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Correlation between tree-ring series as a dendroprovenancing evaluation tool

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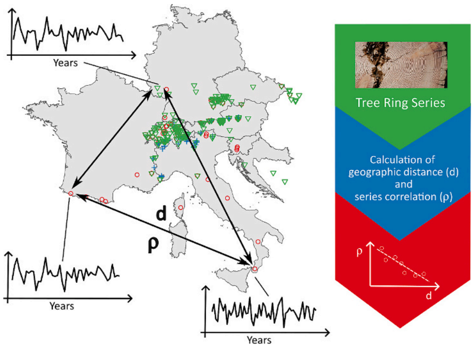
HIGHLIGHTS

- Approximately 12,000 geo-localised tree-ring series were used to identify relationships between correlations and geographical distance.
- Within the same species there is a direct link between correlation and distance.
- Mathematical functions linking the correlations between the series to the distance and their respective confidence limits were identified.
- Our results show that correlation analysis can be used for dendroprovenancing when high correlation values are observed.
- Elevation influences dendroprovenance analyses as at low elevations it becomes more likely to find low or negative correlations.

GRAPHICAL ABSTRACT



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ABSTRACT

The use of correlation between tree-ring series as a proximity indicator in dendroprovenance analyses is often questioned. High correlations may occur between series at a great distance, but conversely, low correlations may occur between series that are close to each other. This discrepancy has prompted the exploration of alternative dendroprovenancing methods, but many of them have proven to be unreliable or impractical. In this study, approximately 12,000 geolocalised tree-ring series from the three main Alpine conifers—spruce, larch, and fir—were analysed to investigate the extent to which correlation analysis can be used as a dendroprovenance tool. The results clearly indicate a significant increase of correlation at low distance and validate the proposed correlation approach. The large dataset also made it possible to develop a simplified quantile regression model that could be used to estimate distance in kilometres based on correlation values between the tree-ring series. Spruce exhibited the most promising results, which is attributed in part to the extensive dataset available, while there were challenges with fir in accurately determining distances between sites. Finally, the study also evaluated the impact of altitude on distance estimation and showed how this environmental factor influences variations in dendroprovenance analyses.

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1. Introduction

Dendroprovenance is a branch of dendrochronology that deals with identifying the origin of timber based on the concept of more similar environments where trees have grown resulting in higher correlations between series (Ermich et al., 1976). The earliest works on dendroprovenance date back to the 1990s (Biger and Liphschitz, 1992; Bonde et al., 1997) and were based on statistical comparison through classical dendrochronological tests: the *t*-test, correlation coefficient (r), Glk (or *Gleichlaeufigkeit*, a measure of percentage agreement between two series, Eckstein and Bauch, 1969), and Glk significance (Jansma et al., 2014; Jansma, 2020). Since then, dendroprovenance analyses have made it possible to identify the origins of numerous artefacts and structures of great historical and archaeological importance in fields such as Flemish painting (Ważny, 2002; Daly and Tyers, 2022), shipbuilding (Guibal, 1992), and constructions from Roman times (Bernabei et al., 2019).

To identify the most probable origin of wood, it is common practice among dendrochronologists to use correlation analysis coupled with classical statistical tests, especially the *t*-test, as in the two versions used by Baillie and Pilcher (1973) and Hollstein (1980). The idea is to measure the correlation between tree-ring series of unknown origin with geolocalised reference series and then to use the corresponding *t* statistics as a proxy of the strength of the association and a measure of spatial closeness (Bridge, 2012; Haneca et al., 2005). However, this line of reasoning does not show a strong statistical foundation since the *t* distribution is used to test the significance of a correlation and not as a direct measure of its strength. In addition, at a more fundamental level, the environmental variables involved in determining correlations between tree-ring series are numerous and can sometimes heavily alter correlation results. For example, Bridge (2012) reports that oaks growing >200 km apart in the British Isles may show higher correlation than oaks growing in adjacent sites.

Other variables that affect the use of correlation during dendroprovenance analysis are the length and replication of the tree-ring series in both samples and reference series. Variations in the number of samples and the length of the series make the signal unstable and strongly influence the results (Gut, 2020; Bernabei, 2022), so correlation test values will be higher with larger overlaps and the better replicated series (cf. Gut, 2018). These inherent and unavoidable factors influence correlation analyses and do not allow for standardisation of the results. Although the use of correlations is commonly regarded as the "classic" method of dendroprovenancing (Čufar, 2007; Bridge and Fowler, 2019), the lack of validation of the potential of correlations as an expression of proximity between chronologies profoundly decreases its credibility.

