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Improved tree-ring archives will support earth-system science

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Abstract

Macroecological studies increasingly benefit from global tree-ring datasets to complement and contextualize shorter-term observational and modeling investigations of forest ecosystems. Yet, considerable community efforts are needed to enhance and sustain the aptitude of this resource for the next decades. We overview the largest public tree-ring archive and advocate for improved i) spatiotemporal coverage of

forest biomes, ii) coordination with recent *in-situ* networks, and iii) consideration of broader research needs.

Main text

Most tree species in seasonal forest ecosystems undergo a regular dormancy that results in the demarcation of annual growth increments. Such tree-rings have been used to derive millennial-length records of forest growth variability and are highlighted in the past several IPCC reports as an important resource to reconstruct pre-instrumental climate. Yet, in light of Earth's reasonably assured climate trajectory, research focus is shifting from pure quantification of climate change towards the understanding of its impacts on ecosystems. Exploring the key question of how forests will respond to unprecedented environmental conditions, extensive compilations of tree-ring data have recently been used to study climate impacts on annual forest growth[1], track biome shifts[2], assess legacies of climate extremes[3], quantify tree physiological responses to climate[4], and benchmark mechanistic models[5]. Owing to public archives such as the International Tree-Ring Data Bank (ITRDB; US National Oceanic and Atmospheric Administration), it is increasingly feasible to tackle these topics along large environmental gradients and at (sub-)annual resolution. Given the growing demand for extensive observational datasets, we find it prudent to briefly pause, take inventory of the ITRDB, and evaluate emergent challenges and opportunities for this archive to continue serving the research communities for the next decades.

The ITRDB currently lists more than 850 contributors and contains tree-ring data from 4200 sites on six continents. The total ring width parameter is available at nearly all sites. Additional parameters (sites) include: earlywood and latewood width (614 and 616), maximum wood density (581), and stable isotope measurements (24). The most common genera are *Pinus*, *Picea*, and *Quercus* that together represent 50% of the ITRDB. The number of available chronologies peak in the mid 20th century and plummets dramatically thereafter: 44% terminate prior to 1990, 77% before 2000, and 98% before 2010. The negative consequences of this drop for palaeoclimatological applications and the need to regularly update existing chronologies have already been pointed out[6]. However, we emphasize the reduced geographic and climate space covered in the most recent decade (Fig 1b,c) that increasingly limits possibilities to integrate the global tree-ring network with newer but shorter-term observations.

The reduced coverage of tree-ring data towards present particularly contrasts with spatially and temporally highly resolved data from satellite retrieved Earth observations (EO; Fig 1a). Large initiatives established by NASA's decadal survey, the Climate Change Initiative of the European Space Agency (ESA), and other programs have fostered technological and scientific progress to monitor vegetation dynamics since the early 1980s[7]. This EO boom is relatively recent in the context of long-term climate change and is expected to dramatically boost with the latest generation of satellites (*e.g.* the ESA Sentinels). However, most currently existing EO records are relatively short when the aim is to contextualize the full range of ecosystem variability. For instance, it is statistically very problematic to address infrequent extreme events at given locations. Provided sufficient spatiotemporal coverage can be achieved and maintained[6], tree-ring records offer opportunities to contextualize EO data on such events by reflecting climate-induced tree growth anomalies over decades to centuries. Further opportunities emerge from comparisons between radial stem increment and canopy dynamics derived from EOs (Seftigen et al., under review) or other *in-situ* measurements related to forest growth, including phenocams, eddy-covariance, and forest inventory type data[8,9]. Regrettably, tree-ring sampling is not standard in most national forest inventories (NFI) – a hitherto missed opportunity to develop continuous records of forest biomass increment at large scales. We expect advances into this direction will enhance the spatial coverage of tree-ring archives, support forest management decisions in a changing climate, and help refining quantifications of terrestrial carbon cycling.

