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Dendrochronological advances in the tropical and subtropical Americas: Research priorities and future directions

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A B S T R A C T

This Special Issue presents recent advancements in tropical dendrochronology in the tropical and subtropical Americas, focusing on the identification of new species for dendrochronological studies, the assessment of climate information contained in tree-ring records, and systematic reviews of past research. The studies included in this issue significantly contribute to our understanding of tree species suitable for dendrochronology and the improvement of dating techniques. Moreover, they delve into the relationships between climate variables and tree growth, offering insights into the response of tropical forests to environmental change and providing tools for reconstructing past climate conditions. These studies also shed light on the challenges associated with accurately distinguishing annual ring boundaries in tropical species with complex anatomical structures and emphasize the importance of integrating complementary dating methods and visualization techniques to enhance the reliability of dendrochronological studies in the tropics. By synthesizing diverse research findings, this Special Issue offers a comprehensive overview of tropical dendrochronology in the American (sub) tropics, revealing gaps in knowledge, and suggesting potential avenues for future research. Ultimately, these advancements promote a deeper understanding of tropical forests, their role in the global climate system, and the need for their sustainable management and conservation.

1. Introduction

During the last few decades, significant advances have taken place in the field of dendrochronology in the tropical Americas. These advances have led to the identification of a number of tree species that are suitable for dendrochronology based on the presence of annual tree rings. Winter cambial dormancy due to decreased temperatures generally stimulates the formation of well-defined tree-ring boundaries in temperate and high latitude regions, but this is not the case in most of the tropics, where similar temperatures tend to prevail throughout the year. However, unfavorable environmental conditions during certain periods of the year, usually related to the hydrological cycle (e.g. wet/dry seasons), can cause cambial dormancy or a decrease in growth rate, resulting in the formation of annual growth layers in some tropical species (e.g. Borchert, 2000).

While several global reviews have described annual tree-ring studies in the world's tropics (Rozendaal and Zuidema, 2011; Brienen et al., 2016; Quesada-Román et al., 2022; Zuidema et al., 2022), with over 220 tree species with annual tree-ring formation reported for the Neotropics (i.e. Central America, the Caribbean, and South America) alone (Schöngart et al., 2017), the tropics remain significantly under-represented in tree-ring studies. This under-representation is evident from the

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limited coverage of tree-ring chronologies available (Fig. 1) in the International Tree-Ring Data Bank (ITRDB) managed by the World Data Service for Paleoclimatology from the National Oceanic and Atmospheric Administration (NOAA). There are 135 tree-ring studies within the tropics and subtropics (mostly in Central America) published in the ITRDB database and 19 newly developed tree-ring chronologies from 15 tree species (10 studies) have been reported in this Special Issue. Fig. 1 also shows 204 tropical and subtropical tree-ring studies identified by Quesada-Román et al. (2022), some of them overlapping with the tree-ring chronologies used in Zuidema et al. (2022). This relative scarcity of tree-ring data in the tropics shows that despite significant recent progress, substantial challenges still exist which preclude a balanced geographic representation of this proxy across the world's terrestrial ecosystems.

One of the key challenges of tropical dendrochronology lies in the visualization strategies used to accurately distinguish real annual ring boundaries from false rings. This fundamental step is especially challenging in tropical species that have complex anatomical structures, eccentricity of radial growth across the tree stem, and/or bimodal growth through the growing season, among other factors. These issues can all contribute to the formation of false rings. Additionally, integrating complementary dating methods can be critically important for independently confirming dendrochronological dates, especially for new tree species or known species in new locations. By combining additional dating methods and new visualization techniques, researchers can obtain a more comprehensive and accurate picture of the tree's growth history, improving the overall reliability and accuracy of dendrochronological studies in the tropics. It is important to note that there are a variety of tropical tree species that can likely not ever be useful for dendrochronology due to the absence of annual growth periodicity, at least with current methodological approaches.

2. Novel contributions from this Special Issue

This Special Issue compiles original research that illustrates recent, cutting-edge dendrochronological advances in the tropical and subtropical Americas. The sixteen papers include studies that can be broadly categorized into three main topics as follows:

1. The first topic involves identifying new tropical species with the potential for dendrochronological studies or improving the dating of previously identified species. These studies aim to expand our knowledge of tree species for tropical dendrochronology and to develop more accurate dating techniques to improve the reliability of tree-ring chronologies.
2. The second focuses on assessing the climate information contained in annual tree-ring records. These studies investigate the relationships between climate variables and tree-ring growth to better understand the response of tropical and sub-tropical forests to environmental

