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Tracing the origins of Stradivari's resonance wood

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ABSTRACT

Stradivari's violins represent the pinnacle of classical instrument making, yet the origins of the wood used to construct their soundboards have long remained unclear. By analysing 314 tree-ring series from 284 authenticated instruments, we show that the majority of soundboards were crafted from Norway spruce (*Picea abies*) that grew at very high elevations during the severe climatic conditions of the Maunder Minimum. Our data reveal that Stradivari frequently used wood from the same tree for multiple instruments and that its sources can be traced to the Eastern Alps. Comparison with 197 reference chronologies indicates that Stradivari's early work drew on diverse and less easily localised sources. During his "golden age" of production from the early eighteenth century onwards, he consistently selected spruce from high-altitude forests in Trentino, Italy, and most likely from the Val di Fiemme in particular. These findings provide the first large-scale dendrochronological evidence for the geographic and environmental origins of Stradivari's wood and offer new insights into both historical instrument making and the interplay between climate, materials, and musical heritage.

1. Introduction

The instruments made by Stradivari are renowned worldwide for their exceptional quality (Farga, 1942), and their sound and construction techniques have been studied extensively (Hill et al., 1909; Beare, 1987, 1993; Morris *et al.*, 2024), with many investigations having explored the alleged "secrets" behind their excellence (Spinella et al., 2017; Harris, 2023). One of the many unresolved questions concerning Stradivari's work is the origin of the resonance wood used for his soundboards, despite the numerous legends surrounding this topic. One

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such legend, which is perhaps the most accredited (Zorzi, 1985), describes Stradivari's spruce as coming from the forests of Val di Fiemme in Trentino. However, similar legends also refer to other places both in Italy and elsewhere, including the Val Saisera forest in Friuli, Italy; the Pokljuka forest in Slovenia; and the Risoud forest in Switzerland. These legends are linked to a mythological and romantic vision of violin making, and although fascinating, they add to the confusion surrounding the origin of Stradivari's resonance wood.

Even from a strict dendrochronological perspective, the tree rings from Stradivari's instruments show peculiar properties (Cherubini, 2021). The tree-ring series obtained from the instruments generally show weak coherence when compared to reference chronologies from all over Europe (Bernabei, 2021). In contrast, correlations are very high when comparing the violins with each other, which is probably due to the frequent use of wood from the same tree trunk (Ratcliff, 2014). Consequently, the origin of Stradivari's resonance wood still remains largely unknown.

Dendroprovenancing analysis is based on the comparison of an already dated tree-ring series with a sufficiently large and spatially well-distributed number of reference chronologies (Ważny, 2005). Higher correlation values indicate that the environmental factors that influenced the tree growth were similar. Therefore, in theory, with all other factors being equal, a higher correlation value between the tree-ring series can be assumed to reflect the smaller distance between the sites at which the trees grew (Bonde et al., 1997; Bernabei and Franceschi, 2024). Environmental conditions, however, can vary considerably, even between sites that are very close to each other. Altitude, for example, is a parameter that greatly influences the correlation values between series and strongly affects dendroprovenance results (Wilson and Hopfmueller, 2001; Wilson and Topham, 2004).

Many other factors can also influence the correlations between the tree-ring series, including site ecology, woodland population dynamics (such as competition between trees), slope exposure, substrate, anthropogenic disturbance, and the replication and reliability of the reference chronologies themselves. Notably, dendroprovenancing analysis becomes increasingly difficult as one looks further back in time because of the rapid decrease in the availability of long and well-replicated reference series. In spite of these uncertainties, establishing correlations between ring-width series remains the most effective method for dating and provenancing when the nature of the object requires absolutely non-invasive treatment (Bridge, 2012; Bernabei and Franceschi, 2025).

The aims of this study are to investigate the resonance wood that Stradivari used, to estimate the altitude and geographic origin of the source trees, and to assess how his material choices evolved over time. To address these objectives, we examine the most extensive dendrochronological dataset ever compiled for Stradivari's violins, which comprises 314 growth-ring series from 284 authenticated instruments. These data were compared with an extensive network of European reference chronologies spanning a broad latitudinal and longitudinal range—from Slovakia eastward to southern France, and from southern Germany southward to central Italy—encompassing five conifer species.

