CO_2 remained the main topic in all periods except for 2020–2023. From 1974 to 1999, atmospheric CO_2, leaves, photosynthesis, plants, and forests were the most prevalent topics, reflecting that basic theories and methods were the dominant focus (e.g., Pearman et al. 1976; Leavitt and Long 1986; Macfarlane et al. 1999; McCarroll and Loader 2004). In the 2000s, water-use efficiency, temperature, and climate became more frequent topics, indicating a shift towards climate change impacts (e.g., Saurer et al. 2004; Peñuelas et al. 2008; Gessler et al. 2009).

Table 2 Top 10 cited articles derived from the analysis including information on respective documents, title, and year of publication

Document	Title	Type
Dawson et al. (2002)	Stable isotopes in plant ecology	Review
McCarroll and Loader (2004)	Stable isotopes in tree rings	Review
Barber et al. (2000)	Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress	Article
Ehleringer and Dawson (1992)	Water-uptake by plants-perspectives from stable isotope composition	Review
Roden et al. (2000)	A mechanistic model for Interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose	Article
Jones et al. (2009)	High-resolution palaeoclimatology of the last millennium: A review of current status and future prospects	Review
Barbour (2007)	Stable oxygen isotope composition of plant tissue: A review	Review
Treydte et al. (2006)	The twentieth century was the wettest period in northern Pakistan over the past millennium	Article
Seibt et al. (2008)	Carbon isotopes and water use efficiency: sense and sensitivity	Review
Hesselbo et al. (2007)	Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal)	Article

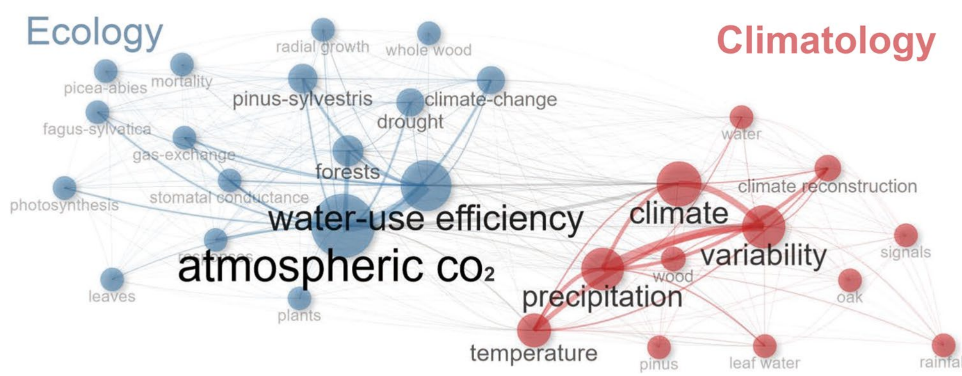

Fig. 6 Co-occurrence network of 'keywords plus' during the period 1974–2023

The 2010s saw even more focus on climate, variability, drought, and reconstruction of past climates using tree ring isotopes (e.g., Leavitt et al. 2011; Brienen et al. 2012; Qin et al. 2015). This possibly results from more frequent and destructive precipitation–related disasters (floods, droughts; IPCC 2021). Most recently in the 2020s, climate, atmospheric CO_2, and precipitation have been dominant (e.g., Mathias and Thomas 2021; Yang et al. 2021; Freund et al. 2023).

Research stages in tree ring stable isotope

According to our bibliometric analysis, the development of tree ring isotope research has gone through three stages: the initial exploration stage, the rapid development stage, and the expansion and integration stage (Fig. 7). During the initial exploration stage (before 2000), the number of articles was 110, with minimal international cooperation. On average, two–three scholars from a single country and institution published an article. Research focused on basic methods and fractionation principles in a few areas (Francey and Farquhar 1982; Roden and Ehleringer 1999).

In the rapid development stage (2000–2009), the number of articles published was 314, with an increase in international cooperation. On average, four scholars from one-two countries and two to three institutions published an article. The number of research sites gradually increased. Some scholars systematically reviewed the principles, methods, and applications of tree ring isotopes (Dawson et al. 2002; McCarroll and Loader 2004), laying a foundation for tree ring isotope research. In addition, long time series of 1000 years began to appear (Treydte et al. 2006).

In the expansion and integration stage (after 2010), up to the present, the number of articles published is about 1,050, with a significant increase in international cooperation. On average, five-six scholars from two countries and three to four institutions published an article. Drought research related to precipitation has increased. More chronologies exceeding 1,000 years have emerged (Grießinger et al. 2017; Büntgen et al. 2021; Yang et al. 2021). Research has expanded from single sites to regional comparisons (Freund et al. 2023; Xu et al. 2023) and research disciplines have expanded to multi-disciplines including forestry. Tree ring isotopes are increasingly closely integrated with mechanistic process models (Zeng et al. 2016, 2017) and atmospheric circulation models (Huang et al. 2019b).

Table 3 Keywords plus frequency (F) during different periods apart from the retrieval terms (e.g., stable carbon isotopes, oxygen isotopes, hydrogen isotopes)

1974–1999		2000–2004		2005–2009		2010–2014		2015–2019		2020–2023	
Terms	F	Terms	F	Terms	F	Terms	F	Terms	F	Terms	F
atmospheric CO_2	45	atmospheric CO_2	44	atmospheric CO_2	51	atmospheric CO_2	81	atmospheric CO_2	114	climate	68
leaves	19	water-use efficiency	20	water–use efficiency	31	water-use efficiency	58	water-use efficiency	88	atmospheric CO_2	67
photosynthesis	12	temperature	19	wood	31	climate	54	variability	74	precipitation	60
plants	11	gas-exchange	15	temperature	28	variability	52	precipitation	68	variability	55
forests	8	plants	14	climate	25	*Pinus sylvestris*	49	climate	66	water-use efficiency	55
water	7	climate	13	variability	25	precipitation	48	climate-change	61	drought	44
wood	7	variability	13	forests	23	climate reconstruction	34	*Pinus sylvestris*	45	climate-change	43
Douglas–fir	6	water	13	leaf water	23	temperature	32	climate reconstruction	44	forests	39
gas-exchange	6	precipitation	12	precipitation	20	gas-exchange	29	drought	44	temperature	34
temperature	6	wood	12	water	18	wood	29	temperature	39	climate reconstruction	32