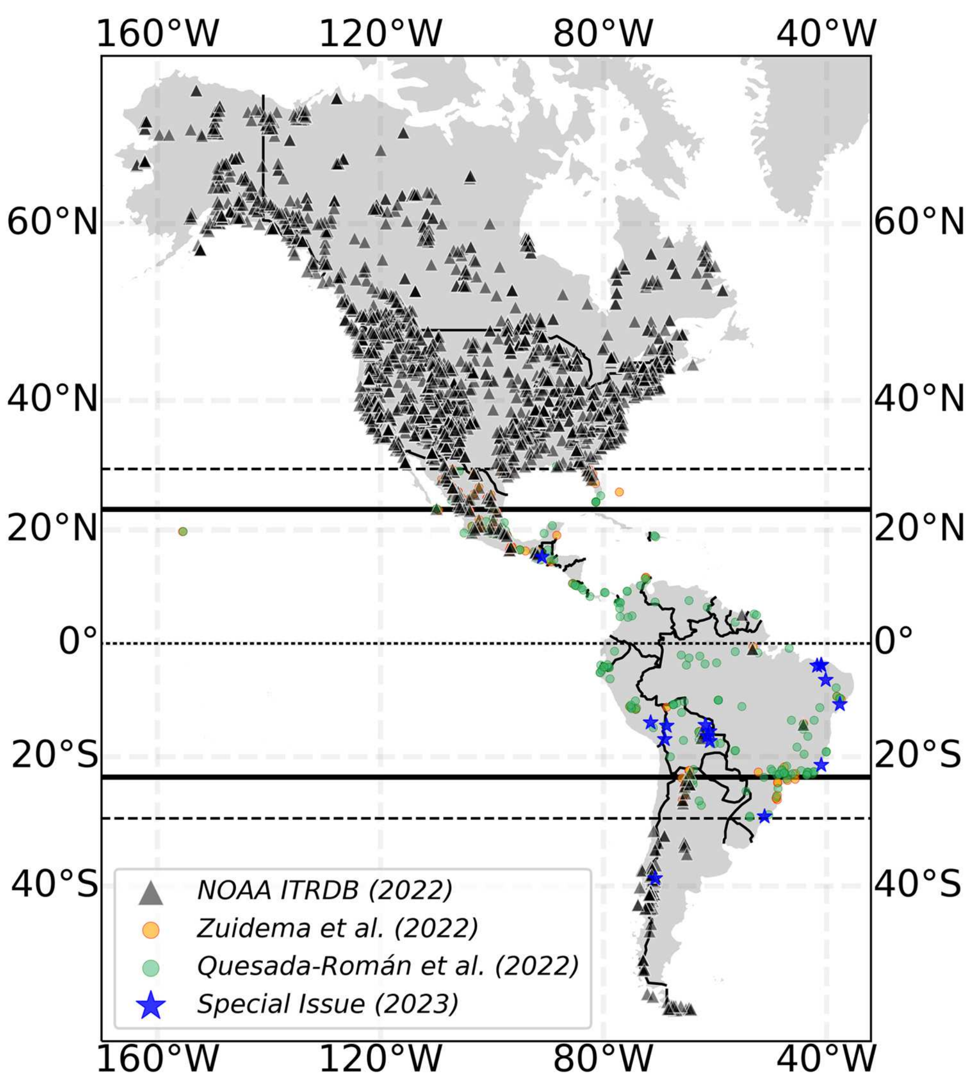

Fig. 1. Map of tree-ring chronologies available (black triangles) from the public archive International Tree-Ring Data Bank (ITRDB) managed by the World Data Service for Paleoclimatology from the National Oceanic and Atmospheric Administration (NOAA). Other tree-ring chronologies were reported in Zuidema et al. (2022) (n = 185, light orange circles), Quesada-Román et al. (2022) (n = 204, light green circles), and this Special Issue (n = 19, blue stars). The Zuidema et al. (2022) and Quesada-Román et al. (2022) datasets share some common records and include some chronologies on the ITRDB. Horizontal black lines represent the latitudinal limits of the tropics (~23°N and ~23°S, solid black line) and subtropics (30°N and 30°S, dashed black line).

change and to develop new tools for reconstructing past climate conditions.
3. The third involves systematic reviews of previous studies within the tropics. These two studies report findings of past dendrochronological research for the genus *Prosopis* and Peru, respectively, highlighting key knowledge gaps and areas for future research.

By bringing together these diverse studies, this Special Issue offers a comprehensive and in-depth overview of the current state of tropical dendrochronological research in the American tropics and a deeper understanding of the dynamics of tropical forests undergoing recent environmental change.

Additionally, this Special Issue highlights the potential for future advances in this field and promotes the use of dendrochronology as a valuable tool for studying these complex ecosystems. Ultimately, we seek to build upon our current understanding of tropical and subtropical forests and their role in the global climate system, and to promote the sustainable management and conservation of this natural heritage.