2. Material and methods

2.1. Stradivari's violins

A total of 284 Stradivari violins were considered in this study (Table 1S, Supplementary Material). Their tree-ring series were dated over recent decades by John Carass Topham (Topham and McCormick, 2000; Topham, 2002, 2003). Among these instruments, 230 soundboards are made up of two parts that are so similar that they are believed to have been made from mirrored sections obtained by splitting the same piece of wood (Bernabei, 2022). In these cases, the tree-ring series of the two halves were averaged, and only the resulting mean curve was considered representative of the instrument. There are 24 soundboards that were made from a single piece of wood, while 30 were made from two pieces, as is customary, but the correlation between the two parts of the same instrument indicated a Student's t value that was below 6, so they were treated as two separate series. Consequently, the total number of tree-ring series analysed was 314.

2.2. Reference chronologies

The tree-ring series of the violins were compared with 197 reference chronologies, which are commonly referred to as master chronologies (Table 2S, Supplementary Material). The master chronologies originate from a geographical area from Slovakia to Southern France and from Germany to Central Italy and includes several species: Norway spruce (*Picea abies* Karst.), European larch (*Larix decidua* Mill.), silver fir (*Abies alba* Mill.), stone pine (*Pinus cembra* L.), and Scots pine (*Pinus sylvestris* L.). Although it is likely that the soundboards of the violins are made of spruce, the other species were also considered to broaden the spatial extent of the comparison and to compensate for gaps in the availability of *Picea abies* master chronologies by including additional conifer species. The complete list of contributors of the master chronologies is provided in Table 3S in the Supplementary Material.

The career of Antonio Stradivari (1644–1737) spanned the second half of the 17th century to the early decades of the 18th century. The tree-ring sequences observed in his instruments often exceed 200 rings, which makes it essential to compare these sequences with reference chronologies covering a period from approximately 1400–1740. This requirement highlights the challenge of finding sufficiently ancient, well-replicated, and geographically distributed reference chronologies for spruce in such analyses. This limitation also eliminated the possibility of *ad hoc* sampling in areas that have been historically reputed to be a source of resonance wood as it is extremely unlikely to find such old living trees. Consequently, it was necessary to rely on reference chronologies constructed primarily from historical and archaeological materials and timber sourced from ancient buildings.

The master chronologies collected in this way may present some critical issues. For instance, the exact origin of the building material is rarely known as it may have been transported over long distances (e.g. Bernabei et al., 2019). Furthermore, the sample depth varies greatly both within and between the reference chronologies. It is also important to note that the selection criteria for construction timber differ significantly from the meticulous standards applied to the selection of violin-making materials, for which defect-free wood with regular rings is highly preferred (Bernabei and Čufar, 2018; Cherubini et al., 2022). These considerations can obviously affect correlations and obscure the results of a dendroprovenancing investigation. Nevertheless, the lack of alternatives prompted us to make our comparisons with all available master chronologies while cautiously evaluating the results and their implications.

2.3. Statistical analysis

The ring-width series of each violin was visually and statistically compared with those of the other instruments and with reference chronologies according to standard methodologies that are commonly applied in the dendrochronological analysis of musical instruments (Bernabei and Čufar, 2019; Čufar et al., 2017; 2022). A substantial portion of the statistical analyses was conducted using R (R Core Team, 2024). To assess the influence of factors such as altitude on the relationship between inter-series correlations and geographical distance, raw individual tree-ring series, that have been georeferenced, were downloaded from the International Tree-Ring Data Bank (ITRDB, Guiterman et al., 2024). Norway spruce was targeted for the reference network due to its traditional use in the construction of violin soundboards. Rather than using archived detrended site chronologies, which are also available on the ITRDB platform, individual tree-ring series were chosen to consistently construct site chronologies to allow for the evaluation of a meaningful inter-series correlation thresholds for grouping violin soundboards.

Data manipulation and plotting were performed using the tidyverse ecosystem (Wickham et al., 2019). Detrending and construction of the site chronologies were performed for dendrochronological analysis in 'dplR' (Bunn et al., 2023), and spatial analyses were performed using the 'sf' package (Pebesma and Bivand, 2023). Uniform Manifold Approximation and Projection (UMAP) was used to visualize the distribution of the individual series in the multidimensional space of the dendrochronological parameters. The exploratory multivariate analysis was performed using the R packages 'tidymodels' and 'embed'. Further processing steps were performed with a set of in-house R scripts, which are available upon request.

