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Are global forests performing in sync? The need to account for spatiotemporal biases in tree-ring records

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Abstract

Populations whose dynamics are driven by correlated environmental stochasticity face increased risk of extinction. Forests in particular are being pushed to their physiological limits under global change; hence, the analysis of common patterns of tree performance across scales becomes crucial to discern early warning signals and tipping points. Here, we critically evaluate customary and recent approaches for the analysis of time series of radial growth based on simple correlations as measure of direction and signal strength shared by spatially-segregated forests (synchrony). By accounting for changes in spatial distribution of populations and temporal coverage of tree-ring records, we show that growth synchrony has not substantially augmented for the past 150 years across Europe, a continent with high availability of tree-ring series. We guard against the use of absolute correlations as a metric of synchrony and stress that robust analytical methods should be applied to evaluate synchrony trends when using biased spatiotemporal databases.

Significance Statement

The increasing availability of tree-ring records globally constitutes an invaluable resource to spot changes in forest dynamics at varying spatiotemporal scales. In this context, assessments of changes in tree growth synchrony are useful to anticipate the fate of forest ecosystems in a warmer world. While relevant patterns may emerge from global syntheses, we are concerned about approaches using absolute correlations as synchrony metrics which may mistakenly lead to the conclusion that trees are progressively performing in sync. We encourage more systematic evaluations of synchrony trends at meaningful biogeographical scales as effective approach to interpret forest dynamics under global change.

Keywords: biogeographical patterns, climate change, dendroecology, International Tree-Ring Data Bank, mixed models, Moran effect, growth synchrony

1. The geography of spatial synchrony: the case of forest growth dynamics

In ecology, spatial synchrony refers to parallel changes in time-varying features of geographically disjunct populations (Liebhold, Koenig, & Bjørnstad, 2004). The main factor engendering population synchronization is assumed to be climatic forcing (i.e., the Moran effect; Moran, 1953). Over the past years, increasing attention has been given to the study of the temporal coherence of tree radial growth in the Anthropocene across bioclimatic gradients (e.g. Briffa et al., 2008; Shestakova et al., 2016, 2018, 2019a,b; Ponocná et al., 2018; Camarero et al., 2021). As a result, intricate and non-generalized temporal trends of common variability of tree growth have been documented, which point to biophysical complexities of the role of emerging abiotic (climatic) limitations and related factors (outbreaks of pests and diseases, fires, etc.) impacting on tree performance, especially since mid-20th century. A recent examination of ring-width records (Manzanedo, Hille Ris Lambers, Rademacher, & Pederson, 2020) concluded that spatial synchrony of tree growth strongly (and consistently) rose worldwide in the past few years. This outcome stemmed from the global analysis of tree-ring chronologies available at the International Tree-Ring Data Bank (ITRDB). Oddly, this phenomenon went unnoticed based on evidence collected so far at local and regional scales, where either positive, stable or negative trends had been reported (Briffa et al., 2008; Shestakova et al., 2016, 2018, 2019a,b; Ponocná et al., 2018; Camarero et al., 2021).

The present correspondence and associated analysis were originally motivated by such a report, which in any case was greatly welcomed owing to its potential for providing a foundation towards understanding the global performance of disjunct forests and its implications for the terrestrial carbon sink. Despite the fact that the paper by Manzanedo et al. (2020) was recently retracted due to "a coding error, correction of which undermines the main conclusions of the study (…)" (Manzanedo, Hille Ris Lambers, Rademacher, & Pederson, 2021), we believe the proposed methodology to infer growth synchrony trends – based on the analysis of absolute correlations – deserves an additional warning, merely because in ecological applications both the sign and strength of the simple correlation coefficient matter. Thus, our (re)evaluation may still provide relevant insights to the dendro- and, in general, the ecological community while serving as cautionary tale about how inappropriate methodologies can yield results that are purely artefactual. In turn, we would also like to draw attention to the prevailing spatiotemporal biases in the ITRDB database, in particular to the decrease in availability and length of updated tree-ring series, which warrant careful examination through the application of suitable analytical approaches.

2. The analysis of trends in growth synchrony: methodological considerations

Traditional methods for assessing synchrony patterns in ring-width chronologies (or other tree-ring traits) include parametric and non-parametric approaches. Among the first, simple (averaged pair-wise) and intra-class (variance-based) correlations provide straightforward metrics for characterizing the strength and nature of the signal shared among time series (Shestakova et al., 2018). The latter, grounded in mixed modelling principles, is also well suited to unbalanced datasets (Shestakova et al., 2016). Non-parametric choices are, among others, the "Gleichläufigkeit" coefficient of coincidence (Eckstein & Bauch, 1969) and Kendall's concordance coefficient (Kendall, 1975). The latter is less sensitive to deviations from normality (as ring-width indices tend towards asymmetry), while it is claimed to detect similarities in variability between series better than simple correlations (Briffa et al., 2008).