2.1. Topic 1: identifying new tropical tree species in the Americas

Six studies in this issue focus on identifying or improving the dating of new tropical species for dendrochronology, while also recognizing their potential for dendroclimatic studies. Quintilhan et al. (2021) showed how recent methodological advancements in tropical dendrochronological studies, such as X-ray densitometry, quantitative anatomy and other physical parameter measurements allow for a multi-proxy analysis of tropical species. In Ortega Rodriguez et al. (2022), the authors used wood density features and chemical elements (S, K, Ca, Mn) to improve the definition of annual ring boundaries and evaluate long-term growth and physiological patterns in 12 tropical tree species from non-flooded forests in the southern Amazon basin. Olmedo et al. (2022) examined the growth patterns of *Schizolobium parahyba* in areas south of its original distribution between latitudes 12°30'S and 30°15'S, analyzing intra- and inter-annual variations in primary and secondary growth. Their correlations with climatic variables were different compared to other studies in the tropics. In Rodríguez-Morata et al. (2022), the authors identified *Polylepis microphylla* as a tree species with annual tree rings. They also showed how quantitative wood anatomy fosters a significant advance in the field generating intra-annual measurements and quantification of anatomical traits within tree rings that provided promising new proxies to reconstruct climate variability in the region. In Ticse-Otarola et al. (2023), the authors analyzed the growth patterns of the recently identified high Andean tree species *Polylepis rodolfovasquezii*, confirming annual radial growth rings and strong climate sensitivity, while highlighting the need for an extensive *P. rodolfovasquezii* tree-ring network for ecological and paleoclimate studies in the tropical Andes. Finally, Oelkers et al. (2023) revealed the annual rings and climate sensitivity of *Juglans boliviana* and thus its suitability for dendrochronological studies.

Overall, two new species joined the list of species with great potential for dendrochronology in the tropical Americas and four studies assessed the potential of new chemical and anatomical features of tree rings to improve calendar dating in the tropics.

2.2. Topic 2: potential for tropical and sub-tropical American tree-ring studies of past climate variability

The eight studies in this section detail our improved understanding of climate signals embedded in tropical tree species. These studies explore the relationship between climate variables and tree-ring growth to develop more accurate dendroclimatic reconstructions of past climate conditions in the tropics. By deciphering these climate signals, these studies provide valuable insights into how tropical forests respond to environmental change over time.

Muñoz-Salazar et al. (2022) showed how *Austrocedrus chilensis*, a South American conifer widely used in tree-ring studies, has the potential to record intra-annual anomalies such as frost events. They found that tree age is a determinant factor affecting the ability of trees to record frost rings, with the maximum frequency occurring at 12 years and the maximum age at which 95% of total frost injuries occurred being about 120 years. Penchenat et al. (2022) examined the use of stable carbon and oxygen isotopes in the cellulose of *Araucaria araucana*, another South American conifer whose tree-ring patterns have been interpreted already from a climate perspective. They assessed the potential of these isotopic parameters for reconstructing past climate variability in the Andes, finding a strong correlation between the carbon isotopic composition and temperature and the vapor pressure deficit of the current growing season. Crispin-DelaCruz et al. (2022) developed a 400-year tree-ring width chronology of the highest-elevation tree species worldwide, *Polylepis tarapacana* from southern Peru, which shows high sensitivity to prior summer precipitation and current year temperature, and a strong positive relationship with the El Niño Southern Oscillation (ENSO) during the current growing season. In Aragão et al. (2022), climate-growth responses were assessed across rainfall gradients in seasonally-dry tropical forests in Northeastern Brazil, finding that precipitation is the main growth-influencing factor. The authors pointed out that dry forests are the most sensitive to drought, suggesting potential vulnerability to future climate change. In Menezes et al. (2022), the authors demonstrated the influence of edaphoclimatic variables and ocean teleconnections on *Cedrela odorata* growth in the seasonally-dry tropical forests of northeastern Brazil, highlighting the importance of tree-ring studies in understanding how these forests respond to climate variations. In Campbell et al. (2022), the authors investigated the dendroclimatological potential of *Paratecoma peroba* in the seasonal semi-deciduous forest in Rio de Janeiro, Brazil, characterizing tree-ring anatomical structures, and identifying precipitation and temperature as the climatic factors that influence this species growth. In López et al. (2022), annual growth rings of *Amburana cearensis* trees were used to estimate temporal and spatial patterns of climate variability in the transition from the dry Chiquitano to the humid Guarayos-southern Amazon forests, revealing that tree growth is sensitive to moisture balance and can record subtle differences in regional precipitation trends across the dry to humid forest transition. In Pons and Rao (2023), tree-ring data from *Abies guatemalensis* was used to reconstruct the streamflow of the Samala River in Guatemala over 125 years, revealing ENSO's influence on streamflow variability and the potential for future use in watershed management.

Collectively, these studies improve our knowledge of the climate signal of tropical tree species and indicate that there is much potential to reconstruct past climate variations at annual to sub-annual resolution in the tropical Americas. Continued improvements in the tropical tree-ring data network will help to fill the gap in low latitude terrestrial paleoclimate studies with annual resolution.

2.3. Topic 3: reviews of tropical American dendrochronology

Finally, two articles present systematic reviews of the state of dendrochronology in tropical and sub-tropical South America. In Ambite et al. (2022), a review of 40 publications from 1931 to 2022 highlights the unique affinity of *Prosopis* species to arid conditions and the use of tree rings as a proxy for historical droughts and variability in the water table depth, while also suggesting opportunities to expand research to more humid climates and incorporate new techniques. Another review by Portal-Cahuana et al. (2023) highlights dendrochronological studies in Peru, summarizing studies using 20 families, 34 genera, and 52 tree species, focusing on climatic reconstruction, forest conservation, and management, while identifying sampling gaps in climatic and geographic complexity.