The Pearson correlation coefficient was used to perform pairwise comparison between the tree-ring series. Prior to comparison, the individual series were always detrended by applying the 5-year-running-average approach proposed by Baillie and Pilcher (Baillie and Pilcher, 1973). The t statistic (t_{BP}) calculated from the Pearson coefficient was chosen as a direct measure of the similarity among two series (Bernabei and Franceschi, 2025). Descriptive statistics for the violin samples and on the individual ITRDB series were calculated by using the 'rwl.stat' function of the 'dplR' package (Pebesma and Bivand, 2023). Each series was characterized by the following parameters: the mean, median, standard deviation, skewness, excess kurtosis (calculated as Pearson's kurtosis minus 3), the Gini coefficient, and first-order autocorrelation. The coefficient of variation was also calculated.

2.4. Dendroprovenance analysis

The dendroprovenance analysis consisted of several sequential steps, which began with:

a) comparing the descriptive tree-ring characteristics from the violins with reference series for *P. abies* available in the ITRDB. This step helped to contextualize the technical characteristics of the wood and provided an estimate of the likely altitude of the growth sites based on parameters extracted from the violin samples.
b) The violin samples were then grouped based on high dendrochronological similarity. A hierarchical iterative algorithm was used to group the individual series into a set of high-similarity groups. The algorithm can be described as a repeated application of a workflow: (a) identification of the pair of series or groups with the largest t similarity and (b) calculation of the average chronology of the pair. The grouping was stopped when the largest similarity among the elements became lower than a pre-set threshold (tth). An objective threshold value ($t\text{th} = 7.3$) was determined by evaluating the 0.999 quantile of the distribution of t values obtained from comparisons between individual *P. abies* tree-ring series belonging to different reference chronologies (i.e., all possible pairs formed by selecting one series from one chronology and one from another) in the ITRDB (see Table 4S in the Supplementary Material). This choice reflects the rationale of identifying a conservative upper limit for t values that may occur between unrelated chronologies, thus ensuring that only genuinely similar series are grouped together.
c) The resulting groups were dendrochronologically validated while considering factors such as series length and medium- to long-term growth trends (Bernabei and Čufar, 2018). This step identified potential anomalies or inaccuracies in the violin series, including missing rings or double-counted rings.
d) The group chronologies were compared against the full set of georeferenced reference chronologies following the approach described by Bernabei and Franceschi (2024); (2025).

3. Results

Table 1 shows the main dendrochronological parameters of Stradivari violins, including the distribution of the various parameters in terms of the 5th and 95th quantiles, the median, and the mean. The table shows that the average number of growth rings in a Stradivari violin is 122, which corresponds to an average ring width of 0.95 mm.

Table 1
Descriptive characteristics of the tree-rings of Stradivari violins. q05: lower quantile, q95 upper quantile, med: median, stdev: standard deviation, skew: skewness, Gini: Gini coefficient, ar1: first-order autocorrelation, c var: coefficient of variation.

Parameter	q05	q95	med	mean
n (tree rings)	68.00	206.00	111.00	122.09
mean	0.52	1.43	0.95	0.95
median	0.48	1.39	0.90	0.89
stdev	0.17	0.51	0.30	0.31
skew	-0.08	1.48	0.49	0.55
Gini	0.11	0.27	0.18	0.18
ar1	0.61	0.94	0.85	0.83
c var	0.19	0.53	0.33	0.34

The UMAP multivariate embedding proved useful for comparing the violin growth ring series with the complete set of series available for *P. abies* from the ITRDB, where the altitude of the series is known. This analysis took into account the six relevant dendrochronological parameters, as shown in Table 1. The results are summarized in Fig. 1, which provides insights into the likely elevation of the spruce trees used by Stradivari for the construction of violin soundboards.

The UMAP representation was used to preserve the local and global structure of the dataset. Each dot in the plot represents one tree series, with circles showing the position of the 6117 individual *P. abies* samples available in the ITRDB, which were part of studies where elevation information was available. The blue crosses highlight the positions of the set from Stradivari. ITRDB series are colour coded to indicate one of five elevation classes. The plot does not show a clear partitioning of the series in groups, while a general trend in elevation along UMAP2 is clearly visible.

Our results indicate that elevation has a more significant effect on the analyzed dendrochronological parameters than the absolute geographical location. The UMAP embedding places the violin series closer to high-altitude samples, which are well represented at the top part of the sample cloud.

Fig. 1B highlights the trend of the series mean ring-width value and coefficient of variation across the five elevation classes, which were compared with the same parameters calculated for the violins. There is a clear trend in the ITRDB dataset for both parameters, which decrease with altitude. The mean shows a straightforward decrease in growth rate with elevation, and the coefficient of variation shows a decrease that suggests a more consistent growth variability at high altitudes.