Various other solutions have been proposed in attempts to circumvent these problems. Haneca et al. (2005) suggested grouping the chronologies of neighbouring sites into a regional chronology, which could reflect the average growth conditions of a larger region. Daly (2007) proposed observing different levels of geographic resolution by moving from comparisons with regional chronologies to increasingly localised chronologies and to individual series in order to gradually increase the spatial resolution. However, this type of solution relies on the availability of many reference series with adequate spatial distribution, which is not always possible and becomes increasingly difficult when going back further in time.

Recently, Drake (2018) proposed the use of the *t*-test combined with a significance criterion (the *Z*-test) to assess the representativeness of *t*-values in identifying possible sources. Combined with Bayesian statistics, this method makes it possible to assess the robustness and calculate the probability of each potential source of timber. Gut (2018) finds that the similarities between series depend strongly on high-frequency signal differences between sites and proposed the *k*-NN statistical process (*k*-nearest neighbours leave one-out cross-validation) to validate dendroprovenance analyses. Later, Gut (2020) suggests the use of "ideal" pseudo-chronologies constructed through statistical simulation to overcome the poor geographical representativeness of reference series built on historical timber with unclear origins. The pseudo-chronologies are constructed based on dendrochronological series of standing plants and can be extended backwards for an indefinite time while preserving the local signal.

Statistical techniques involving cluster analysis (Garcia-Gonzalez, 2008), principal component gradient analysis (Buras et al., 2016), or other hierarchical clustering methods (D'Andrea, 2023) are very useful for detecting ecological gradients in population time series. However, they are of little use in dendroarchaeological practice because they require complete correlation matrices, which are very difficult to obtain unless working with standing trees. Conversely, time series in the historical field often prove to be extremely variable in terms of extent and reference period, and as a result, correlation matrices are always incomplete. For British-Isles oak, Bridge and Fowler (2019) propose subtracting the regional growth signal and using residuals before comparing sites to focus on local-scale growth variation. The correlation is then spatially verified on appropriately constructed maps that are valid for the region.

It is clear thus far that the use of correlation in dendroprovenance analysis remains controversial and is not unanimously accepted, even though it is widely used in dendrochronological and dendroarchaeological practice. The lack of precise statistical validation of correlations as descriptors of spatial distance poses a risk of subjective use of correlation tests and could cast doubt on the results of already published research. Other possibilities have recently been explored to overcome these uncertainties, including the use of strontium isotopes (English et al., 2001; D'Andrea, 2023), quantitative wood anatomy (von Arx et al., 2016), and a multi-variable system (Akhmetzyanov et al., 2019; D'Andrea et al., 2024). These techniques rely on small samples of wood, but obtaining such samples is practically impossible for objects such as ancient violins, panel paintings, or archaeological finds. Therefore, although these techniques are worthy of consideration, they are virtually impracticable for most objects in the field of cultural heritage.

In this context, the aim of this work is to perform an extensive validation of a correlation-based approach to dendroprovenance. Starting from a large set of geo-referenced tree-ring series of European Alpine conifers, we demonstrate that correlation can indeed be used as an expression of spatial distance. In addition, we propose an approximated quantile regression model that could be used to estimate possible provenance. Finally, species-specific differences and the effects of altitude on dendroprovenancing are investigated.

2. Material and methods

11,972 individual raw and georeferenced tree-ring series were downloaded from the ITRDB site (International Tree Ring Data Bank, United States' National Oceanic and Atmospheric Administration Paleoclimatology Program and World Data Centre for Paleoclimatology, https://www.ncei.noaa.gov/products/paleoclimatology/tree-ring, Guiterman et al., 2024). These series were obtained from three important Alpine species: Norway spruce (*Picea abies* Karst., PCAB), larch (*Larix decidua* Mill., LADE), and silver fir (*Abies alba* Mill., ABAL). The individual tree-ring series were chosen rather than the site chronologies that are also found on the ITRDB site in order to start with a uniform dataset with the lowest possible degree of manipulation.