Alternatively, the mean absolute correlation between pairs of chronologies has been recently proposed as a metric of synchrony (Manzanedo et al., 2020). Although this methodology might be suitable to unveil increasingly large (both positive and negative) coherent growth responses being ‘in sync’ at large distances due to climatic forcing (i.e. climate dipoles), it has two relevant problems. First, it mistreats opposing values of the simple (pair-wise) correlation coefficient, hence resulting in a (fully predictable) positive synchrony between tree-ring chronologies – even when there is none. Indeed, ignoring the sign of the correlation coefficient will inevitably fallout in artificially inflated positive relationships. Second, overlooking the nature (sign) and geographical structure of the common signal shared by a set of chronologies hampers the mechanistic interpretation of large-scale drivers of tree growth, thereby obstructing the identification of on-going ecological repercussions of global change across regions and biomes. It must be noted that the presence of sizeable negative correlations at large distances is highly unlikely (Shestakova et al., 2018), as it is at odds with the observation that atmospheric circulation patterns often affect neighbour regions very disparately (Allen, Breshears, & McDowell, 2015). As an alternative to absolute correlations, correlograms are an obvious choice to evaluate the spatial distribution of common growth patterns among pairs of chronologies (Bjørnstad, Ims, & Lambin, 1999; Koenig, 1999). They are grounded in simple correlations and facilitate understanding and testing the magnitude and nature of the metric across scales.

An additional matter of concern related to the use of absolute correlations as a metric of synchrony is the sharp decrease in availability of ITRDB series occurring immediately before the turn of this century. This bias is widely acknowledged by the dendro-community (Babst, Poulter, Bodesheim, Mahecha, & Frank, 2017; Zhao et al., 2019). Indeed, a change in geographic coverage of chronologies coupled with a poorer temporal coverage in recent years can be responsible of a sudden increase in mean absolute correlation simply because of higher chances of (large) spurious correlations contributing to this metric.

3. An example: Europe-wide analysis of tree growth across the Anthropocene

In order to critically evaluate the performance of the aforementioned methodologies, which are based on correlation principles of temporal signals, we *(i)* carried out a reanalysis of European tree-ring chronologies (990 chronologies; 24.5% of the ITRDB database) following the methodology applied in Manzanedo et al. (2020), and *(ii)* compared the results with alternative approaches for evaluating synchrony trends in tree growth (i.e. averaged pairwise and intra-class correlations; Shestakova et al., 2018). The metrics were calculated for 50-year periods to retrieve moving-window estimates of synchrony trends. The rise in synchrony estimated from absolute correlations mostly vanished once the dataset was filtered for chronologies spanning at least 25 years within each 50-year period (Figure 1a). In fact, the spatial distribution of pairwise correlations for equally spaced 50-year periods, starting in 1850, showed an increase of spurious associations achieving either high or low erratic values during the period of 1967–2016 (Supplementary Figure S1). This observation coincided with an acute decrease in chronology length (Figure 1b), distance between sites and number of available chronologies (Supplementary Figure S2). If raw (not absolute) correlations were used, the rising trend in synchrony disappeared (Figure 1a). By using the intra-class correlation metric of synchrony (Shestakova et al., 2018), which efficiently deals with the unbalance of partially overlapping tree-ring data (but not with changes in their spatial coverage), the increasing trend in synchrony could still be observed, but in a much lower degree (Figure 1a). Indeed, these results put into question the existence of a global trend towards rising temporal coherence of tree growth. Although we restricted our analyses to Europe, a continent with the highest availability of tree-ring series (together with North America), other regions are likely to display similar patterns.

4. Interpretation and attribution of changes in spatial synchrony of forest growth

The attribution of synchronous tree growth dynamics at large spatiotemporal scales to exogenous (e.g. climate) factors is highly relevant to forecast potential ecological consequences of global change and the role of forests as carbon sinks. Unquestionably, attribution analyses should be carefully performed and interpreted. However, bigger efforts have been customarily placed on ascertaining relationships between tree rings and climate for stability at local rather than broader (regional, continental) scales (Allen et al., 2018). In this regard, disentangling the role of long- and short-term changes in exogenous variables on the geographical patterns of synchrony in tree-ring networks can be problematic. This is mainly because of two independent issues: an imperfect availability of spatially-explicit environmental data with sufficient resolution, and the spurious regression problem that arises when linking unrelated non-stationary variables in longitudinal studies (Shestakova et al., 2019a).