For clarity, only the 10 most common words per period are displayed

Key findings, debated issues, and limitations of tree ring isotopes

Key findings

Tree ring isotopes are crucial in paleoclimatology research. The length of tree ring isotope chronologies has increased over time, with long chronologies spanning 6700 years in Asia (Yang et al. 2021), 1944 years in Europe (Büntgen et al. 2021), and some covering geological periods (Ren et al. 2021). The temporal resolution has also increased through more frequent intra-annual high-resolution studies, providing detailed climate change (Zeng et al. 2016 and 2017; Szymczak et al. 2019; Xu et al. 2021, 2022; Bing et al. 2022). In addition, tree ring isotope research has expanded spatially to include tropical low latitudes (Xu et al. 2023) and Arctic high latitudes (Xu et al. 2020). In addition to trees, shrubs have also attracted attention (Huang et al. 2019a; Wernicke et al. 2019; Driscoll et al. 2020; Li et al. 2020).

In ecology, tree ring isotopes have provided valuable insights. Intrinsic water-use efficiency is found to have increased in recent decades (Huang et al. 2017; Adams et al. 2019; Grießinger et al. 2019; Liu et al. 2019). Globally and regionally, enhanced photosynthesis rather than reduced stomatal conductance is the primary cause of increased intrinsic water-use efficiency (Guerrieri et al. 2019; Mathias and Thomas 2021). However, such increased efficiency may not improve tree growth due to water stress and nutrient limitations (Rahman et al. 2019; Wang et al. 2021a, b; Yang et al. 2022; Li et al. 2023). Additionally, tree ring isotopes have tracked variability of vegetation productivity in the eastern USA and northeastern China (Belmecheri et al. 2014; Levesque et al. 2019; Diao et al. 2023). Further, a conceptual model using tree ring isotopes assessed mechanisms and predispositions of drought-induced tree mortality (Gessler et al. 2018), providing a promising retrospective tool for physiological mechanisms.

Debated issues

CO_2 fertilization.

The effects of rising atmospheric CO_2 on tree growth remain controversial (Laffitte et al. 2023). Some tree ring isotope studies from northwestern China (Liu et al. 2014) and the southeastern Tibetan Plateau (Silva et al. 2016) reveal a positive tree growth response to elevated CO_2, while other researches from the tropics suggest constraints from drought stress or nutrient availability override the influence of the CO_2 increase on tree growth (Rahman et al. 2019). Further efforts are needed to clarify such complex relationship.

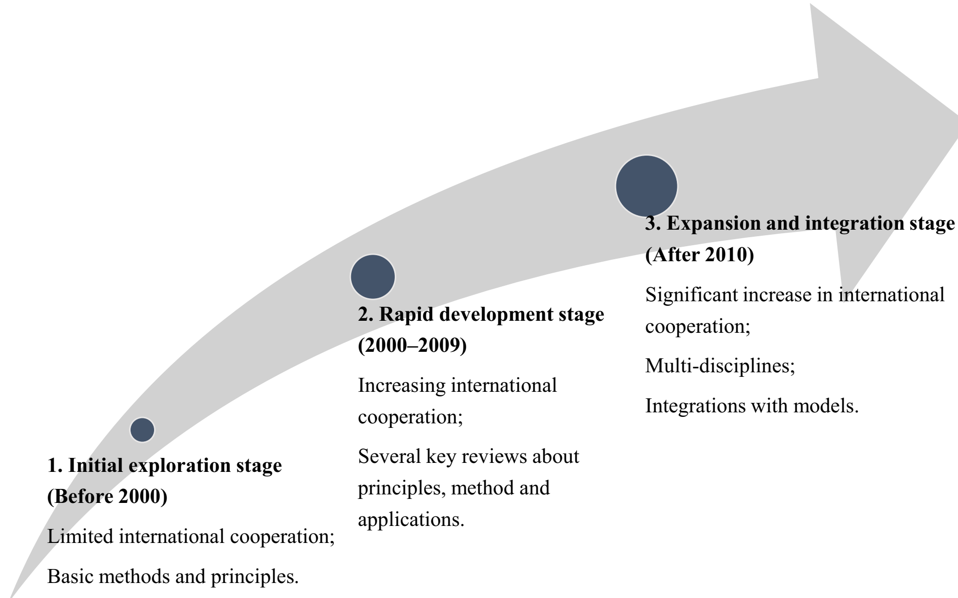

Fig. 7 Three stages of tree ring isotopes research

Detrend or not for tree ring oxygen isotopes.

Whether age-related trends exist in tree ring oxygen isotopes remains under discussion. Studies in northern Pakistan detected an age-related trend in the oxygen isotope chronology (Treydte et al. 2006), while research in the UK and Czech Republic did not (Duffy et al. 2019; Büntgen et al. 2020). Given their potential influence on climate reconstructions, this warrants further attention.

Limitations

The limitations of tree ring isotopes are: (1) stresses can lead to a mismatch between leaf and tree ring isotopes (Andreu-Hayles et al. 2022). Stem growth and carbon allocation to the stem may rapidly decline under stress before decreases in photosynthesis occur (Dobbertin 2005). This incomplete carbon transfer can result in unclear isotopic signals in the tree rings; (2) a temporal mismatch also arises from the use of different carbon pools for growth, each with unique isotopic signatures (Andreu-Hayles et al. 2022). While stored assimilates such as starch and sugars contain a blend of isotopic signals from previous and current seasons, their values diverge from newly produced assimilates (Kagawa et al. 2006). Such limitations should be considered in data analysis.

New frontiers in tree ring stable isotopes

Global synthesis for paleoclimatic reconstruction

The number of tree ring isotope sampling sites worldwide is increasing (e.g., Shestakova and Martínez-Sancho 2021; Freund et al. 2023; Xu et al. 2023). Creating global networks of tree ring isotope data can improve the accuracy of paleoclimatic reconstructions. This involves collecting data from various regions around the world and integrating it into a unified framework. Previous work has been done to create a global network of tree ring oxygen isotopes (Konecky et al. 2020). Further efforts should consider adding carbon and hydrology isotopes to obtain a much clearer picture of climate variability.

