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PERSPECTIVE

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Scrutinizing tree-ring parameters for Holocene climate reconstructions

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Abstract

Independent evidence from Europe and Asia shows that tree-ring stable isotopes can reveal persistent long-term hydroclimate trends that are generally not captured by more traditional dendroclimatic studies using tree-ring width or density. Since the recently observed long-term discrepancy between flatter "growth-dependent" and more varying "growth-independent" climate proxy data is unrelated to possible biases of statistical age-trend removal, I call for a conceptual rethinking of the predictive power of different tree-ring parameters for reconstructing climate variability on interannual to multimillennial timescales. I describe why traditional "growth-dependent" tree-ring width and wood density measurements usually lack abiotic signals on ultra-long timescales, whereas "growth-independent" carbon and oxygen isotopic ratios from tree-ring cellulose can capture environmental variation well beyond the segment length of individual tree-ring samples. Caution is therefore advised when information from diverse tree-ring parameters is combined in multiproxy reconstructions of Holocene climate that aim to reflect the full range of interannual to multimillennial variability. This *Perspective* not only emphasizes the paleoclimatic value that can be obtained from tree-ring stable isotopes in living and relict wood. It also stresses the need for developing new high-resolution isotopic datasets from different species and regions in both hemispheres to supplement the existing tree-ring record.

This article is categorized under:

Paleoclimates and Current Trends > Paleoclimate

KEYWORDS

climate reconstructions, dendrochronology, Holocene, paleoclimate, stable isotopes, tree rings

1 | INTRODUCTION

Two recent studies of tree-ring stable isotopes provide independent evidence for long-term drying trends in central Europe and monsoon Asia over the past two and seven millennia (Büntgen et al., 2021; Yang et al., 2021), respectively (Figure 1). Statistically significant, these multimillennial-long hydroclimate trajectories have been interpreted as the negative

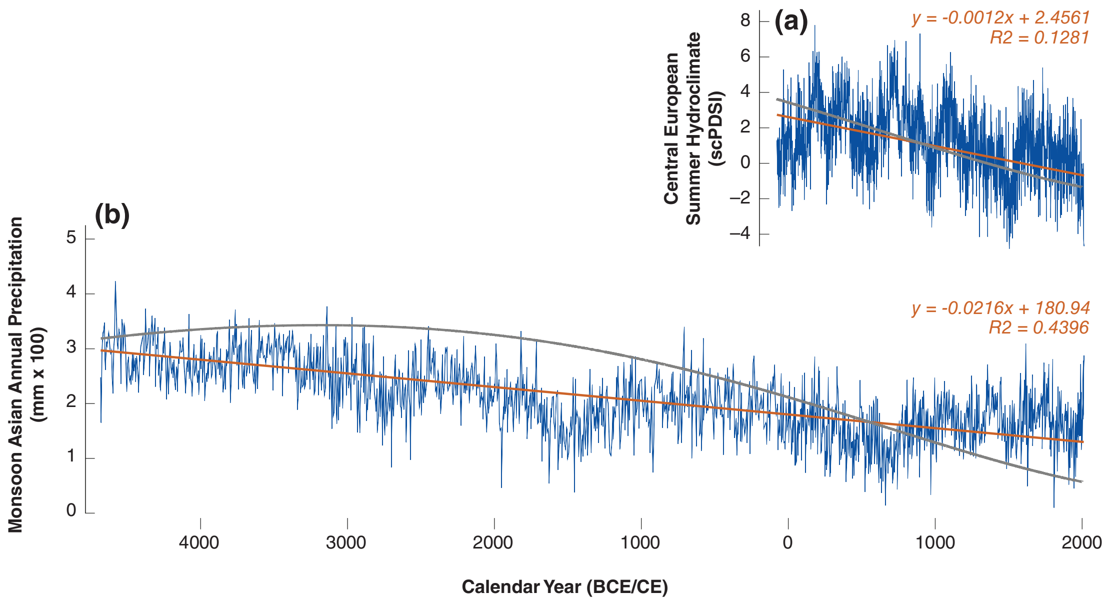

FIGURE 1 "Growth-independent" tree-ring stable isotopes reflect long-term climate trends on multimillennial timescales.
(a) Reconstructed summer (June–August) hydroclimate for central Europe using tree-ring stable carbon and oxygen isotope measurements ($\delta^{13}C$ and $\delta^{18}O$) from living and relict oak wood collected in the Czech Republic and southeast Germany (Büntgen et al., 2021).
(b) Reconstructed annual (prior August to current July) precipitation totals for monsoon Asia using tree-ring stable oxygen isotope measurements ($\delta^{18}O$) from living and relict juniper wood collected on the eastern Tibetan Plateau (Yang et al., 2021). Dark and light blue curves are the reconstructions and their uncertainty ranges, together with their linear trends (red lines and equations). Gray lines refer to orbital-induced changes in net summer surface radiation between circa 80 and 86 W m^{-2} (reproduced from Bader et al., 2020). scPDSI, self-calibrated Palmer Drought Severity Index