Spurious regression refers to the case where a pair of independent, non-stationary series exhibiting similar trends shows too frequently a significant relationship (high r^2 and significant t-values) according to standard inference in ordinary least squares regression (i.e. nonsense regression; Murray, 1994). For example, a generalized rise in growth synchrony can be easily mistaken as an early sign of current warming and extreme weather events affecting forest ecosystems. This is relevant because sharp spikes in synchrony may anticipate widespread swings in carbon sink strength as trees sync with global temperature. The same problem is applicable to alternative drivers of tree growth showing a generalized increment over the last decades, such as atmospheric CO_2 concentrations. On the other hand, our re-analysis (as shown in Figure 1) suggests that a global increase in temporal coherence of tree growth is unlikely to occur, at least until recently, owing to the (barely) existing shifts in synchrony observed across the entire European continent. In fact, if warmer temperatures and rising atmospheric CO_2 were to improve growing conditions, a decrease in synchrony could be expected as climate decreases its importance as a global "synchronizer" whilst local conditions (topography, soil, tree-to-tree interactions) gain relevance. The opposite interpretation – namely that warmer conditions progressively lead to both enhanced and more homogeneous growth – is therefore not tenable. Alternatively, increased warming-induced drought stress may make trees gradually limited by water shortage and increase synchrony at large (e.g. subcontinental) scales (Shestakova et al., 2016; Babst et al., 2019).

It is therefore obvious that searching for evidences of the role of temperature as a synchronizing cue controlling forest dynamics must properly address the spurious regression problem that plagues non-stationary time series (i.e. with variable mean and variance) analysis. Indeed, the role of potential (external) drivers of growth synchrony changes should be always examined at the high-frequency domain by accounting for stochastic non-stationary fluctuations. This can be readily achieved through e.g. cointegration analysis, which looks for stationary linear combinations of non-stationary random variables (Engle & Granger, 1987; Shestakova et al., 2019a). Importantly, it is highly possible for a pair of time series (e.g. synchrony changes and climate) to have weak/strong correlation but strong/weak cointegrating relationships (Murray, 1994).

In the end, by properly identifying local and regional environmental controls of forest ecosystems, spatial and species-specific growth patterns can be better connected with temperature and moisture variations within particular climatic zones. This should enable ecologically meaningful interpretations of synchrony changes for their respective forests (Babst et al., 2013; Shestakova et al., 2019b). Other relevant factors to tree performance such as global dimming, permafrost melting or N deposition may also play a role as drivers of synchrony depending on the spatiotemporal coverage of the analysis and the targeted ecosystem(s). In addition to the ultimate influence of such exogenous drivers, it is important to note that the ability of different forests to cope with short-term stresses and disturbances (e.g. an extreme drought) is related to phenotypic plasticity, which strongly varies among species or functional types. While some (plastic) species may better adapt to future conditions, others might undergo collapse or extinction (Nogués-Bravo et al., 2018).

5. Concluding remarks

Global change impacts on forests will likely be traced back with increasing precision and higher spatiotemporal coverage provided a larger number of dendrochronological records is progressively available worldwide (Babst et al., 2017). For this purpose, a particularly informative approach is the analysis and interpretation of synchrony patterns in comprehensive tree-ring networks. This effort can be pursued at different spatial scales depending on the desired research emphasis on local, regional or global factors controlling tree performance and its past and potential future effects. While relevant patterns may emerge from global syntheses, these should be carefully evaluated bearing in mind prevailing spatiotemporal biases in assembled datasets. Altogether, we strongly encourage systematic assessments of growth synchrony at meaningful biogeographical scales as an effective approach to interpret forest dynamics under global change, and guard against the use of absolute correlations as a metric of synchrony, particularly in unbalanced datasets.