Evaluation of recent droughts in a long-term context

Drought has a significant impact on human beings. In recent years, an era of global warming has occurred, resulting in increased frequency and severity of droughts. Answering questions about the long-term historical perspective on recent droughts and their main driving factors requires long-term drought history data. Tree ring isotopes can record drought history and evaluate the severity of current droughts and their driving factors on a long-term scale (Feng et al. 2022; An et al. 2023; Wang et al. 2023; Zhao et al. 2023b). However, current tree ring isotope drought research is limited to a few regions like Europe (Liu et al. 2022; An et al. 2023; Freund et al. 2023), South America (Brienen et al. 2012), Northern America (Leavitt et al. 2011) and China (Yang et al. 2021). More efforts are needed in areas like Africa.

Reconstructing past vegetation productivity using tree ring stable isotopes

Vegetation productivity, which reflects the net carbon balance between photosynthesis and respiration, is a key indicator of ecosystem function and carbon cycling. However, long-term, high-resolution estimates of vegetation productivity across large spatial scales are generally scarce. Tree ring carbon and (or) oxygen isotopes have captured the interannual variability of ecosystem productivity in temperate forests (Belmecheri et al. 2014; Levesque et al. 2019; Diao et al. 2023). Such results suggest a potential of tree ring isotopes for reconstructing past vegetation productivity.

Understanding the physiological mechanisms of tree decline and mortality

The effects of global warming are manifesting as a decrease or mortality in numerous forests globally (Hammond et al. 2022). Tree ring widths provide fundamental insights into how tree growth has adapted to these changes (Rai et al. 2020; Yu and Liu 2020). Additionally, isotopes in tree rings furnish supplementary data on long-term physiological alterations in trees, such as changes in water-use efficiency and water sources (Sarris et al. 2013; Cherubini et al. 2021; Lehmann et al. 2021; Quadri et al. 2021; Siegwolf et al. 2023; Strange et al. 2023). This is crucial to understanding the physiological mechanisms of forest decline or death (Gessler et al. 2018; Valor et al. 2020). For example, early-warning signs of tree decline can be inferred from a reduced intrinsic water-use efficiency in the short-term (López et al. 2021).

Conclusion

Tree ring stable isotopes (C, O, H) are increasingly being used as an important tool in ecological, climatological, and forest research, with fruitful outputs. In this study, we conducted a bibliometric analysis to better understand trends in the current research during the period 1974–2023 with the retrieval type of "tree ring" and "stable isotope" in the topic. We found that the annual numbers of 1475 SCI/SSCI-indexed documents and citations increased. Forestry, multidisciplinary geosciences, and environmental sciences are the main subjects of this increase during 1974–2023, and *Tree Physiology* was the most popular journal for researchers. There was a shift from pure ecology and plant science to forestry (more applied topics). Additionally, CAS, WSL, and the University of Arizona are the most productive institutions, with more than 200 records. Different countries exhibit differing dominance for the total number of publications, the number of publications by the corresponding author, total citations, and average article citations. The most cited papers are mainly originating from reviews such as Dawson et al. (2002) and McCarroll and Loader (2004), with > 1000 citations. "Atmospheric CO_2" has been the most common theme, and precipitation-related studies have been given increasing attention since 2010.

Moreover, tree ring isotopes have undergone three distinct stages of development: the initial exploration stage (before 2000), the rapid development stage (2000–2009), and the expansion and integration stage (since 2010). These stages have been characterized by increasing international cooperation and significant contributions to the fields of (paleo) climatology and ecology. However, there remain unresolved issues, such as the effects of CO_2 fertilization and age-related effects in tree ring oxygen isotopes. In addition, attention should be given to the decoupling between leaf and tree ring isotopes, as well as the temporal mismatch of isotopic signatures due to the use of different carbon pools for growth.

We are aware that there might be some limitations within this analysis. At first, some relevant tree ring isotope studies were not included due to the limitation of the retrieval type. More specifically, papers whose title, abstract and keywords did not contain retrieval terms were not detected. In addition, articles in other languages besides English were not included. Moreover, the most recent studies about tree ring isotopes are not included (e.g., Freund et al. 2023; Xu et al. 2023; Zhao et al. 2023c) and the most highly cited papers are biased toward older papers because older studies tend to be more highly cited than newer ones (Belter 2015). Despite such disadvantages, the results of this study may offer an important insight of the tree ring stable isotope literature and can act as a helpful guide for researchers to master the relevant literature.

Acknowledgements Xiaoyu Feng is grateful for the support from the UCAS Joint PhD Training Program.

References

Adamo M, Chialva M, Calevo J, Bertoni F, Dixon K, Mammola S (2021) Plant scientists' research attention is skewed towards colourful, conspicuous and broadly distributed flowers. Nat Plants 7(5):574–578. https://doi.org/10.1038/s41477-021-00912-2

Adams MA, Buckley TN, Turnbull TL (2019) Rainfall drives variation in rates of change in intrinsic water use efficiency of tropical forests. Nat Commun 10(1):3661. https://doi.org/10.1038/s41467-019-11679-8

Ai X, Ma MG, Wang XM, Kuang HH (2022) A novel bibliometric and visual analysis of global geoscience research using landscape indices. Front Earth Sci 16(2):340–351. https://doi.org/10.1007/s11707-021-0875-z

An W, Li J, Wang S, Xu C, Shao X, Qin N, Guo Z (2022) Hydrological extremes in the upper Yangtze River over the past 700 yr inferred from a tree ring $\delta^{18}O$ Record. J Geophys Res Atmos 127(10):e2021JD03619. https://doi.org/10.1029/2021jd036109

An W, Xu C, Marković SB, Sun S, Sun Y, Gavrilov MB, Govedar Z, Hao Q, Guo Z (2023) Anthropogenic warming has exacerbated droughts in southern Europe since the 1850s. Commun Earth Environ 4:232. https://doi.org/10.1038/s43247-023-00907-1

Andreu-Hayles L, Lévesque M, Guerrieri R, Siegwolf RT, Körner C (2022) Limits and strengths of tree-ring stable isotopes. stable isotopes in tree rings: inferring physiological, climatic and environmental responses. Springer, Cham, pp 399–428

Aria M, Cuccurullo C (2017) Bibliometrix: An R-tool for comprehensive science mapping analysis. J Informetr 11(4):959–975. https://doi.org/10.1016/j.joi.2017.08.007