radiative effect of orbital forcing (i.e., insolation changes due to the Earth's axial precession) (Hays et al., 1976; Milankovitch, 1941). The new tree-ring stable isotope records from the Czech Republic and the Tibetan Plateau, however, challenge previous work that used tree-ring width measurements for reconstructing summer hydroclimate in the same regions but that did not reveal any low-frequency variability beyond multidecadal or centennial timescales (Cook et al., 2010, 2015; Ionita et al., 2021; Yang et al., 2014). Albeit recognising possible biases of statistical age-trend removal – that is, tree-ring standardization (Briffa et al., 1992; Esper et al., 2003) – the observed long-term discrepancy is manifested in the raw stable carbon and oxygen isotope measurements ($\delta^{13}C$ and $\delta^{18}O$) (Büntgen, 2019), which have been extracted from annually resolved and absolutely dated samples of alpha cellulose of hundreds of living and relict trees.

Here, I call for a conceptual rethinking of the predictive power of different tree-ring parameters when aiming to reconstruct the full spectrum of high- to low-frequency Holocene climate variability (Osborn & Briffa, 2004) and argue for a refinement of our methodological and epistemological understanding of dendroclimatology (Büntgen, 2019). Firstly, I outline why composite chronologies of tree-ring width and wood density measurements cannot capture multi-millennial climate variability; information which has been obtained from other geophysical proxies used in Holocene temperature reconstructions (Bova et al., 2021; Kaufman et al., 2020; Marcott et al., 2013; Osman et al., 2021). I then outline why tree-ring stable isotopes can reflect a more complete (i.e., colorful) picture of past environmental changes (i.e., including all spectral properties) compared to traditional dendroclimatic studies that consider tree-ring width and density measurements. Finally, I discuss future research priorities in high-resolution paleoclimatology.

2 | LIMITATIONS OF "GROWTH-DEPENDENT" TREE-RING PARAMETERS

Plant growth mainly depends on the availability of nutrients, carbon dioxide and light, as well as adequate amounts of water and warmth. Of these growth controlling factors, at least one constrains the vigor and survival of perennial plants at their species-specific distribution limit—known as "Liebig's Law." For instance, small temperature changes during the growing season can affect the width, density, and anatomy of xylem rings formed near the upper elevational or poleward latitudinal treeline (Körner, 2021). Yet, if surface temperatures would, hypothetically, increase over very long periods of time, and no other constrains would arise, continuously improving growing conditions would change biogeographic distribution patterns as well as physiological survival requirements accordingly. However, the principle of phenotypic plasticity and genetic adaptation, which is so important for the evolution of life on Earth, implies a biological boundary for tree ring-based climate reconstructions, as well as an epistemological challenge for paleoclimatic research. As a result, when growth limiting factors are utilized to reconstruct past climate or environmental conditions (Kapteyn, 1914), very long trends, far beyond the lifespan of individual specimens, are most likely missing. Though not directly relevant to the multimillennial-long trends found in raw tree-ring isotopes, climate signals in ring width and wood density must always be evaluated in the context of tree age and site ecology (Fritts, 1976). It is for this reason why ring width and density measurements, that is, "growth-dependent" tree-ring parameters, always require some sort of statistical age-trend removal before conversion into dimensionless climate indices (Briffa et al., 1992). The removal of age-related growth trends (Esper et al., 2003), however, may also eliminate an element of the expected abiotic information, both on timescales within and beyond the segment length of individual tree-ring samples (Cook et al., 1995).