By integrating tree-rings with EOs and other *in-situ* networks across biomes, systematic coverage of forests in terms of climate zones, species composition, and forest demography becomes a reachable goal. Yet, the ITRDB currently does not fully meet this ambition, despite the remarkable coverage of the climate space with MAT < 15 °C (Fig. 1b). Representativeness is likely reduced because site selection has favored marginal growth environments to maximize the climatic signals preserved in tree-ring records – a bias that potentially affects conclusions drawn from large-scale studies. This bias is particularly problematic given that few EOs and gridded climate products resolve these very local conditions. Computational options to improve the spatial coverage of tree-ring data include statistical upscaling with machine-learning techniques, whereby climate variables selected based on observed climate-growth relationships are used to hindcast radial tree growth in areas without existing records. Promising results have also been achieved with process-based modeling approaches to produce synthetic tree-ring records based on relatively simple and globally available input parameters[10]. Still, global tree-ring networks will never be able to keep up with EO acquisition in near real time and priorities regarding locations and parameters for future research efforts need to be set. We recommend that these priorities should:

1) *Strengthen systematic coverage of forest biomes* through targeted sampling efforts and rapid contribution of new records to the ITRDB. We suspect that more open data policies could already amend the presently unbalanced geographic distribution of ITRDB sites (Fig 1c) and thereby increase the use of tree-ring data for global environmental change research. Upcoming field campaigns should increasingly consider the direction of predicted climate change to augment the particularly modest data coverage in warmer regions (Fig 1b). As this concerns many remote (sub-)tropical areas, intensified international collaborations are required to overcome logistical barriers to sampling these highly productive and rapidly diminishing forests. Collecting tree-ring and biometric data should thereby be more feasible than *e.g.* installing longer-term research sites that are equally sparse in the tropics[11]. Although a constraint on tropical dendrochronology is the unknown rhythm of growing and dormant seasons in many species, regular annual growth rings have already been confirmed in 230 species[12].

2) *Increase coordination with more recent observation networks* such as FLUXNET, NEON, ICOS, and NFIs. Adjusting tree-ring data collection to meet broader needs will bring mutual benefits among research communities but requires versatile sampling schemes. Furthermore, the sparse metadata associated with sites on the ITRDB should be extended to include key variables common to national forest inventories (*e.g.* stand density, tree species, dimensions, and demography). Efforts are under way to facilitate and standardize the collection and archiving of such information[13]. This will

increase site control, data compatibility, and possibilities to estimate broadly relevant parameters such as annual biomass increment.

3) *Promote measurements of parameters beyond radial growth increment*. Continuous advances in wood anatomical, stable isotope, and image analysis technologies allow for increasingly rapid processing of tree-ring samples at sub-annual resolution. These emergent data streams complement information obtained via radial growth and allow for refined comparisons with other temporally highly resolved *in-situ* measurements. This widens possible research avenues in ecophysiology, structure-function tradeoffs, and climate reconstruction. Hence, we recommend that the list of parameters on the ITRDB be extended to facilitate the dissemination of novel records.

By 2099, 11.8% of the global land surface is projected to experience temperature conditions without historical analogue (CMIP5 climate model ensemble; greenhouse gas emission scenario RCP 8.5). This planetary warming, together with the unprecedented rise in atmospheric CO_2 concentration, nitrogen deposition, and disturbances adds uncertainty to projections of ecosystem states and changes. Mechanistic model structures have been identified as the primary source of uncertainty in this context[14] that urgently need refinement to advance understanding of causalities and response thresholds in the earth system. These endeavors will greatly benefit from an integrated suite of empirical observations with proven abilities to combine with mechanistic models, including tree rings, EOs, and forest monitoring datasets[3-5,7,10,15]. We expect that joint observational and computational approaches will continue to improve projections of climate impacts on forest ecosystems. Yet, the necessary *in-situ* data can only be developed and maintained through targeted community-wide efforts.

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References

[1] St.George, S. and Ault, T.R. (2014) The imprint of climate within Northern Hemisphere trees. *Quarternary Science Reviews* 89, 1-4

[2] Beck, P.S.A. et al. (2011) Changes in forest productivity across Alaska consistent with biome shift. *Ecology Letters* 14, 373-379

[3] Anderegg, W.R.L. et al. (2015) Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. *Science* 349, 528-532

[4] Frank, D.C. et al. (2015) Water-use efficiency and transpiration across European forests during the Anthropocene. *Nature Climate Change* 5, 579-583

[5] Babst, F. et al. (2013) Site- and species-specific responses of forest growth to climate across the European continent. *Global Ecology and Biogeography* 22, 706-717

[6] Larson, E.R. et al. (2013) The need and means to update chronologies in a dynamic environment. *Tree-Ring Research* 69, 21-27