Barber VA, Juday GP, Finney BP (2000) Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405(6787):668–673. https://doi.org/10.1038/35015049

Barbour MM (2007) Stable oxygen isotope composition of plant tissue: a review. Funct Plant Biol 34(2):83–94. https://doi.org/10.1071/FP06228

Belmecheri S, Maxwell RS, Taylor AH, Davis KJ, Freeman KH, Munger WJ (2014) Tree-ring $\delta^{13}C$ tracks flux tower ecosystem productivity estimates in a NE temperate forest. Environ Res Lett 9(7):074011. https://doi.org/10.1088/1748-9326/9/7/074011

Belter CW (2015) Bibliometric indicators: opportunities and limits. J Med Libr Assoc JMLA 103(4):219–221. https://doi.org/10.3163/1536-5050.103.4.014

Bing X, Fang K, Gong X, Wang W, Xu C, Li M, Ruan C, Ma W, Li Y, Zhou F (2022) The intra-annual intrinsic water use efficiency dynamics based on an improved model. Clim Change 172(1–2):16. https://doi.org/10.1007/s10584-022-03368-1

Bovi RC, Romanelli JP, Caneppele BF, Cooper M (2022) Global trends in dendrogeomorphology: A bibliometric assessment of research outputs. CATENA 210:105921. https://doi.org/10.1016/j.catena.2021.105921

Brienen RJ, Helle G, Pons TL, Guyot JL, Gloor M (2012) Oxygen isotopes in tree rings are a good proxy for Amazon precipitation and El Nino-Southern Oscillation variability. Proc Natl Acad Sci USA 109(42):16957–16962. https://doi.org/10.1073/pnas.1205977109

Büntgen U, Kolář T, Rybníček M, Koňasová E, Trnka M, Ač A, Krusic PJ, Esper J, Treydte K, Reinig F, Kirdyanov A, Herzig F, Urban O (2020) No age trends in oak stable isotopes. Paleoceanogr Paleoclimatol 35(4):e2021PA003831. https://doi.org/10.1029/2019PA003831

Büntgen U, Urban O, Krusic PJ, Rybníček M, Kolář T, Kyncl T, Koňasová E, Čáslavský J, Esper J, Wagner S, Saurer M, Tegel W, Dobrovolný P, Cherubini P, Reinig F, Trnka M (2021) Recent European drought extremes beyond Common Era background variability. Nat Geosci 14(4):190–196. https://doi.org/10.1038/s41561-021-00698-0

Cao T, Han D, Song X (2021) Past, present, and future of global seawater intrusion research: A bibliometric analysis. J Hydrol 603:126844. https://doi.org/10.1016/j.jhydrol.2021.126844

Chen W, Ding H, Li J, Chen K, Wang H (2022) Alpine treelines as ecological indicators of global climate change: Who has studied? What has been studied? Ecol Inform 70:101691. https://doi.org/10.1016/j.ecoinf.2022.101691

Cherubini P, Battipaglia G, Innes JL (2021) Tree vitality and forest health: Can tree-ring stable isotopes be used as Indicators? Curr for Rep 7(2):69–80. https://doi.org/10.1007/s40725-021-00137-8

Dawson TE, Mambelli S, Plamboeck AH, Templer PH, Tu KP (2002) Stable isotopes in plant ecology. Annu Rev Ecol Syst 33(1):507–559. https://doi.org/10.1146/annurev.ecolsys.33.020602.095451

Diao H, Wang A, Gharun M, Saurer M, Yuan F, Guan D, Dai G, Wu J (2023) Tree-ring $\delta^{13}C$ of Pinus koraiensis is a better tracer of gross primary productivity than tree-ring width index in an old-growth temperate forest. Ecol Indic 153:110418. https://doi.org/10.1016/j.ecolind.2023.110418

Dobbertin M (2005) Tree growth as indicator of tree vitality and of tree reaction to environmental stress: a review. Eur J for Res 124(4):319–333. https://doi.org/10.1007/s10342-005-0085-3

Driscoll AW, Bitter NQ, Sandquist DR, Ehleringer JR (2020) Multidecadal records of intrinsic water-use efficiency in the desert shrub *Encelia farinosa* reveal strong responses to climate change. Proc Natl Acad Sci USA 117(31):18161–18168. https://doi.org/10.1073/pnas.2008345117

Duffy JE, McCarroll D, Loader NJ, Young GH, Davies D, Miles D, Bronk Ramsey C (2019) Absence of age-related trends in stable oxygen isotope ratios from oak tree rings. Global Biogeochem Cycles 33(7):841–848. https://doi.org/10.1029/2019GB006195

Ehleringer J, Dawson T (1992) Water uptake by plants: perspectives from stable isotope composition. Plant Cell Environ 15(9):1073–1082. https://doi.org/10.1111/j.1365-3040.1992.tb01657.x

Feng XH, Epstein S (1994) Climatic implications of an 8,000-year hydrogen isotope time-series from Bristlecone-pine trees. Science 265(5175):1079–1081. https://doi.org/10.1126/science.265.5175.1079

Feng X, Huang R, Zhu H, Liang E, Bräuning A, Zhong L, Gong Z, Zhang P, Asad F, Zhu X, Grießinger J (2022) Tree-ring cellulose oxygen isotopes indicate atmospheric aridity in the western Kunlun Mountains. Ecol Indic 137:108776. https://doi.org/10.1016/j.ecolind.2022.108776

Francey RJ, Farquhar GD (1982) An explanation of $^{13}C/^{12}C$ variations in tree rings. Nature 297(5861):28–31. https://doi.org/10.1038/297028a0

Freund MB, Helle G, Balting DF, Ballis N, Schleser GH, Cubasch U (2023) European tree-ring isotopes indicate unusual recent hydroclimate. Commun Earth Environ 4(1):26. https://doi.org/10.1038/s43247-022-00648-7

Fu HZ, Waltman L (2022) A large-scale bibliometric analysis of global climate change research between 2001 and 2018. Clim Change 170(3–4):36. https://doi.org/10.1007/s10584-022-03324-z