3. Current challenges, research priorities, and future prospects

In the following sections we briefly review some of the opportunities and current challenges for advancing dendrochronological applications in the tropical Americas, and define research priorities and prospects.

3.1. Improving visualization of tropical tree-ring boundaries

Visualizing annual tree-ring boundaries in the tropics presents a unique challenge partly due to variations in environmental conditions that affect tree growth in the lower latitudes. As noted above, distinct seasonal changes and cold temperatures at higher latitudes contribute to produce well-defined growth rings, whereas many tropical trees often feature less distinct ring boundaries due to a less marked dormant season in association with weaker temperature seasonality.

One approach for improving tropical tree-ring boundary visualization is the use of **Quantitative Wood Anatomical (QWA)** techniques. QWA methods combine high-resolution imaging and digital image analysis of histological cuts (xylem microsections) to enhance the visibility of subtle differences in density or cell structure within the rings. This approach may require specialized software to quantify differences in brightness, contrast, or color between different parts of the tree ring to develop QWA trait chronologies with annual and intra-annual resolution (von Arx and Carrer, 2014; Prendin et al., 2017); the pioneering *Polylepis microphylla* QWA records presented in this Special Issue being a good example (Rodríguez-Morata et al., 2022). The analytical observation of high-quality microsections of transverse stem cuts has recently demonstrated that very subtle anatomical structures are useful traits to define tree-ring boundaries, which under classical methodologies (based on observing sanded samples under a stereomicroscope) may pass unnoticed (Pacheco-Solana et al., 2023).

In additon to wood anatomical analyses, **X-ray fluorescence (chemical)** and **X-ray densitometry** techniques also proved useful for better visualizing the tree-ring annual boundaries in tree species. Ortega Rodriguez et al., 2022 combined various anatomical, densitometric, and chemical data via wood anatomical analyses. Quintilhan et al. (2021) also demonstrated the value of histological cuts and X-ray densitometry for accurate visualization of tree-ring boundaries. X-ray densitometry is less laborious and time-consuming than long histological cuts of the stem tissue. Density profiles are obtained by scanning a wood sample with an X-ray beam, which is absorbed to different degrees by the wood and transformed into a density value by the sensor. This process produces a continuous, precise and accurate output that can be superimposed to the QWA series to help identify true tree-ring boundaries.

Yet another very promising methodology that has been recently developed to overcome the problem of tree-ring boundary visualization is the so-called **wood autofluorescence**. By using specific wavelengths from the multispectral light emitted by a fluorescence stereomicroscope such as green fluorescent protein (GFP), red fluorescent protein (RFP), or UV filter, it is possible to enhance the visualization of wood anatomical features in comparison with visualization using natural light. Fluorescence can help visualize growth-ring boundaries in tree species with previously indistinct growth rings under natural light. In addition to aiding in the identification of false rings in species with clear tree-ring boundaries such as *Cedrela fissilis* and *Hymenaea courbaril* (Godoy-Veiga et al., 2019), this method has the potential to be used for other wood anatomical analyses. For instance, wood autofluorescence can be employed for wood identification and automated measurements of anatomical features, further broadening its utility beyond the identification of tree-ring boundaries.

These are just some of the key methodologies that are proving to be valuable tools for scientists grappling with challenges related to tree-ring identification and cross-dating, especially in the tropics where tree-ring visualization can be particularly challenging.

3.2. Low common variability within and between individuals

Even if tropical tree species present visible ring-like structures, they often do not represent annual growth, and thus they are not suitable for dendrochronology. To ensure accurate dating of each ring in a sample, it is essential to consider other factors such as a shared common growth pattern among individuals within a stand.

Crossdating is a critical step to ensure that tree-ring samples are well dated (Stokes and Smiley, 1968) and it is fundamental, even in the tropics, when the agreement among growth patterns can be lower for some tree species. The identification of pointer years regarding the width of the rings (i.e. extremely narrow or wide) and/or the appearance of particular rings, together with the observation of analogous growth patterns among trees in certain decades, is the way to be certain that each individual ring is correctly assigned to a calendar year according to dendrochronological techniques. Any attempt to simply mark boundaries and measure the width of the rings without a comparison among samples within the same tree and among several trees within a site will very likely result in incorrectly dating the material, thus producing tree-ring chronologies without absolute precise calendar dates.