Interestingly, for both parameters, the distribution of the violin samples was comparable with or even more extreme than the one observed for ITRDB samples collected at very high altitudes. According to the internal correlation between samples in the same series, the violin samples showed a distribution in line with that of the ITRDB data (Fig. 1S in the Supplementary Material). The presence of groups with mean inter-series t_{BP} larger than 10 suggests the recurrent use of wood from the same tree (Table 2).

For reliable dendroprovenancing, it is greatly beneficial to average several individual series into coherent groups, which helps to remove sample-to-sample variability and to make the results more consistent. In the case of the violin samples, however, this step is challenging due to the absence of prior information regarding sample grouping. To address this, we adopted an untargeted strategy (see Materials and Methods) based on recursive merging of sample pairs or groups of samples that exhibit t_{BP} values that exceed a threshold. The threshold was determined empirically through analysis of the ITRDB dataset (Fig. 2S in the Supplementary Material). The results of this automatic algorithm were then visually inspected and dendrochronologically validated. At the end of

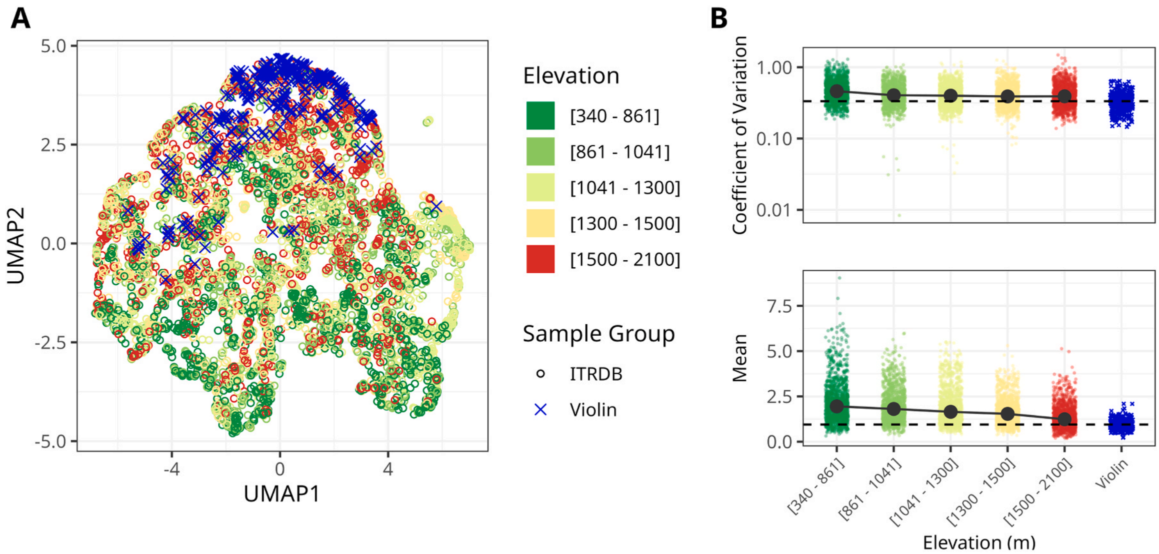

Fig. 1. Comparison of the dendrochronological parameters of the violins with the full set of *P. abies* series available at the ITRDB where the altitude of the series is known. (**A**) Bidimensional UMAP projection of the series in the multivariate space of the parameters. (**B**) Coefficient of variation and mean value of the tree-ring series. The black dots in the altitude classes highlights the median values, and the horizontal dashed line marks the median value of the violins.

Table 2
Characteristics of the 11 violin groups.

Group id	Number of tree-ring series	Median inter-series t_{BP}	First year	Last year
G4	134	5.4	1527	1723
G3	116	4.0	1431	1695
G2	24	13.1	1554	1715
G1	14	11.6	1609	1717
G10	5	7.8	1581	1697
G11	4	5.7	1624	1713
G5	4	8.1	1579	1656
G6	4	10.7	1571	1674
G7	4	8.8	1471	1651
G8	3	10.1	1634	1709
G9	2	14.4	1631	1710

the process, the 314 series were grouped into 11 distinct groups, which are shown in Fig. 2, and their individual characteristics are summarised in Table 2.

Untargeted clustering resulted in highly heterogeneous groups in terms of the number of samples. Groups G3 and G4 account for most of the violin samples (~80 %), and only four groups are composed of more than 10 samples. As can be expected, the median intragroup similarity is lower for large groups, which are expected to account for a large amount of diversity in the individual samples.