Gessler A, Brandes E, Buchmann N, Helle G, Rennenberg H, Barnard RL (2009) Tracing carbon and oxygen isotope signals from newly assimilated sugars in the leaves to the tree-ring archive. Plant Cell Environ 32(7):780–795. https://doi.org/10.1111/j.1365-3040.2009.01957.x

Gessler A, Cailleret M, Joseph J, Schonbeck L, Schaub M, Lehmann M, Treydte K, Rigling A, Timofeeva G, Saurer M (2018) Drought induced tree mortality-a tree-ring isotope based conceptual model to assess mechanisms and predispositions. New Phytol 219(2):485–490. https://doi.org/10.1111/nph.15154

Grießinger J, Bräuning A, Helle G, Hochreuther P, Schleser G (2017) Late Holocene relative humidity history on the southeastern

Tibetan plateau inferred from a tree-ring $\delta^{18}O$ record: Recent decrease and conditions during the last 1,500 years. Quat Int 430:52–59. https://doi.org/10.1016/j.quaint.2016.02.011

Grießinger J, Bräuning A, Helle G, Schleser G, Hochreuther P, Meier W, Zhu H (2019) A dual stable isotope approach unravels common climate signals and species-specific responses to environmental change stored in multi-century tree-ring series from the Tibetan Plateau. Geosciences 9(4):151. https://doi.org/10.3390/geosciences9040151

Guerrieri R, Belmecheri S, Ollinger SV, Asbjornsen H, Jennings K, Xiao JF, Stocker BD, Martin M, Hollinger DY, Bracho-Garrillo R, Clark K, Dore S, Kolb T, Munger JW, Novick K, Richardson AD (2019) Disentangling the role of photosynthesis and stomatal conductance on rising forest water-use efficiency. Proc Natl Acad Sci USA 116(34):16909–16914. https://doi.org/10.1073/pnas.1905912116

Hammond WM, Williams AP, Abatzoglou JT, Adams HD, Klein T, Lopez R, Saenz-Romero C, Hartmann H, Breshears DD, Allen CD (2022) Global field observations of tree die-off reveal hotter-drought fingerprint for Earth's forests. Nat Commun 13(1):1761. https://doi.org/10.1038/s41467-022-29289-2

Hartmann H, Bastos A, Das AJ, Esquivel-Muelbert A, Hammond WM, Martinez-Vilalta J, McDowell NG, Powers JS, Pugh TAM, Ruthrof KX, Allen CD (2022) Climate change risks to global forest health: emergence of unexpected events of elevated tree mortality worldwide. Annu Rev Plant Biol 73:673–702. https://doi.org/10.1146/annurev-arplant-102820-012804

Hesselbo SP, Jenkyns HC, Duarte LV, Oliveira LC (2007) Carbon-isotope record of the Early Jurassic (Toarcian) Oceanic Anoxic Event from fossil wood and marine carbonate (Lusitanian Basin, Portugal). Earth Planet Sci Lett 253(3–4):455–470. https://doi.org/10.1016/j.epsl.2006.11.009

Huang R, Zhu H, Liu X, Liang E, Grießinger J, Wu G, Li X, Bräuning A (2017) Does increasing intrinsic water use efficiency (iWUE) stimulate tree growth at natural alpine timberline on the southeastern Tibetan Plateau? Glob Planet Change 148:217–226. https://doi.org/10.1016/j.gloplacha.2016.11.017

Huang R, Zhu H, Liang E, Grießinger J, Dawadi B, Bräuning A (2019a) High-elevation shrub-ring $\delta^{18}O$ on the northern slope of the central Himalayas records summer (May–July) temperatures. Palaeogeogr Palaeoclimatol Palaeoecol 524:230–239. https://doi.org/10.1016/j.palaeo.2019.03.038

Huang R, Zhu H, Liang E, Grießinger J, Wernicke J, Yu W, Hochreuther P, Risi C, Zeng Y, Fremme A, Sodemann H, Bräuning A (2019b) Temperature signals in tree-ring oxygen isotope series from the northern slope of the Himalaya. Earth Planet Sci Lett 506:455–465. https://doi.org/10.1016/j.epsl.2018.11.002

Huang L, Chen K, Zhou M (2020) Climate change and carbon sink: a bibliometric analysis. Environ Sci Pollut Res 27(8):8740–8758. https://doi.org/10.1007/s11356-019-07489-6

Huang R, Zhu H, Liang E, Bräuning A, Zhong L, Xu C, Feng X, Asad F, Sigdel SR, Li L, Grießinger J (2022) Contribution of winter precipitation to tree growth persists until the late growing season in the Karakoram of northern Pakistan. J Hydrol 607:127513. https://doi.org/10.1016/j.jhydrol.2022.127513

IPCC (2021) Climate Change 2021 The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press

Jonathan A (2013) The fourth age of research. Nature 497(7451):557–560. https://doi.org/10.1038/497557a

Jones PD, Briffa KR, Osborn TJ, Lough JM, Van Ommen TD, Vinther BM, Luterbacher J, Wahl ER, Zwiers FW, Mann ME, Schmidt GA, Ammann CM, Buckley BM, Cobb KM, Esper J, Goosse H, Graham N, Jansen E, Kiefer T, Kull C, Kuttel M, Mosley-Thompson E, Overpeck JT, Riedwyl N, Schulz M, Tudhope AW, Villalba R, Wanner H, Wolff E, Xoplaki E (2009) High-resolution palaeoclimatology of the last millennium: a review of current status and future prospects. Holocene 19(1):3–49. https://doi.org/10.1177/0959683608098952

Kagawa A, Sugimoto A, Maximov TC (2006) Seasonal course of translocation, storage and remobilization of ^{13}C pulse-labeled photoassimilate in naturally growing *Larix gmelinii* saplings. New Phytol 171(4):793–804. https://doi.org/10.1111/j.1469-8137.2006.01780.x

Konecky BL, McKay NP, Churakova OV, Comas-Bru L, Dassié EP, Delong KL, Falster GM, Fischer MJ, Jones MD, Jonkers L, Kaufman DS, Leduc G, Managave S, Martrat B, Opel T, Orsi AJ, Partin JW, Sayani HR, Thomas EK, Thompson DM, Tyler JJ, Abram NJ, Atwood AR, Cartapanis O, Conroy JL, Curran MA, Dee SG, Deininger M, Divine DV, Kern Z, Porter TJ, Stevenson S, von Gunten L (2020) The Iso2k database: a global compilation of paleo-$\delta^{18}O$ and $\delta^{2}H$ records to aid understanding of Common Era climate. Earth Syst Sci Data 12(3):2261–2288. https://doi.org/10.5194/essd-12-2261-2020