Because many tropical species have irregular radial growth along the stem, the application of crossdating techniques can be quite difficult, particularly when processing cores instead of whole cross-sections. First, poor agreement among radii of the same tree is often noted because the width of a particular year can be very variable. This width variability of a ring along the stem could be associated with the eccentricity of non-cylindrical trunks and/or the fact that tree-ring width is not consistent along the trunk circumference. The latter can take place in cylindrical trunks as well. This makes crossdating very challenging because the ‘width’ is not always a useful parameter for the identification of a particular ring along the circumference (i.e. lack of circuit uniformity). Second, distinguishing false from true ring boundaries under the microscope can become very difficult when using cores as only a small portion of the radial growth of a tree is visible and anatomical traits can appear similar between different rings. In many cases, only a cross-sectional slab allows for accurately identifying real from false rings based on the continuity or discontinuity, respectively, of the cellular traits defining the ring boundaries along the circumference. False rings can be identified in a cross section since the boundary lines visually defining rings can be very evident in some portions of the slab but become blurred or even fade in others. A real ring will always be continuous along the circumference, or if absent in some portion of the slab, its boundary will be continuous and clearly merge with the previous tree-ring boundary (i.e. partially missing ring).

Herrera-Ramirez et al. (2017) showed that a tree-ring chronology with some misdated tree-ring series erroneously included still held some common growth variability (albeit in the low range of significance) and even recorded a coherent climate signal. This finding suggests that when the amount of variance shared by the trees from a particular stand is on the lower range of significance, statistical procedures to validate dating, as those used in Cofecha (Holmes, 1983) for example, can abide some flaws. The inclusion of misdated tree-ring series in a chronology cannot really be condoned however. Therefore, when building tropical tree chronologies with new species or sites, crossdating must be checked both visually and statistically, and further, when common ring-width variability among trees is low, additional independent validation of calendar dating is recommended.

3.3. Complementary dating tools

Despite the overwhelming evidence that some tree species form annual rings in tropical regions, due to a myriad of complexities, in some cases it is advisable to use a variety of visualization (see sections above) and/or additional dating techniques. The integration of independent dating tools is particularly important when developing chronologies for new sites or species to ensure that the calendar dates provided by dendrochronological methods are accurate.

One popular method for dating validation in tree rings relies on using the mid-20th century nuclear bomb pulse signature in modern atmospheric radiocarbon records (Hua et al., 2013) that serve as a temporal reference for atmospheric transport and relative radiocarbon uptake in the terrestrial biome. Hua et al. (2021) recently published an updated dataset of calibration curves representative of atmospheric radiocarbon variability in the Northern and Southern Hemispheres from 1950 to 2019, defined by the extraordinary peak of tropospheric radiocarbon caused by nuclear bomb testing in the mid-20th century. This monthly-resolved compilation includes radiocarbon data from both in-situ air measurements and tree-ring records across the globe and has been used as a reference tool for dating.

Several tree-ring studies in South America have benefited from using radiocarbon analyses as a tool for dating rings from complex neotropical wood. Radiocarbon measurements of tree-ring cellulose have confirmed the calendar dates assigned via traditional dendrochronological approaches (Andreu-Hayles et al., 2015; Santos et al., 2020; Rodríguez-Morata et al., 2022; Giraldo et al., 2023), contributed to the detection of missing or false rings (Pacheco-Solana et al., 2023; Oelkers et al., 2023), or clarified that well-defined rings did not represent annual growth increments (Herrera-Ramirez et al., 2017; Baker et al., 2017).

The Schulman convention (Schulman, 1956) has been widely applied in studies in South America to assign the most recent complete ring to the calendar date when the tree start growing. It considers that in the Southern Hemisphere, the growing season usually spans through two calendar years with different onsets and terminations from approximately the austral Spring (i.e. September to December) to the austral Fall (i.e. March to June). However, across the tropical Americas, there are sites with different growing season lengths depending on latitudinal and altitudinal gradients, and thus some trees can start growing from January onwards during the current calendar year. In these cases, perhaps the Schulman convention should not be used. Some authors have opted for not applying the Schulman convention, as for instance in a *Cedrela odorata* chronology located near the equator in Brazil, where most of the growth took place during the wet season from February to July (Granato-Souza et al., 2019). Following these criteria, the application of the Schulman convention may be entirely relevant to when xylogenesis and ring formation start. Still, it can be argued that Schulman should be applied to all the chronologies from South America regardless of the growing season to follow the 1956 convention and avoid potential confusions. Nevertheless, careful documentation of the dating strategy is needed on a case-by-case basis. This topic should be reviewed in-depth by our scientific community to reach an agreement of good practices as we move forward with generating more chronologies in the tropics.

In the tropical Americas there are still many tree species with unknown seasonal information that impede the determination of the onset and termination of tree growth that defines the length of the growing season. Information regarding the timing of wood formation can be gathered through permanent plots (e.g. RAINFOR, rainfor.org) and/or dendrometers, together with phenological observations, or experiments including weekly micro-core extractions or cambial wounding. It is necessary to conduct these types of studies in the tropics to know whether the radial growth onset occurs at the end or at the beginning of the calendar year in tropical species, and thus to unequivocally assign the calendar year to the ring closest to the bark, always noting if the Schulman convention (1956) is applied.