The date marked on the violin label was considered as an independent validation of the proposed approach. The label is not always original, or the year indicated on the label cannot always be considered reliable as the actual year of manufacture of individual violins (Bernabei and Čufar, 2018), but it can be used as an approximate indication of the manufacturing period. The association between the four most represented sample groups and the date marked on the violin labels is shown as a dotplot in Fig. 3. Each dot in the figure represents a violin sample, and the pattern of the dots highlights the distribution in time of the samples belonging to each group. The most striking aspect of the figure is the clear partitioning between the samples belonging to G3 and the ones associated with G4/G1/G2. The large majority of G3 samples is indeed coming from violins which were potentially crafted before 1706, while the other three groups were almost exclusively belonging to violins of later production.

A plot showing the group level similarity is included in the Supplementary Information (Fig. 3S). Among the larger groups, G4, G1, and G2 (G4 - G1 ($t_{BP} = 5.9$), G4 - G2 ($t_{BP} = 6.9$)) appear more closely related to each other than G4 and G3 ($t_{BP} = 4.1$). This further suggests a partitioning between early and late violins. Importantly, no label information was used to perform the unsupervised grouping, so these results can be considered an independent validation of the proposed grouping approach.

3.1. *The origin of Stradivari's wood*

The average series of the 11 groups were matched with the full set of 197 reference chronologies. The top three matches for the violin groups with reference chronologies are summarized in Table 4S in the

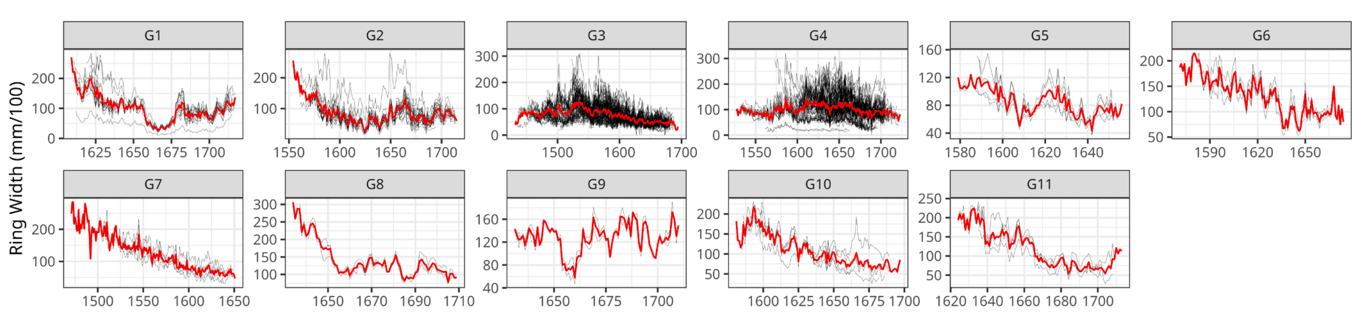

Fig. 2. Average chronologies of the 11 violin groups (Y-axis: ring width in mm/100).

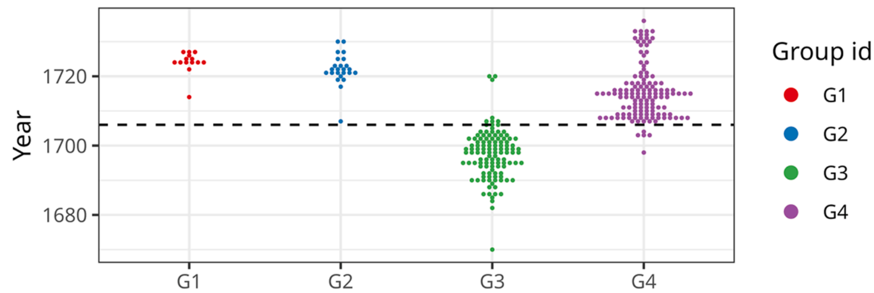

Fig. 3. Association between the year marked on the violin label and the results of the series grouping. The horizontal line highlights the year 1706. Only groups with more than 10 samples are represented.

Supplementary Material. For the four largest clusters (G1, G2, G3 and G4), matches with a t_{BP} greater than 6 were identified with reference chronologies of *Picea abies* and *Abies alba*. The two larger groups G3 and G4 showed positive matching only with *P. abies*, which is consistent with established practice in violin making. The *A. alba* masters show stronger correlations for the two smaller clusters G2 and G1. In the particular case of G1, three out of four matches were with *A. alba* (Table 4S).