All statistical analyses were performed in R (R Core Team, 2024). Data manipulation and plotting were performed using the tidyverse ecosystem (Wickham et al., 2019). Specific dendrochronological analyses (detrending and construction of the site chronologies) were performed in dplR (Bunn et al., 2023), and spatial analyses were performed using the sf package (Pebesma and Bivand, 2023). Further processing steps were performed with a set of in-house R scripts, which are freely available at https://github.com/pietrofranceschi/dendrochronology.

The total number of site chronologies was 447. The most represented species was spruce with 256 sites, followed by fir with 124 sites and larch with 67 sites. Comparisons between tree-ring series were considered valid only if they had >50 overlap rings. Pearson's correlation coefficient (*r*) was used as a measure of similarity. A direct comparison with *t* values that are routinely used in dendroprovenance was performed by converting *r* to *t* as follows with a reference overlap (*n*) of 100 years: $t = r * \sqrt{(n-2)/(1-r^2)}$.

When elevation data were available, the series were separated into high and low-elevation groups to assess the effects on correlations. For this purpose, a different threshold to separate low and high-altitude sites was identified for each species based on their natural distribution range (Caudullo et al., 2017). Quantile regression modelling was applied to estimate the conditional 0.95 quantile of the correlation as a function of the geographical distance. Quantile regression was preferred over ordinary least-squares regression because it is more robust in the presence of outliers and is not affected by violations of the assumptions of normality and constant variance (Koenker, 2005). Quantile models were estimated using the quantreg package (Koenker, 2023), while confidence intervals (CIs) of the model parameters were calculated using the jtools package with the default parameters (Long, 2022).

3. The choice of detrending method

The choice of detrending method is always delicate and mainly depends on the objectives of the study. Different methods may produce very different-looking tree-ring series (Fig. S1), in which the long, medium, or short-term signals may be emphasised. Consequently, it seems logical to assume that the choice of method may directly influence dendroprovenance analyses.

To better understand the effects of detrending on dendroprovenancing, comparisons were made between site chronologies as a function of the detrending method. The correlations between chronologies were then quantified as a function of spatial distance for different detrending methods. Analyses were performed on the raw data (without detrending) and on a range of detrending methods, which involved the cubic smoothing spline (Cook and Peters, 1981), the 5-year moving average and logarithmic transformation respectively used by Baillie and Pilcher (1973) and Hollstein (1980) for the *t*-test calculation, and Friedman's supersmoother method (Friedman and Silverman, 1989). This last method is among the most effective in emphasising the annual (high-frequency) signal of the series and offers a solution in cases where the "spline" or the linear fit contains zeros or negative values, which would lead to invalid ring-width indices (Bunn et al., 2023). Thus, it can be applied to a larger number of cases.

4. Results

Fig. 1 shows the spatial distribution of the full set of site chronologies. From a geographic-ecological point of view, the chronologies are distributed on a continental scale in a territory that spans Sicily, the Pyrenees, and Central Europe but is mainly centred on the Alpine area. This distribution has ensured high geomorphological and ecological variability. It is clear from the plot that LADE shows a more compact distribution, which is consistent with its expected distribution across Europe (Caudullo et al., 2017). The 447 site chronologies are extremely variable in terms of replication and length (Table 1 and Figs. S2 and S3).

In general, the correlation values between the series increase as the distance decreases, regardless of the detrending method used (Fig. S4). However, as noted by Gut (2018), the effect is more pronounced when the multi-year oscillation component is removed. A comparison of the same series detrended by different methods shows that there are more similarities between the series in which high frequency is emphasised (Fig. S5), as well as the relationship linking the correlations between the chronologies to geographical distance being more pronounced (Fig. S4). For this reason, high-frequency detrending methods, particularly the Friedman supersmoother, were chosen for the following analyses. Table S1 (Supplementary material) shows the statistical parameters for the calculation of the mathematical functions referring to the raw data and the other detrending methods.

Fig. 2 shows the association between correlations and geographical distance within and between species. Each dot represents the correlation between a pair of site chronologies, and the colour highlights the length of the overlap in years. The presence of decreasing trends in the large majority of the cases is clear, and these trends are more marked for intraspecific correlations. In other words, larger correlation values are found between series of the same species with lower spatial separations. The expected increase of the correlation with the overlap is clearly visible for only L-L, but this species also shows the longest series, which also results in large overlaps. The trends in the previous plots can be approximated with a simplified linear association with the following form:

$$r = a^{*}log10(d) + b$$

where *r* is the correlation coefficient, *d* the distance in kilometres, *a* is the slope, and *b* is the *y*-intercept.