3.4. Tree longevity, biodiversity, and replication in the tropics

Replication, or the number of trees used to form a robust tree-ring chronology, is crucial for accurately representing the environmental signal shared by individual trees in a stand. However, in a typical highly diverse tropical forest, finding enough trees of the same species in a particular location can be challenging. As we increase the sample depth of our chronologies and the spatial coverage of chronologies across a region, we can better establish the calendar dating of specific sites and also use the growth agreement among site chronologies within the network as an additional validation of the calendar dates assigned. Tropical and sub-tropical tree-ring networks across South America are definitively expanding, and these efforts will contribute to filling knowledge gaps in the region.

With high rates of deforestation in some regions, the average age of the remaining forests is limiting the potential length of the tree-ring records in the tropical Americas. This is exacerbated by the intrinsic characteristics of tropical species, effects of climate change, and further anthropogenic disturbances such as forest fires, firewood collection and agriculture, to name but a few. Current records based on tree-ring studies show that some tropical lowland trees can live up to 600 years old, with rare older exceptions; but the average age of these tropical trees is 186 years old, which is about half of the observed in temperate regions (Locosselli et al., 2020b). Quesada-Román et al. (2022) reported in a global review of 459 dendrochronological studies between 30°N and 30°S that tree species average age was approximately 200 years old, with a mean age of 132 ± 129 for 218 sites located in low latitudes across the Americas.

In addition to the prospects of decreased longevity of many tropical species due to global warming and intensification of the dry season, there is considerable anthropogenic pressure across the region caused by communities that traditionally use forest resources for various activities. Such relative absence of old-aged trees, for instance, is common across the tropical Andes, where finding trees older than 200 years is quite rare nowadays. *Polylepis tarapacana*, a multi-century long living tree species located in semi-arid high-altitude environments in the Altiplano (Morales et al., 2020), is an exception (Quesada-Román et al., 2020). Overall, it is remarkable that human settlements can be found in even the most remote and inaccessible locations, with significant impacts on the surrounding natural areas. For instance, in Peru, fire and logging activities are impacting the high elevation Andean *P. rodolfovasquezii* forests (Ticse-Otarola et al., 2023). Forest harvesting activities commonly encourage the felling of long-lived trees by implementing minimum cutting diameter limits as defined by local laws (FAO and WRI, 2022), while typically not imposing maximum limits. In Bolivia, *Amburana cearensis* forests, for instance, are also affected by the expansion of monocultures and intensive cattle ranching (López et al., 2022). Overall, human activities led to a reduction of forests' natural distribution and a decline in the mean average age of trees.

As the lifespan of trees in tropical regions is often limited, with few exceptions, the creation of long tree-ring records may require an intensive search for ancient samples beyond the actual natural living forests. Subfossil tree material can be found well preserved in lake sediments or gravels, for example, as well as in very dry arid environments. Dendroarchaeology, which involves the study of tree-ring patterns in timbers from historical structures, is also a promising avenue. This discipline offers the possibility of generating chronologies covering older time periods, spanning decades, several centuries, or even millennia, thereby providing valuable insights into past climatic and environmental conditions. Additionally, these studies will also contribute to the knowledge of cultural heritage (Miyahara et al., 2022) by providing accurate dating of constructions and historical artifacts, for example from pre-Columbian times in the central Andes (Morales et al., 2013).

3.5. Timber tracing

Illegal logging and trade are main drivers of forest degradation (IUFRO, 2016) and cause a financial loss of $6 to $9 billion per year in potential fiscal revenues (World Bank, 2019). Some of the international policies to fight this practice are the European Union's Forest Law Enforcement, Governance and Trade (FLEGT) action plan, U.S. Lacey Act, Australian Illegal Logging Prohibition Act, and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). However, the implementation of these policies requires expertise in species identification and knoweldge of geographical origin of the timber. Identification methods used to date include genetics (Honorio Coronado et al., 2020), mass spectrometry (Deklerck et al., 2019), near-infrared spectroscopy (Bergo et al., 2016), stable isotopes (Förstel et al., 2011), chemical elements (Boeschoten et al., 2022), wood anatomy (Wheeler, 2011), and dendrochronology (Akhmetzyanov et al., 2020).

Through the analysis of temporal variation of tree-ring width timeseries and the comparison of their spatial patterns, dendroprovenancing shows great potential for the identification of timber origin (Bridge, 2012). As more tree-ring chronologies become available, dendroprovenancing approaches appear to be a possible method for determining the forest or site of origin from which the illegal logs were extracted. In the following years, it may be possible to combine dendroprovenancing techniques with other methods currently being developed. For example, stable isotopes (Kagawa and Leavitt, 2010; Paredes-Villanueva et al., 2022) and rare earth and trace elements (Hajj et al., 2017; D'Andrea et al., 2023) could become effective tools for timber tracing.