To obtain an estimated dendroprovenance, the quantile regression approach introduced by Bernabei and Franceschi (2024) was applied to the Pearson correlation coefficients of the four violin groups with the master chronologies of *P. abies*. The maximum radius resulting from the correlations expressed in kilometres is included in Table 4S and illustrated in Fig. 4 for the four largest clusters.

The larger violin group G4 showed the highest confidence in dendroprovenance. High correlation was indeed found with the ITPA01 and ITPA02 master chronologies with estimated distances of 37 and 30 km, respectively. The second one is relative to the Trentino region, while the first, which shows the largest correlation value, was reconstructed from specimens collected in the Val di Fiemme forests (ITPA01, Tables 2S and 3S). The results obtained for group G3 were less definitive. The average series indeed shows a larger correlation coefficient with the Austrian master ATPA115 from the Lech region. The correlation coefficient was low, however ($corr = 0.4$, estimated $d < 306$ km), allowing only a vague estimation of the dendroprovenance.

For the smaller G2 and G1, the results were not conclusive. The matching with the master of *P. abies* produced correlation coefficients that are compatible with reasonably small distances (G2: $corr = 0.5$, estimated $d < 101$ with ATPA113, G1 $corr = 0.54$, estimated $d < 57$ with ATPA01), but the larger matching of the two groups occurred with masters for *A. alba*. It is also important to highlight that the replication of G1 and G2 is rather small and could lead to less reliable results.

4. Discussion

Stradivari violins are distinguished by their narrow growth rings (mean value = 0.95 mm, standard deviation = 0.31 mm), which are significantly smaller than those observed in many other instruments from the classical period (Bernabei et al., 2022). Such reduced ring widths are generally indicative of trees growing under high-altitude temperature-limited conditions. This inference is supported by Fig. 1, which compares the dendrochronological parameters of Stradivari's violins with the complete spruce dataset from the ITRDB. Even when accounting for potential environmental variables, the characteristics of the wood that Stradivari used seem to indicate that it came from altitudes even higher than those currently occupied by spruce in the Alps (Fig. 1B). We hypothesize that the formation of growth rings was influenced by the enhanced limiting factor of lower temperatures and/or low insolation, possibly associated with the Maunder Minimum (Burckle and Grissino-Mayer, 2003). This period lasted from 1645 to 1715 and was characterized by reduced solar activity, which led to a drop in global average temperatures by between 1 and 2°C, with temperatures treelines lower on a regional scale (Büntgen et al., 2006), resulting in slower tree growth rates and lower relative upper tree-line compared to the present day.

In general, all 314 series show high mutual correlation (Fig. 1S), and more than 90 show $t_{BP} > 10$ when compared with the average series of