[7] Zhu, Z. et al. (2016) Greening of the Earth and its drivers. *Nature Climate Change*, DOI:10.1038/nclimate3004

[8] Delpierre, N. et al. (2015) Wood phenology, not carbon input, controls the interannual variability of wood growth in a temperate oak forest. *New Phytologist* 210, 459-470

[9] Clark, J.S. et al. (2007) Tree growth inference and prediction from diameter censuses and ring widths. *Ecological Applications* 17, 1943-1953

[10] Li, G. et al. (2014) Simulation of tree-ring widths with a model for primary production, carbon allocation, and growth. *Biogeosciences* 11, 6711-6724

[11] Schimel, D. et al. (2015) Observing terrestrial ecosystems and the carbon cycle from space. *Global Change Biology* 21, 1762-1776

[12] Brienen, R.J.W. et al. (2016) Tree Rings in the Tropics: Insights into the Ecology and Climate Sensitivity of Tropical Trees. *Tropical Tree Physiology* 6, 439-461

[13] Brewer, P.W. and Guiterman, C.H. (2016) A new digital field data collection system for dendrochronology. *Dendrochronologia*, DOI:10.1016/j.dendro.2016.04.005

[14] Shao, J. et al. (2016) Uncertainty analysis of terrestrial net primary productivity and net biome productivity in China during 1901-2005. *Journal of Geophysical Research: Biogeosciences*, DOI:10.1002/2015JG003062

[15] Luyssaert, S. et al. (2010) The European carbon balance. Part 3: forests. *Global Change Biology* 16, 1429-1450

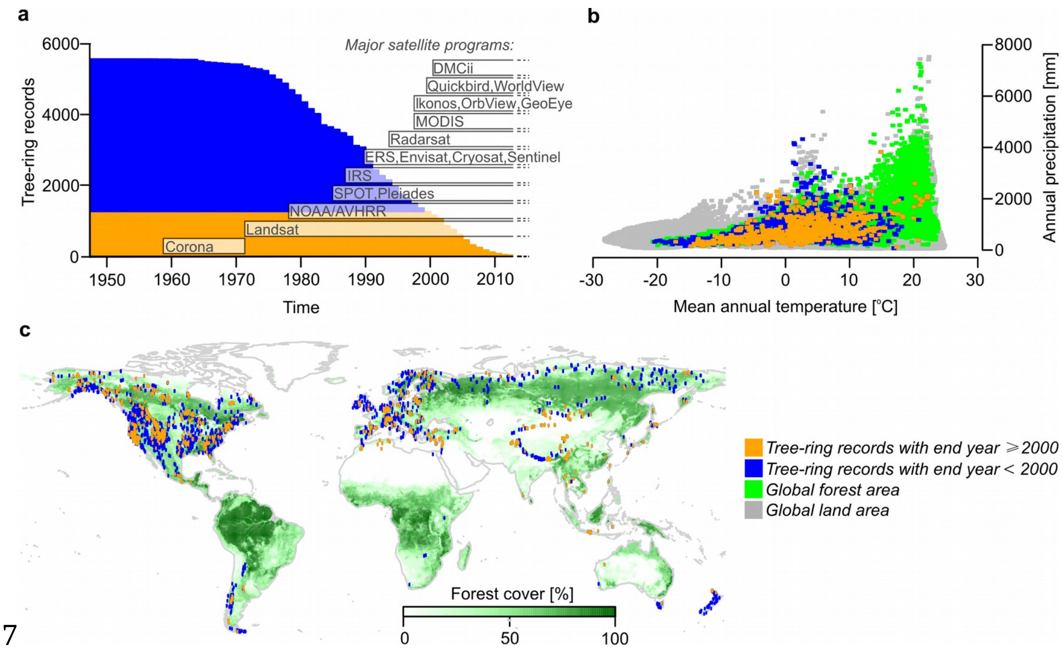

Figure 1: Changes in the coverage of tree-ring and satellite records since 1950. The end dates of all available tree-ring records from the international tree-ring data bank (ITRDB) and the time span of major polar-orbiting satellite programs (incomplete list) are shown in panel (a). The reduced coverage of climate (b) and geographic space (c) of ITRDB data in the recent decade are illustrated. Global forest cover data was obtained from MODIS and forests were defined where the fraction of a grid cell was greater 60%.