Laffitte B, Seyler BC, Li P, Ha Z, Tang Y (2023) Using tree rings to detect a CO_2 fertilization effect: a global review. Trees 37:1299–1314. https://doi.org/10.1007/s00468-023-02438-w

Leavitt SW, Long A (1986) Stable-carbon isotope variability in tree foliage and wood. Ecology 67(4):1002–1010. https://doi.org/10.2307/1939823

Leavitt SW, Woodhouse CA, Castro CL, Wright WE, Meko DM, Touchan R, Griffin D, Ciancarelli B (2011) The North American monsoon in the U.S. Southwest: potential for investigation with tree-ring carbon isotopes. Quat Int 235(1):101–107. https://doi.org/10.1016/j.quaint.2010.05.006

Lehmann MM, Vitali V, Schuler P, Leuenberger M, Saurer M (2021) More than climate: Hydrogen isotope ratios in tree rings as novel plant physiological indicator for stress conditions. Dendrochronologia 65:125788. https://doi.org/10.1016/j.dendro.2020.125788

Levesque M, Andreu-Hayles L, Smith WK, Williams AP, Hobi ML, Allred BW, Pederson N (2019) Tree-ring isotopes capture interannual vegetation productivity dynamics at the biome scale. Nat Commun 10(1):742. https://doi.org/10.1038/s41467-019-08634-y

Li Q, Liu Y, Nakatsuka T, Zhang QB, Ohnishi K, Sakai A, Kobayashi O, Pan Y, Song H, Liu R (2020) Oxygen stable isotopes of a network of shrubs and trees as high-resolution plaeoclimatic proxies in Northwestern China. Agric for Meteorol 285:107929. https://doi.org/10.1016/j.agrformet.2020.107929

Li Y, Xu C, Huang Y, Huo X, Shi F, Pan Y, Ren L, Wu X (2023) Tree growth and intrinsic water use efficiency of Chinese pine plantations along a precipitation gradient in northern China. For Ecol Manage 528:120609. https://doi.org/10.1016/j.foreco.2022.120609

Liu X, Wang W, Xu G, Zeng X, Wu G, Zhang X, Qin D (2014) Tree growth and intrinsic water-use efficiency of inland riparian forests in northwestern China: evaluation via $\delta^{13}C$ and $\delta^{18}O$ analysis of tree rings. Tree Physiol 34(9):966–980. https://doi.org/10.1093/treephys/tpu067

Liu, Y., An, W., Wang, X. and Xu, C., 2022. Moisture history in the Northeast China since 1750s reconstructed from tree-ring cellulose oxygen isotope. Quat. Int., 625, 49–59. https://doi.org/10.1016/j.quaint.2022.03.009

Liu X, Zhao L, Voelker S, Xu G, Zeng X, Zhang X, Zhang L, Sun W, Zhang Q, Wu G, Li X (2019) Warming and CO_2 enrichment modified the ecophysiological responses of Dahurian larch and Mongolia pine during the past century in the permafrost of northeastern China. Tree Physiol 39(1):88–103. https://doi.org/10.1093/treephys/tpy060

López R, Cano FJ, Rodríguez-Calcerrada J, Sangüesa-Barreda G, Gazol A, Camarero JJ, Rozenberg P (2021) Tree-ring density and carbon isotope composition are early-warning signals of drought-induced mortality in the drought tolerant Canary Island pine. Agric for Meteorol 310:108634. https://doi.org/10.1016/j.agrformet.2021.108634

Macfarlane C, Warren CR, White DA, Adams MA (1999) A rapid and simple method for processing wood to crude cellulose for analysis of stable carbon isotopes in tree rings. Tree Physiol 19(12):831–835. https://doi.org/10.1093/treephys/19.12.831

Mathias JM, Thomas RB (2021) Global tree intrinsic water use efficiency is enhanced by increased atmospheric CO_2 and modulated by climate and plant functional types. Proc Natl Acad Sci USA 118(7):e2014286118. https://doi.org/10.1073/pnas.2014286118

McCarroll D, Loader NJ (2004) Stable isotopes in tree rings. Quat Sci Rev 23(7–8):771–801. https://doi.org/10.1016/j.quascirev.2003.06.017

Mou YM, Fang O, Cheng X, Qiu H (2019) Recent tree growth decline unprecedented over the last four centuries in a Tibetan juniper forest. J for Res 30(4):1429–1436. https://doi.org/10.1007/s11676-018-0856-6

Nakatsuka T, Sano M, Li Z, Xu CX, Tsushima A, Shigeoka Y, Sho K, Ohnishi K, Sakamoto M, Ozaki H, Higami N, Nakao N, Yokoyama M, Mitsutani T (2020) A 2600-year summer climate reconstruction in central Japan by integrating tree-ring stable oxygen and hydrogen in isotopes. Clim past 16(6):2153–2172. https://doi.org/10.5194/cp-16-2153-2020

Ning L, Zhan C, Luo Y, Wang Y, Liu L (2019) A review of fully coupled atmosphere-hydrology simulations. J Geog Sci 29(3):465–479. https://doi.org/10.1007/s11442-019-1610-5

Pearman GI, Francey RJ, Fraser PJB (1976) Climatic implications of stable carbon isotopes in tree rings. Nature 260(5554):771–773

Peñuelas J, Hunt JM, Ogaya R, Jump AS (2008) Twentieth century changes of tree-ring $\delta^{13}C$ at the southern range-edge of *Fagus sylvatica*: increasing water-use efficiency does not avoid the growth decline induced by warming at low altitudes. Glob Chang Biol 14(5):1076–1088. https://doi.org/10.1111/j.1365-2486.2008.01563.x

Polinko AD, Coupland K (2021) Paradigm shifts in forestry and forest research: a bibliometric analysis. Can J for Res 51(2):154–162. https://doi.org/10.1139/cjfr-2020-0311