3 | ADVANTAGES OF "GROWTH-INDEPENDENT" TREE-RING PARAMETERS

Rethinking is necessary if instead of more traditional "growth-dependent" ring width or wood density measurements, "growth-independent" tree-ring stable isotopes are employed in paleoclimatology. Comparable to the utilization of isotopic ratios from different terrestrial and marine archives in multi-proxy climate reconstructions (Konecky et al., 2020), the conceptual difference comes from the fact that plant growth is not a direct derivative of the isotopic composition of CO_2 and H_2O entering through stomata and roots. In other words, tree-ring stable isotopes primarily, and ideally, reflect the structure of their atmospheric, hydrospheric and/or geogenic resources; but not those of plant physiological factors. This independence between signal and proxy (i.e., "growth independent"), which is not the case for ring width and wood density (i.e., "growth dependent"), mainly pertains to oxygen ($\delta^{18}O$), and to a lesser extent to carbon ($\delta^{13}C$). Tree-ring stable carbon isotopes, however, co-depend on eco-physiological factors, such as stomatal conductance and photosynthetic activity that are both sensitive to soil moisture, air humidity and temperature (via vapor pressure deficit). Further complexity emerges from the fact that tree-ring $\delta^{13}C$, the concentration of which is also influenced by climate-induced changes in leaf size and the translocation of assimilates (i.e., the plant internal movement of photosynthetic products, such as sugar in the phloem) (Belmecheri & Lavergne, 2020), requires some degree of correction for atmospheric $\delta^{13}C$ depletion from anthropogenic emissions (McCarroll et al., 2009). Despite these challenges, tree-ring stable isotopes often do not require rigorous age-trend removal before their utilization in climate reconstructions (Büntgen et al., 2020). In fact, many studies have recently demonstrated the ability of $\delta^{18}O$ and $\delta^{13}C$ to reconstruct a wide range of climatic parameters at various spatiotemporal scales (see Saurer et al., 1997; McCarroll & Loader, 2004; Treydte et al., 2007; Loader et al., 2013; Belmecheri & Lavergne, 2020 for theoretical and methodological insights of how to use tree-ring stable isotopes for reconstructing climate).

Compared to ring width and maximum latewood density chronologies, which require substantially larger sample sizes and more careful site selection, the combined assessment of annually resolved and absolutely dated stable $\delta^{18}O$ and $\delta^{13}C$ isotopic ratios from α-cellulose samples of healthy trees, growing under non-extreme conditions (where traditional tree-ring parameters generally fail to capture distinct climate signals), can reveal a more nuanced picture of past climate variability on interannual to multimillennial timescales.

4 | IMPLICATIONS AND CONCLUSIONS

The limitation of "growth-dependent" proxy archives is most evident under the hypothetical scenario of constantly improving environmental conditions, such as a warmer and wetter climate, which would not result in infinite ring widths and wood densities. Despite this fundamental restriction, I am optimistic that the quality and quantity of historical, archeological and subfossil wood preserved for hundreds and thousands of years (with little to no degradation of cellulose), together with recent advances in ultra-high-resolution accelerator mass spectrometry, should allow new tree-ring stable isotope studies to extend over much of the Holocene. Whether the reconstructed climate trends will be in line with the estimated rate of orbital forcing known from other non-biological proxy records (Chen et al., 2015; Haug et al., 2001; Liu et al., 2014a) remains an open question. Since the climatic effects of long-term changes in the Earth's orbital parameters vary with season and latitude (Lücke et al., 2021), proxy-based summer reconstructions and model-based simulations may exhibit opposing temperature trends throughout the Holocene (Bader et al., 2020; Hartl-Meier et al., 2017).

New tree-ring stable isotope records are therefore expected to play an important role in resolving the so-called "Holocene Conundrum" (i.e., a yet unresolved discrepancy between proxy-based preindustrial cooling since around the "Holocene Climate Optimum" ~8000–6000 years ago, and transient model simulations that are indicative of a relatively warmer late Holocene during which global temperatures increased steadily) (Liu, Zhu, et al., 2014; Wanner, 2021). Nonetheless, caution is advised when information from "growth-dependent" and "growth-independent" tree-ring parameters is combined in multi-proxy network approaches, because reconstructing climate from different archives of diverse spatiotemporal resolution is challenging (von Storch et al., 2004). In a collective, cross-disciplinary effort, scientists should therefore aim to reconstruct the full range of high- to low-frequency climate variability, which is essential for providing realistic orientation for climate model simulations, and for understanding the relative contributions of natural and anthropogenic climate forcing factors.

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CONFLICT OF INTEREST
The author has declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT
Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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