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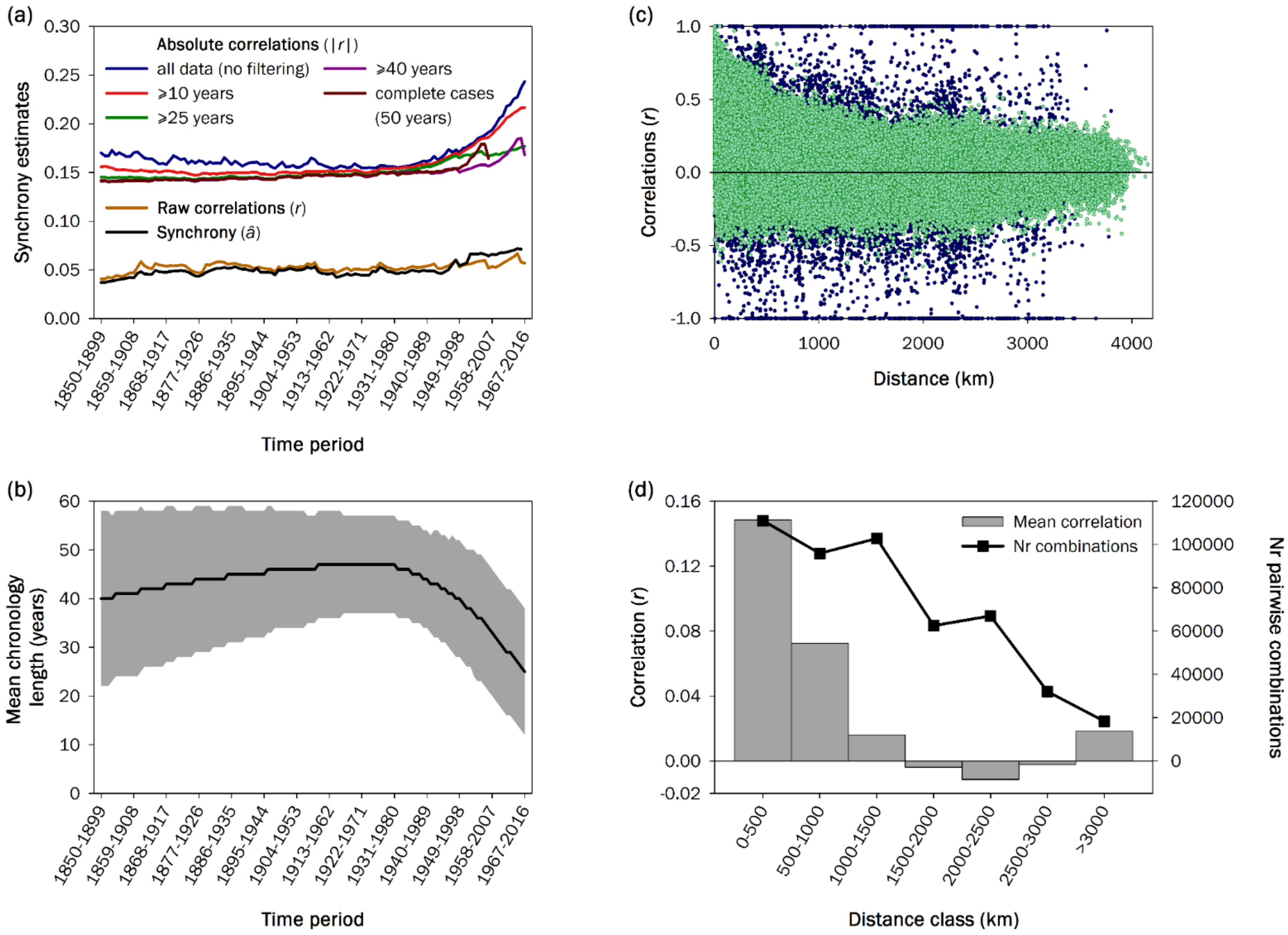
(a)
Synchrony estimates
Absolute correlations (|r|)
all data (no filtering)
⩾10 years
⩾25 years
⩾40 years
complete cases
(50 years)
Raw correlations (r)
Synchrony (â)
Time period
(b)
Mean chronology length (years)
Time period
(c)
Correlations (r)
Distance (km)
(d)
Correlation (r)
Nr pairwise combinations
Mean correlation
Nr combinations
Distance class (km)

Figure 1. Assessments of global growth synchrony are affected by spatiotemporal biases. **a,** Measures of tree growth synchrony across Europe based on ITRDB dataset calculated for 50-year periods lagged by 1 year over the period of 1850–2016 using absolute correlations ($|r|$), raw correlations (r) and intra-class correlations based on mixed modelling ($\hat{a}$). Note that $|r|$ values show a recent increasing trend driven by changes in the spatiotemporal coverage of the dataset, as suggested by **b,** a concomitant decrease in mean chronology length. A sensitivity analysis of $|r|$ values filtering for increasingly high number of common (i.e. overlapping) years between pairs of chronologies (10, 25, 40 and 50 years) for each 50-year period is also presented, pointing to non-relevant temporal trends after controlling for chronology length. Note that $|r|$ values for complete (i.e. 50-year length) chronologies are truncated starting from the period 1958–2007 (i.e. when the number of available chronologies at the ITRDB drops below 10% of the total amount). **c,** Pairwise correlations as a function of distance between (unfiltered) chronologies (blue dots) and **d,** correlogram of pairwise correlations showing a distance-dependent decay in mean correlation and a typical threshold of 1,000 km for sizeable common tree growth signals, respectively. Spurious (i.e. unusually high and low) correlations are evident across distances as the result of very limited temporal overlapping for particular pairs of chronologies, which disappear after filtering for pairs of chronologies including at least 25 common years (green dots in panel **c**). This problem gets worse for the most recent 50-year periods of the study period, hence boosting $|r|$ (see Supplementary Figures S1 and S2).