Qin C, Yang B, Bräuning A, Grießinger J, Wernicke J (2015) Drought signals in tree-ring stable oxygen isotope series of Qilian juniper from the arid northeastern Tibetan Plateau. Glob Planet Change 125:48–59. https://doi.org/10.1016/j.gloplacha.2014.12.002

Quadri P, Silva LCR, Zavaleta ES (2021) Climate-induced reversal of tree growth patterns at a tropical treeline. Sci Adv 7(22):eabb7572. https://doi.org/10.1126/sciadv.abb7572

R Core Team. (2023) R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing

Rahman M, Islam M, Gebrekirstos A, Bräuning A (2019) Trends in tree growth and intrinsic water-use efficiency in the tropics under elevated CO_2 and climate change. Trees 33(3):623–640. https://doi.org/10.1007/s00468-019-01836-3

Rai S, Dawadi B, Wang Y, Lu X, Huang R, Sigdel SR (2020) Growth response of *Abies spectabilis* to climate along an elevation gradient of the Manang valley in the central Himalayas. J for Res 31(6):2245–2254. https://doi.org/10.1007/s11676-019-01011-x

Ren J, Schubert BA, Lukens WE, Quan C (2021) Low oxygen isotope values of fossil cellulose indicate an intense monsoon in East Asia during the late Oligocene. Palaeogeogr Palaeoclimatol Palaeoecol 577:110556. https://doi.org/10.1016/j.palaeo.2021.110556

Roden JS, Ehleringer JR (1999) Observations of hydrogen and oxygen isotopes in leaf water confirm the craig-gordon model under wide-ranging environmental conditions. Plant Physiol 120(4):1165–1174. https://doi.org/10.1104/pp.120.4.1165

Roden JS, Lin G, Ehleringer JR (2000) A mechanistic model for interpretation of hydrogen and oxygen isotope ratios in tree-ring cellulose. Geochim Cosmochim Acta 64(1):21–35. https://doi.org/10.1016/S0016-7037(99)00195-7

Sarris D, Siegwolf R, Körner C (2013) Inter- and intra-annual stable carbon and oxygen isotope signals in response to drought in Mediterranean pines. Agric for Meteorol 168:59–68. https://doi.org/10.1016/j.agrformet.2012.08.007

Saurer M, Siegwolf RT, Schweingruber FH (2004) Carbon isotope discrimination indicates improving water-use efficiency of trees in northern Eurasia over the last 100 years. Glob Chang Biol 10(12):2109–2120. https://doi.org/10.1111/j.1365-2486.2004.00869.x

Seibt U, Rajabi A, Griffiths H, Berry JA (2008) Carbon isotopes and water use efficiency: sense and sensitivity. Oecologia 155:441–454. https://doi.org/10.1007/s00442-007-0932-7

Senf C, Buras A, Zang CS, Rammig A, Seidl R (2020) Excess forest mortality is consistently linked to drought across Europe. Nat Commun 11(1):6200. https://doi.org/10.1038/s41467-020-19924-1

Shestakova TA, Martínez-Sancho E (2021) Stories hidden in tree rings: a review on the application of stable carbon isotopes to dendrosciences. Dendrochronologia 65:125789. https://doi.org/10.1016/j.dendro.2020.125789

Siegwolf RTW, Brooks JR, Roden J, Saurer M (2022) Stable isotopes in tree rings: inferring physiological, climatic and environmental responses. Springer, Cham. https://doi.org/10.1007/978-3-030-92698-4

Siegwolf RTW, Lehmann MM, Goldsmith G, Churakova OV, Mirande-Ney C, Timoveeva G, Weigt RB, Saurer M (2023) Updating the dual C and O isotope-gas-exchange model: a concept to understand plant responses to the environment and its implications for tree rings. Plant Cell Environ 46(9):2606–2627. https://doi.org/10.1111/pce.14630

Silva LC, Sun G, Zhu-Barker X, Liang Q, Wu N, Horwath WR (2016) Tree growth acceleration and expansion of alpine forests: The synergistic effect of atmospheric and edaphic change. Sci Adv 2(8):e1501302. https://doi.org/10.1126/sciadv.1501302

Song YJ, Zhao TZ (2013) A bibliometric analysis of global forest ecology research during 2002–2011. Springerplus. https://doi.org/10.1186/2193-1801-2-204

Strange BM, Monson RK, Szejner P, Ehleringer J, Hu J (2023) The North American Monsoon buffers forests against the ongoing megadrought in the Southwestern United States. Glob Change Biol 29(15):4354–4367. https://doi.org/10.1111/gcb.16762

Szymczak S, Bräuning A, Häusser M, Garel E, Huneau F, Santoni S (2019) The relationship between climate and the intra-annual oxygen isotope patterns from pine trees: a case study along an elevation gradient on Corsica. France Ann for Sci 76(3):1–14. https://doi.org/10.1007/s13595-019-0860-9

Treydte KS, Schleser GH, Helle G, Frank DC, Winiger M, Haug GH, Esper J (2006) The twentieth century was the wettest period in northern Pakistan over the past millennium. Nature 440(7088):1179–1182. https://doi.org/10.1038/nature04743

Treydte KS, Frank DC, Saurer M, Helle G, Schleser GH, Esper J (2009) Impact of climate and CO_2 on a millennium-long tree-ring carbon isotope record. Geochim Cosmochim Acta 73(16):4635–4647. https://doi.org/10.1016/j.gca.2009.05.057

Valor T, Camprodon J, Buscarini S, Casals P (2020) Drought-induced dieback of riparian black alder as revealed by tree rings and oxygen isotopes. For Ecol Manage 478:118500. https://doi.org/10.1016/j.foreco.2020.118500