Although polynomial functions or non-parametric statistics would have approximated the distribution of the data more accurately, a linear function was chosen to simplify the interpretation of the results. The logarithmic scale provides the best representation of the trend within

Table 1
Replication and length of site chronologies by species.

Species	Min	Max	Mean
Replication (samples)			
ABAL	2	1248	27.6
LADE	5	141	29.1
PCAB	1	324	25.8
Length (years)			
ABAL	46	424	174
LADE	43	1062	320
PCAB	24	699	179

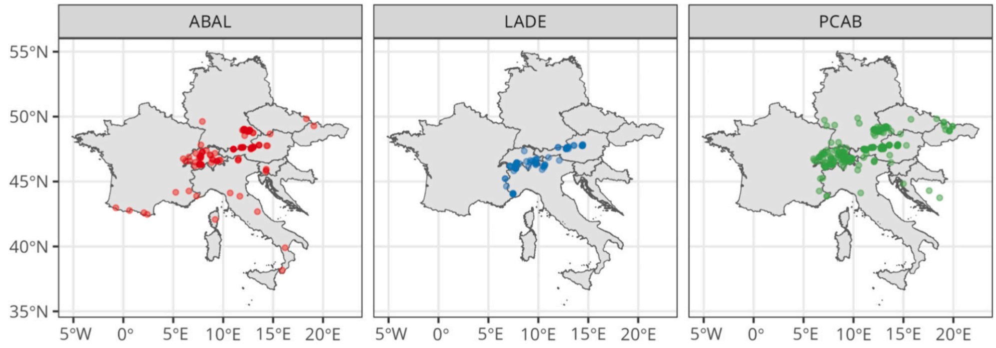

Fig. 1. Spatial distribution of the sites. Each dot represents the geographic position of the individual site chronologies.

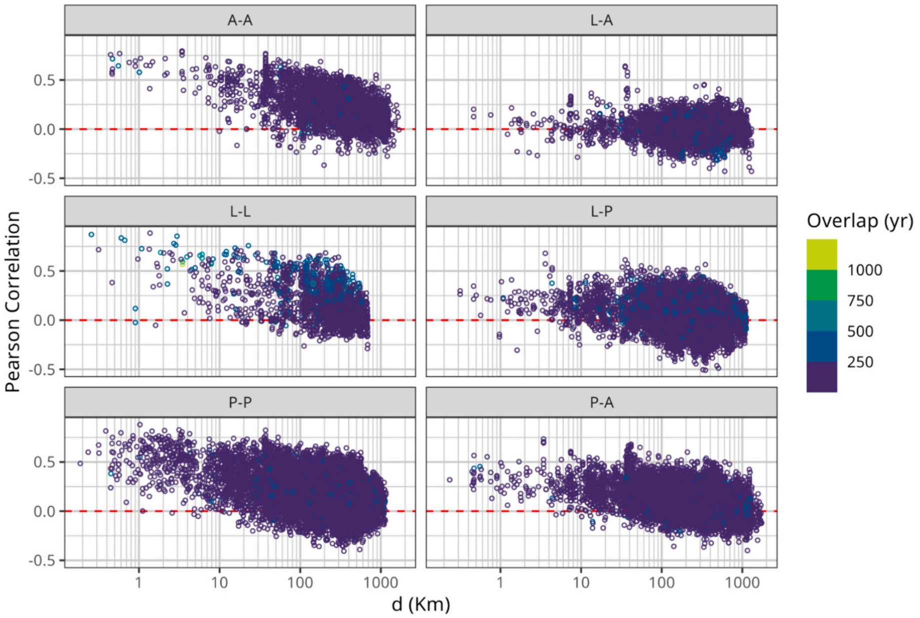

Fig. 2. Intra- and interspecific correlation values represented as functions of distance on a logarithmic scale. A, *Abies alba*, L, *Larix decidua*, P, *Picea abies*.

the large dataset. Quantile regression was used to estimate the coefficients of the previous model, which can be used to identify an upper boundary of the distribution of the correlation values observed at each spatial separation (corresponding to the 0.9 and 0.95 quantiles of the conditional distribution of *r*). The full set of coefficients relative to the intraspecific correlation is shown in Table 2 and in a plot in the Supplementary material (Fig. S6). In particular, for the slope, the results show coherent results for the three species, so we illustrate the overall approach showing the quantile regression obtained in consideration of the three conifers simultaneously. The resulting plot is shown in Fig. 3.