3.6. Reconstructing past hydroclimate

In the Americas, especially in the deep tropics close to the equator, climate-sensitive tree-ring width chronologies are still very limited in length and spatial coverage (Fig. 1). Regional hydroclimate reconstructions for tropical South America have been mostly produced from the ancient *Polylepis tarapacana* living in the semiarid Altiplano (Crispín-DelaCruz et al., 2022; Morales et al., 2023), although some other tree species have also been used from the genus *Juglans* and *Cedrela* from montane forests (Layme-Huaman et al., 2018; Humanes-Fuente et al., 2020), or *Cedrela odorata* from the Brazilian Amazon (Granato-Souza et al., 2020), to mention a few. Nonetheless, the tree-ring width chronologies used to generate the South American Drought Atlas (SADA, Morales et al., 2020) were almost entirely located in subtropical and temperate latitudes, limiting the northern extent of the SADA product to latitudes higher than 18°S due to the absence of long tree-ring records in the deep tropics.

Stable oxygen and carbon isotopes in tree rings are a very powerful tool to reconstruct tropical and sub-tropical climate variability (e.g. precipitation, temperature, Vapor Pressure Deficit) in the austral summer season. In the tropics, tree-ring stable oxygen isotopes record a very strong signal of hydroclimate variability during the current growing season, whereas the signal in ring-width is expressed in the previous year season (Rodríguez-Caton et al., 2021). The potential of tree-ring stable oxygen isotopes to provide annually-resolved information on past hydroclimate changes has been demonstrated for precipitation over the Amazon during the wet (Brienen et al., 2012; Baker et al., 2015; Volland et al., 2016; Baker et al., 2022; Ortega Rodriguez et al., 2023; Vargas et al., 2022) and dry seasons (Cintra et al., 2022). Tree-ring stable oxygen isotopes have also been related to local and regional hydroclimate in semiarid regions of northeastern Brazil (Pagotto et al., 2021), the Atacama in Chile (Olson et al., 2020) and the Altiplano (Ballantyne et al., 2011; Rodríguez-Caton et al., 2022).

Given the influence of ENSO on hydroclimate variability in this region, tree-ring stable oxygen isotopes are positively correlated with sea surface temperatures in the tropical Pacific Ocean (Brienen et al., 2012; Volland et al., 2016; Rodríguez-Caton et al., 2022). Therefore, there is the promise to use this proxy beyond local and regional climate (e.g. to reconstruct aspects of ENSO) and inform about large-scale processes related to global atmospheric circulation as well.

There are still underexplored research avenues, including the measurement of stable oxygen isotopes in stem cellulose, which could help establish interannual rhythmic growth patterns. This may assess inter- to intra- annual resolution climate variability (Locosselli et al., 2020a), and it can be particularly useful in areas with less pronounced seasonality and consequently, an absence of clear tree-ring boundaries (Evans and Schrag, 2004; Giraldo et al., 2022). Furthermore, studies on plant physiology and dendroecology could benefit by measuring isotopes in tree rings, but these studies are still very scarce in the tropical Americas (Gómez-Guerrero et al., 2013; Rodríguez-Caton et al., 2021).

3.7. Natural hazards and risk mitigation

The area of Latin America and the Caribbean is the second most disaster-prone region in the world, with 152 million people affected by 1205 disasters between 2000 and 2019 (OCHA, 2020). Among them, floods are the most common natural hazard in the region, followed by tropical storms and hurricanes, earthquakes, droughts, landslides, wildfires, extreme temperatures and volcanic events (OCHA, 2020). The assessment of current natural hazards requires a record of the number and magnitude of past events at a site. When this information is not available, natural archives that remain in the landscape such as tree rings can preserve evidence of past events associated with calendar dates with annual or sub-annual resolution over recent centuries (Stoffel et al., 2010). Evidence for past natural disasters represented in tree-ring series may include mechanical damage such as exposed roots, tilted trunks, mutilated branches and scars, with the combined effect of all these injuries leading to a specific response in tree growth pattern (Stoffel and Wilford, 2012). In addition, there can be chemical changes in the wood such as a shift in the concentration of metals following a volcanic eruption (Alfaro-Sánchez et al., 2020).

Most tree-ring studies on natural hazards have focused on alpine environments in Europe and North America, whereas other parts of the world and ecosystems have been widely neglected by researchers so far (Stoffel and Bollschweiler, 2008). Specifically, in Latin America, to the best of our knowledge, very few studies have been carried out. Some notable examples are the analysis of landslides in subtropical Argentina (Paolini et al., 2005) or the reconstruction of snow avalanches in Patagonia (Casteller et al., 2017; Mundo et al., 2007). In the tropical America, these studies are also scarce. Some recent examples include in Mexico a reconstruction of lahar events in the Pico de Orizaba volcano (Franco-Ramos et al., 2020) and the assessment of volcanic activity at the treeline of the Popocatepetl volcano (Alfaro-Sánchez et al., 2020), and in Costa Rica the reconstruction of past flood events in the General River (Quesada-Román et al., 2020). The reason for this scarcity is probably related to the inherent difficulties of dating tropical trees (Silva et al., 2019) and the paucity of old individuals. However, in recent years, the incorporation of new species with proven annual resolution and visible rings suitable for dendrochronological studies in the tropical Americas, together with the development of new methodologies and diversity of tree-ring proxies, is opening up new horizons for tree-ring studies. We therefore encourage researchers to focus on these new tree species and explore their potential to develop tree-ring based natural hazards research that will facilitate future mitigation strategies.