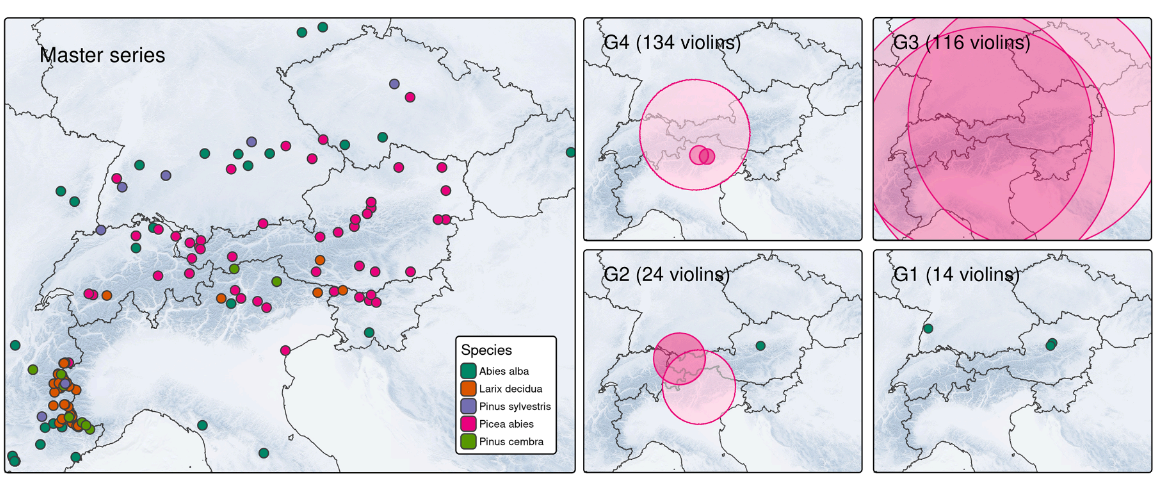

Fig. 4. The left map shows the spatial distribution of the set of the 197 reference chronologies used for cross dating. Different colours highlight the tree species. Regional references were assigned to the centroid of the area. The four maps on the right highlight the position of the three highest matches resulting from the dendroprovenancing of the larger violin groups (G1, G2, G3, and G4). The radii of the circles are proportional to the estimated distance. Additional details about the matching are presented in Table 4S. For the green dots of the silver fir masters, the distance estimate based on correlation is less consistent (Bernabei and Franceschi, 2024) and therefore the distance circle has not been represented.

all the other series. This generalised similarity has caused many difficulties in recognising wood from the same tree and in creating groups with high internal correlation. The repeated use of the same tree can be partly attributed to economic reasons, but it likely reflects a deliberate choice by the maker when he encountered wood with optimal acoustic, workability, and aesthetic properties. This hypothesis is supported by the observation of contrasting cases in which a piece of wood was used only once and then discarded, probably due to unsatisfactory performance. From a statistical perspective, there are several cases in which high Pearson correlation coefficients ($\rho > 0.9$) were found between tree-ring series associated with violins bearing label dates up to 20 years apart (see Supplementary Fig. 4S).

The two-step approach combining an automatic algorithm with dendrochronological validation led to the identification of 11 high-similarity groups. However, the vast majority of samples were concentrated in just two clusters: G3, comprising 116 samples, and G4, comprising 134 samples. Notably, the samples assigned to these two clusters also exhibit a clear chronological division based on the dates reported on the violin labels (Fig. 3). Cluster G3 comprises almost exclusively violins made before 1706, whereas G4 (along with G1 and G2) includes instruments crafted in later years. This division not only supports the validity of the clustering, which is corroborated by its alignment with the labelled production dates, but also suggests a shift in the selection of wood sources over time.

Among the 11 identified violin groups, matches with t_{BP} greater than 6 were found only for the four largest clusters (G1, G2, G3, and G4; Table 4S), and exclusively with master chronologies related to *P. abies* and *A. alba*. A relatively low t_{BP} threshold of 6 was adopted to allow for the detection of potential matches with other species, particularly in regions where reference series for spruce might be lacking. For G3 and G4, which together account for ~80 % of the samples, high correlation values were found exclusively with *P. abies* chronologies.

The situation for G1 and G2 is less clear: while *P. abies* remains a consistent match, in many cases, master chronologies for *A. alba* yielded stronger correlations. This suggests that the possible use of silver fir for soundboards in these groups cannot be entirely excluded, although G1 and G2 exhibit lower replication. Notably, the presence of silver fir in Stradivari violins has not been previously documented, although its use has been reported in other prominent violin-making traditions, such as the Tuscan school (Bernabei et al., 2010; Bernabei and Bontadi, 2011). While the observed similarity between spruce and silver fir chronologies may be attributed to ecological proximity, the high correlation values between the average series of G1 and G2 and several *A. alba* chronologies, particularly Austrian ones, remain noteworthy.

For all groups, the results are consistent with a provenance of wood from the Alpine region, specifically within an area encompassing parts of Italy, Switzerland, and Austria. The accuracy of the origin determination varies considerably among groups, primarily due to differing levels of correlation with the master chronologies. As a general rule, a correlation coefficient greater than 0.5 is considered informative and corresponds to an estimated spatial precision of approximately 100 km (Bernabei and Franceschi, 2024). Because the typical overlaps observed in this study range between 150 and 200 years, this level of correlation is associated with a t_{BP} value exceeding 7.

Among all the groups, G4 exhibited the highest similarity, reaching t_{BP} values of 9.81 and 8.57 with the ITPA02 and ITPA01 master chronologies, respectively. The strongest match was with the Trentino spruce chronology (ITPA02), while the second-best match corresponded to the Val di Fiemme chronology (ITPA01), which is shorter, thus resulting in a reduced overlap with the group chronology. Although dendroprovenancing is based primarily on t_{BP} values (which account for overlap length), we note that the correlation coefficients slightly modify the relative ranking of the two Trentino chronologies, with the Val di Fiemme showing the highest r value. This secondary evidence is consistent with a dendroprovenancing radius of approximately 30 km and further supports the attribution to the eastern Trentino region, particularly the area surrounding the Val di Fiemme forest.