The previous plot highlights the overall coherence of the trends observed in the three species. The regression line in the plot can be used to identify a rational upper boundary for the correlation observed at each distance, which can then be used to deduce an upper limit for the distance from an observed correlation value. The arrows in the figures illustrate this idea. Suppose that the correlation between an unknown series and a reference series is 0.75. Fig. 3 indicates that this level of similarity is unlikely to be found for distances larger than 7 km, so this distance can be used to obtain an approximate dendroprovenance.

In a more quantitative way, the 0.95 quantile regression line shows a slope of −0.2 (with sandwich CIs at 2.5 % and 97.5 % of −0.21 and −0.19, respectively). The estimated intercept was 0.91 (CI 0.89–0.93). Table S1 in the Supplementary material shows the values obtained by other detrending methods. Thus, the equation becomes $r = -0.2^{*}\mathrm{Log10}(d) + 0.91$, which leads to the distances in Table 3 when solved for *d* (km). For the same table, to perform a direct comparison with the standard *t*-based approach, the corresponding *t* statistics were calculated while assuming an overlap of 100 years. The proposed approach was applied to the three individual species, and the corresponding quantile model coefficients for $q = 0.95$ and $q = 0.9$ are included in Table 2. The species with the best distance approximation was spruce, while fir was

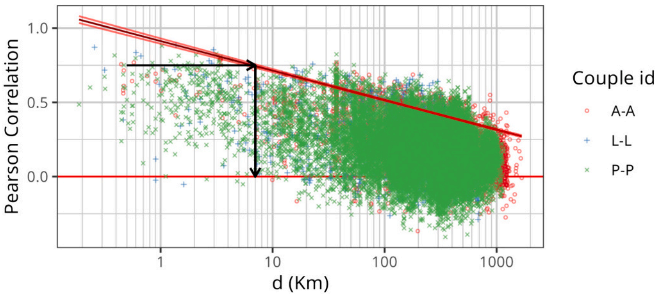

Fig. 3. Interspecific correlation values represented as a function of distance logarithmic scale. A, *Abies alba*, L, *Larix decidua*, P, *Picea abies*. The 0.95 quantile regression line is shown in red. The black arrows show an example of the potential use of the previous plot to estimate *d* from a correlation measure.

Table 2
Coefficients of the quantile regression for the different species (0.9 and 0.95 quantile). In all cases Friedman supersmoother was used as a detrending strategy. Confidence intervals were calculated by bootstrap. Couple_id: A, *Abies alba*, L, *Larix decidua*, P, *Picea abies*.

Couple_id	Term	Values	Conf.low	Conf.high	Quantile
A-A	b	0.97	0.92	1.02	0.90
A-A	a	−0.22	−0.24	−0.20	0.90
A-A	b	0.99	0.93	1.05	0.95
A-A	a	−0.22	−0.24	−0.19	0.95
L-L	b	1.01	0.95	1.07	0.90
L-L	a	−0.26	−0.29	−0.23	0.90
L-L	b	0.99	0.93	1.06	0.95
L-L	a	−0.22	−0.25	−0.20	0.95
P-P	b	0.80	0.78	0.81	0.90
P-P	a	−0.18	−0.18	−0.17	0.90
P-P	b	0.88	0.86	0.90	0.95
P-P	a	−0.19	−0.20	−0.18	0.95

Table 3
Distance in km (d) reconstructed from the correlation values r and the corresponding *t*-test between the tree ring series (95 % confidence level). A number of rings equal to 100 were imposed for the *t*-test.

Conifers		
r	*t*	d (km)
0,1	0,99	12,174
0,2	2,02	3827
0,3	3,11	1203
0,4	4,32	378
0,5	5,72	119
0,6	7,42	37
0,7	9,70	12
0,8	13,20	4
0,9	20,44	1

the worst.