3.8. Urban dendrochronology

Tree-ring analysis in urban trees represents a relatively new area of research for dendrochronologists. Historically, such studies have been discouraged due to the myriad of influences the urban environment exerts on tree growth, which can potentially limit the traditional applications of dendrochronology to urban trees in these areas (Schweingruber, 1996). However, recent studies covering a broad spectrum of climate conditions and city sizes illustrate the potential of urban dendrochronology to promote academic advances and support evidence-based decision-making in urban planning (Miyahara et al., 2022). Management plans for urban trees can be improved based on tree-ring data, which provides information on tree ages, changes in growth rate due to senescence, and tree responses to climate extremes and air pollution (Albayrak et al., 2020; Battipaglia et al., 2010).

In South America, the vulnerability of urban tree species to climate and air pollution has been evaluated in cities in Brazil (Canetti et al., 2017; de Vasconcellos et al., 2019; Locosselli et al., 2018) and Chile (Moser et al., 2018; Pretzsch et al., 2017). Other applications assess urban risks such as the impact of drought on water supply in the city of São Paulo, Brazil (Locosselli et al., 2020a), and changes in the chemical composition of the urban environment mainly due to air pollution in Mexico City and San Luis Potosi, Mexico (Beramendi-Orosco et al., 2013; Geraldo et al., 2014) and São Paulo, Brazil (Locosselli et al. 2018). The use of dendrochemistry (i.e. the study of the chemical composition of tree rings), is the main application of urban dendrochronology to date (Miyahara et al., 2022) and can support public health by establishing the nexus between sources of pollution and health outcomes (Sheppard et al., 2007). In South America, these applications still lag behind than in other continents (Miyahara et al., 2022), despite the great potential of native and exotic tree species that produce tree rings in South American cities. Local urban planning would very likely profit from local tree-ring studies in the coming years.

3.9. Investment of resources

There remains a scarcity of tree-ring records from subtropical to inner tropical regions. In addition to the aforementioned intrinsic challenges, tropical regions have historically received fewer resources than temperate regions, particularly in Europe and North America. The under-representation of tree-ring data from the tropics is partially due to the lack of accessibility to information, funding, and resources for scientists from these regions (Zhao et al., 2019), highlighting a 'spatial bias' and inequities among regions. There is a need to increase the awareness of these knowledge gaps in the tropics among the scientific community and policy-makers in order to improve the homogeneity of coverage of tree-ring research worldwide.

Despite the various challenges of tropical dendrochronology, investing additional resources from national and international funding agencies is warranted. With tree species now proven suitable and more methodological approaches available, there is currently a momentum for investing significantly more resources to conduct field campaigns for sample collection and lab processing to generate new records. Furthermore, there is an urgency to act quickly to salvage these precious tree-ring archives due to the increasing anthropogenic pressure on old-growth forests with logging, mining, and other activities.

Ongoing and future projects should also include training for local students, and opportunities for professional development for researchers from local institutions. Strategies that guarantee trained students and researchers to continue dendrochronological studies in the long-term should be implemented beyond the duration of particular projects or specific workshops. By funding more studies and training more local researchers in the coming decades, we can expect that inequalities in access to information and knowledge production will be reduced or even disappear in the tropical Americas.

4. Conclusions

Despite early perceptions that tropical dendrochronology was not feasible, significant progress has been made in the past 20 years, demonstrating the potential of this field (Worbes, 2002). It is now widely acknowledged that certain tropical tree species do indeed form annual rings. Nevertheless, there remains a need for further progress in establishing a more extensive and well-replicated network of multi-centennial tree-ring records, particularly in the inner tropics, where records longer than 250 years are quite rare (Locosselli et al., 2020b; Quesada-Román et al., 2022).

In some cases, visible tree-ring boundaries may not accurately represent annual rings, especially when there is limited agreement among tree growth patterns. Consequently, conventional dendrochronological methods may not yield optimal results in such situations. Yet, several studies show the utility of using complementary dating techniques to verify annual dating (e.g. Baker et al., 2017; Herrera-Ramirez et al., 2017) combined with new visualization methodologies (e.g. Oelkers et al., 2023; Pacheco-Solana et al., 2023) in the inner tropics. The reported experiences detailed in this Special Issue suggest a thorough revision of some tree-ring sites claimed as annual records that may be included in global and regional reviews.

Technological advances, as showcased in this Special Issue, provide valuable tools for improving tree-ring identification and are in fact essential for the successful dating of many challenging tropical tree species. As outlined here, these tools have the potential to significantly advance the field of tropical dendrochronology in the coming years and enhance its application for the environmental sciences.

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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.

Data availability

No data was used for the research described in the article.

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