Unlike the observations for G4, the dendrochronological match for G3 is less informative. The correlation is below 0.5 for ATPA115, an Austrian master chronology from the Lech region, and as such, this result cannot support more than a vague provenance determination. As discussed by Bernabei and Franceschi (2014), low correlation values can also occur at short geographic distances, making the results for this group largely inconclusive. Additional evidence, however, highlights the peculiar nature of G3. First, it shows limited overlap with the entire set of master chronologies, with only one match with a t_{BP} value greater than 6, as shown in Fig. 3S. Furthermore, it exhibits the lowest median internal similarity ($t_{BP} = 4.0$), as well as weak similarity with G4 ($t_{BP} = 2.2$). Notably, group G3 encompasses the overwhelming majority of samples associated with violins manufactured prior to 1706. As discussed above, this observation suggests a significant change in Stradivari's wood-procurement strategy after 1706, with a transition towards sourcing timber from the Val di Fiemme forests.

Three principal phases are usually recognized in the production of Antonio Stradivari's instruments, and each one is distinguished by specific constructional and artistic characteristics (Beare, 1987; Morris and Smith, 2024). The "early period" (c. 1666–1680) is marked by instruments modelled after those of Nicola Amati, featuring smaller dimensions, refined craftsmanship, and an emerging acoustic quality that has not yet fully matured. The "transition period" (c. 1680–1700) is characterized by increased experimentation, with larger instrument dimensions and a noticeable enhancement in tonal quality. The "golden age" (around 1700–1725) represents the peak of Stradivari's production, when he crafted instruments of remarkable formal and acoustic excellence with luminous varnishes.

This was followed by a late period (1725–1737), during which there was a gradual decline in production and a potential decrease in overall quality, although several instruments from this phase still display exceptional characteristics. The transition from group G3 to group G4 (Fig. 3) coincides with Stradivari's transition from his experimental phase to his period of maturity. Around 1700, Stradivari seems to have stopped using wood from mixed or variable sources and instead identified an optimal source in the high-altitude forests of eastern Trentino, most likely in the Val di Fiemme area, with only a few sporadic exceptions later occurring northward, as suggested by the correlations of groups G1 and G2 with Austrian reference chronologies (Table 4S, Supplementary Material).

5. Conclusions

Numerous legends surround Stradivari's violins, which are often rooted in a mythologized perception of the luthier. This study represents the most comprehensive dendrochronological investigation ever conducted on Stradivari's violin production. The results revealed frequent use of wood that was from the same trunk, from high-altitude sites, and subject to an enhanced growth-limiting factor, which was probably related to low temperatures as a consequence of the Maunder Minimum. The vast majority of the material was traced back to the Eastern Alps and adjacent Central European regions. The identification of groups with high internal similarity suggests that around the early 1700 s, Stradivari ceased using materials of mixed provenance and began to favour wood sourced from high-altitude forests in the Val di Fiemme area. This result supports the well-documented qualitative evolution of Stradivari's craftsmanship, which reached its peak known as the "golden period" in the early 18th century.

CRediT authorship contribution statement

Nicola La Porta: Writing – review & editing, Data curation. **Frédéric Guibal:** Writing – review & editing, Data curation. **Michael Grabner:** Writing – review & editing, Data curation. **Katarina Čufar:** Writing – review & editing, Data curation. **Pietro Franceschi:** Writing – review &

editing, Writing – original draft, Validation, Supervision, Software, Methodology, Investigation, Formal analysis, Data curation. **Mauro Bernabei:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Klaus Pfeifer:** Writing – review & editing, Validation, Data curation. **Olivia Pignatelli:** Writing – review & editing, Data curation. **Nicoletta Martinelli:** Writing – review & editing, Data curation. **Paolo Cherubini:** Writing – review & editing, Data curation. **Rob Wilson:** Writing – review & editing, Data curation, Conceptualization. **Marco Carrer:** Writing – review & editing, Data curation. **John Carass Topham:** Writing – review & editing, Data curation, Conceptualization. **Ulf Büntgen:** Writing – review & editing, Data curation. **Willy Tegel:** Writing – review & editing, Data curation. **Ilaria Stefani:** Writing – review & editing, Investigation, Data curation. **Andrea Seim:** Writing – review & editing, Data curation.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2026.126480.

Data availability

Data will be made available on request.

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