Voelker SL, Merschel AG, Meinzer FC, Ulrich DEM, Spies TA, Still CJ (2019) Fire deficits have increased drought sensitivity in dry

conifer forests: Fire frequency and tree-ring carbon isotope evidence from Central Oregon. Glob Chang Biol 25(4):1247–1262. https://doi.org/10.1111/gcb.14543
Wang WZ, Liu XH, Xu GB, Shao XM, Qin DH, Sun WZ, An WL, Zeng XM (2013) Moisture variations over the past millennium characterized by Qaidam Basin tree-ring $\delta^{18}O$. Chin Sci Bull 58(32):3956–3961. https://doi.org/10.1007/s11434-013-5913-0
Wang L, Liu H, Leavitt S, Cressey EL, Quine TA, Shi J, Shi S (2021a) Tree-ring $\delta^{18}O$ identifies similarity in timing but differences in depth of soil water uptake by trees in mesic and arid climates. Agric for Meteorol 308:108569. https://doi.org/10.1016/j.agrformet.2021.108569
Wang W, McDowell NG, Liu X, Xu G, Wu G, Zeng X, Wang G (2021b) Contrasting growth responses of Qilian juniper (*Sabina przewalskii*) and Qinghai spruce (*Picea crassifolia*) to CO_2 fertilization despite common water-use efficiency increases at the northeastern Qinghai-Tibetan Plateau. Tree Physiol 41(6):992–1003. https://doi.org/10.1093/treephys/tpaa169
Wang P, Liu LJ, Dong BC, Zhang WH, Schmid B (2022a) Bibliometric analysis of journal of plant ecology during 2017–2021. J Plant Ecol 15(6):1316–1323. https://doi.org/10.1093/jpe/rtac107
Wang Z, Liu X, Wang K, Zeng X, Zhang Y, Ge W, Kang H, Lu Q (2022b) Tree-ring $\delta^{15}N$ of Qinghai spruce in the central Qilian Mountains of China: Is pre-treatment of wood samples necessary? J Arid Land 14(6):673–690. https://doi.org/10.1007/s40333-022-0065-1
Wang L, Liu H, Grießinger J, Chen D, Sun C, Fang C (2023) Enhanced variability and declining trend of soil moisture since the 1880s on the southeastern Tibetan Plateau. Water Resour Res 59(3):202233953. https://doi.org/10.1029/2022wr033953
Wernicke J, Stark G, Wang L, Griessinger J, Brauning A (2019) Air moisture signals in a stable oxygen isotope chronology of dwarf shrubs from the central Tibetan Plateau. Ann Bot 124(1):53–64. https://doi.org/10.1093/aob/mcz030
Xu C, Buckley BM, Wang S-YS, An W, Li Z, Nakatsuka T, Guo Z (2020) Oxygen isotopes in tree rings from greenland: a new proxy of NAO. Atmosphere 12(1):39. https://doi.org/10.3390/atmos12010039
Xu C, Zhu H, Wang S-YS, Shi F, An W, Li Z, Sano M, Nakatsuka T, Guo Z (2021) Onset and maturation of Asian summer monsoon precipitation reconstructed from intra-annual tree-ring oxygen isotopes from the southeastern Tibetan Plateau. Quat Res 103:139–147. https://doi.org/10.1017/qua.2020.28
Xu G, Liu X, Hu J, Dorado-Liñán I, Gagen M, Szejner P, Chen T, Trouet V (2022) Intra-annual tree-ring $\delta^{18}O$ and $\delta^{13}C$ reveal a trade-off between isotopic source and humidity in moist environments. Tree Physiol 42(11):2203–2223. https://doi.org/10.1093/treephys/tpac076
Xu C, Wang S-YS, Borhara K, Buckley B, Tan N, Zhao Y, An W, Sano M, Nakatsuka T, Guo Z (2023) Asian-Australian summer monsoons linkage to ENSO strengthened by global warming. Clim Atmos Sci 6:8. https://doi.org/10.1038/s41612-023-00341-2
Yang B, Qin C, Bräuning A, Osborn TJ, Trouet V, Ljungqvist FC, Esper J, Schneider L, Grießinger J, Büntgen U, Rossi S, Dong GH, Yan M, Ning L, Wang JL, Wang XF, Wang SM, Luterbacher J, Cook ER, Stenseth NC (2021) Long-term decrease in Asian monsoon rainfall and abrupt climate change events over the past 6,700 years. Proc Natl Acad Sci USA 118(30):e2102007118. https://doi.org/10.1073/pnas.2102007118
Yang RQ, Zhao F, Fan ZX, Panthi S, Fu PL, Bräuning A, Grießinger J, Li ZS (2022) Long-term growth trends of Abies delavayi and its physiological responses to a warming climate in the Cangshan Mountains, southwestern China. For Ecol Manage 505:119943. https://doi.org/10.1016/j.foreco.2021.119943
Yu J, Liu Q (2020) Larix olgensis growth–climate response between lower and upper elevation limits: an intensive study along the eastern slope of the Changbai Mountains, northeastern China. J for Res 31:231–244. https://doi.org/10.1007/s11676-018-0788-1
Zeng X, Liu X, Evans MN, Wang W, An W, Xu G, Wu G (2016) Seasonal incursion of Indian Monsoon humidity and precipitation into the southeastern Qinghai-Tibetan Plateau inferred from tree ring $\delta^{18}O$ values with intra-seasonal resolution. Earth Planet Sci Lett 443:9–19. https://doi.org/10.1016/j.epsl.2016.03.011
Zhang Y, Chen Y (2020) Research trends and areas of focus on the Chinese Loess Plateau: a bibliometric analysis during 1991–2018. CATENA 194:104798. https://doi.org/10.1016/j.catena.2020.104798
Zhao Q, Xu C, An W, Liu Y, Xiao G, Huang C (2023a) Increasing tree growth in subalpine forests of central China due to earlier onset of the thermal growing season. Agric for Meteorol 333:109391. https://doi.org/10.1016/j.agrformet.2023.109391
Zhao Y, Xu C, Liu Y, An W, Guo Z (2023b) Irrawaddy River experienced more frequent hydrological drought events with global warming: Evidence from a 400-year tree ring oxygen isotope record. CATENA 232:107455. https://doi.org/10.1016/j.catena.2023.107455
Zhao Y, Yang B, Zhang P, Luo J, Grießinger J, Zhang H, Liang C, Ma Z, Gu H, Zhang Y et al (2023c) Zhao Y, Yang B, Zhang P, Luo J, Grießinger J, Zhang H, Liang C, Ma Z, Gu H, Zhang Y. (2023c) Inter-tree correlation and climatic response of tree-ring $\delta^{18}O$ in Chinese fir: Implications for cross-dating and climatic reconstruction in Central East China. Dendrochronologia 81:126134. https://doi.org/10.1016/j.dendro.2023.126134