For a subset of the full dataset of site chronologies, the altitude was also included in the metadata since this factor is known to be relevant in determining the growth patterns of trees (Dittmar et al., 2012). We performed a correlation analysis using low and high-elevation groups, and the results are shown in Fig. 4. The plots reveal that the overall structure of the cloud of correlation coefficients persisted in both cases.

In the low-elevation group, negative correlation values are more represented, which suggests an overall weaker association at low altitudes, particularly for long distances. The plot for *Abies* and *Larix* shows a marked difference in the number of observations for one of the two altitude classes, which could be expected due to the species-specific ecological niche. The results for *Picea* seem to suggest a less pronounced increase of the correlation at low distances for high-altitude samples, but this is likely due to the limited number of series recorded at low distance in the high-altitude group.

5. Discussion

In general, the correlation values between the series increases as the distance decreases, regardless of the detrending method used (Fig. S4). However, the detrending method strongly influences the dendroprovenance analysis, and the best results are obtained with methods that emphasise high frequency, such as those commonly used in the *t*-test calculation (5-year moving average or logarithmic transformation, Fig. S5). Within the same species, correlation between tree-ring series is a significant indicator of proximity, and in all cases, the cloud of correlation measure is shifted towards positive values at almost all distances. This indicates that coherent growth patterns are also observed at physical separations of thousands of kilometres.

In contrast, the association between distance and correlation was less pronounced when comparing different species. Remarkably, the worst-case scenario was observed with species characterised by different ecology, such as larch and fir (Fig. 2 L-A), which also show the most pronounced partitioning in elevation distribution. In the case of *Picea*, although a certain general trend remains visible, negative correlations become numerous, even for rather short distances, as in the L-P comparison (Fig. 2), where negative values are observed even at only 10 km.

Table 3 shows the distances in kilometres (*d*), which were reconstructed from the *r* and *t* correlation tests for the three species at different CIs (Fig. 2). Spruce showed the best results, and its formula for the 95th quantile solved for *d* is:

$$d = 10\hat{}((r - 0.88)/ - 0.19)$$

For this species, an *r* of 0.6 corresponds to a *t*-test result of 7.42 and translates to a distance of 30 km. Fir is a species that dendroarchaeologists consider to be poorly suited to dendroprovenance as correlations between distant or very distant series tend to be high (Büntgen et al., 2013; Bernabei et al., 2016). In fact, our analyses showed that fir had the slowest decrease at large spatial separation. This is somehow averaged out by the quantile regression but is clearly visible in Fig. 2. Only fir had correlation values higher than 0.5 at distances larger than 700 km.

Regardless of these species-specific considerations, it is likely that the differences between the species can be attributed more to the different numbers of samples and their differently homogeneous spatial distributions. For example, fir is represented by about half the sites compared to spruce and occupies a much larger area. On the other hand, for the continental size scale considered, the accuracy obtained for this species is surprisingly high.

The general model that is valid for the three conifers (Fig. 3, Table 2) confirms the reliability of the distance estimation. The greater number of data and the better distribution of the sites considered overall allow the distance limits to be defined with good approximation (37 km with $r = 0.6$, $t = 7.42$, 95 % confidence). The results presented refer to the Friedman standardisation method, but data for other standardisation methods can be derived easily from Table S1. The similarity between the models of the three species and the general model in terms of coefficients (slope and *y*-intercept) and confidence limits (Table 2) confirms the correctness of the approach, although it must always be considered that the reliability of a simple linear approximation decreases at the extremes of the range of distances considered.

It is important to highlight the large range of *r* observed for almost all spatial separations. This means that a low value of *r* can also be obtained easily for series that are close in space. This observation is consistent with the expected confounding effect of the environmental variables on the growing patterns of the trees. Regarding dendroprovenance, this implies that while an estimation of the distance is possible with high correlation values, much less can be concluded with low levels of similarity.

One of the greatest problems in dendroprovenancing is the unpredictability and variability of the characteristics of tree-ring series, especially with regard to replication and length in both samples and reference series. The latter can be extremely variable even within themselves in regard to the number of samples, with more and less reliable traits. Although this problem is difficult to overcome, interestingly, the equations presented are based on tree-ring series with extreme variability in terms of replication (numbers of samples vary from 1 to 1248 with an average of 27.5) and series length (from 24 to 1062 years

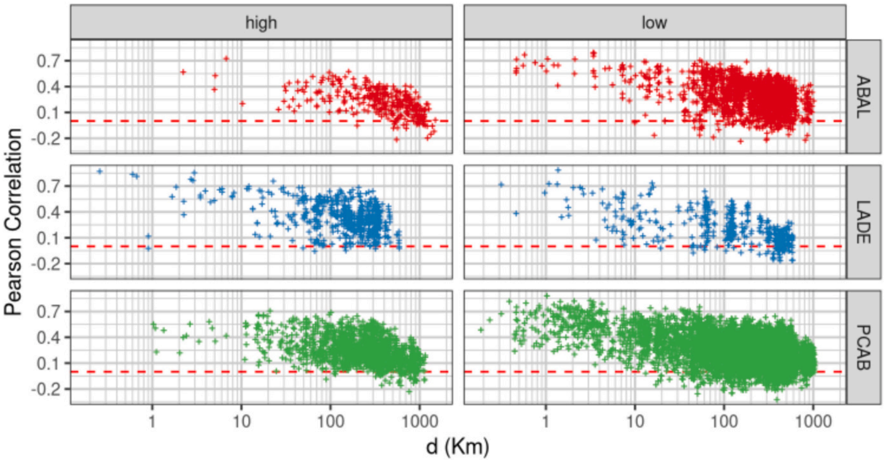

Fig. 4. The effect of altitude on correlations between site chronologies separated into high and low-elevation sites with different threshold per species calculated from their natural distribution (Caudullo et al., 2017). PCAB = 1500 m; ABAL = 1300 m; LADE = 1700 m.

with an average of 224). Thus, all possible cases are taken into account.

Regarding the effects of elevation on the correlations between chronologies, it is well known that elevation is perhaps the most important factor influencing the cross-dating results. At higher altitudes, climatic forcings are more pronounced and leave a stronger signal on the tree-ring series, which is reflected in high correlation values. Our analyses show the presence of a significant negative association between distance and correlation (Fig. 4) at both low and high elevation. In general, the overall trend seems to be comparable, but negative correlation values are always visible at large spatial separations and are most likely to be found at low elevation. Although data are scarce for some species (primarily fir), this indicates that at high elevations, the series remain correlated over larger distances, even if faintly, which confirms that the climatic/environmental forcing at high elevations is more homogeneous and encompasses large regions.

In summary, this study demonstrates that correlation analysis can indeed be used for estimating dendroprovenance, particularly when high correlations for relatively long series are observed. The similarity between Friedman's method and the standardisation routines used for calculating the *t*-test (Fig. S4) makes these results applicable to standard cross-dating operations as well. We must also highlight the importance of visual inspection of raw correlation plots for further validation of the obtained results. For using r or t, the same principles should apply as for the *t*-test in cross-dating. Even in cross-dating routines, we know that the *t*-test can sometimes fail and give incorrect results associated with accidentally high correlation values, or conversely, it can fail to recognise correct dates when associated with accidentally low results (Sander and Levanic, 1996). However, this does not prevent its use, which is widely accepted and agreed upon (Bernabei, 2022).

Likewise, in dendroprovenancing analyses, it is appropriate to use correlation values as indicators of proximity. However, it is important to remember that this is a statistical procedure based on probabilistic results and that the relationship between correlations and distance follows a semi-logarithmic function. This means that while high correlation values provide a good estimate of distance, the accuracy decreases rapidly as the correlation values decrease.

6. Conclusions

Spruce, larch, and fir with distribution over a continental range were examined to shed light on correlation tests between series as distance detectors in dendroprovenance analyses. The results showed that within the same species, there is a direct link between correlation and distance, but this relationship loses its effectiveness when comparing different species. A linear equation was proposed to reconstruct the distance in kilometres between the series as a function of correlation tests with different confidence limits. In general, the equations for the individual species and the overall equation for the three conifers show comparable statistical characteristics and provide an acceptable distance estimate. Spruce provided the most accurate estimation, while fir showed the worst results. Altitude also affects the results. Although at both low and high elevations, the relationship between correlations and distance remains significant for the three species, correlations at low elevations tend to give negative values even at short distances, so they are less reliable.

CRediT authorship contribution statement

Mauro Bernabei: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Pietro Franceschi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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

The data are freely available.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.176516.

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