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Lisa Shindo, Mélanie Saulnier, Hendrik Raese, Frédéric Guibal, Jean-Louis Edouard, et al.. European larch sapwood: A model for predicting the cambial age and for a more accurate dating. *Dendrochronologia*, 2024, 83, pp.1-11. 10.1016/j.dendro.2023.126150 . hal-04504206

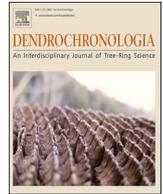
HAL Id: hal-04504206

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European larch sapwood: A model for predicting the cambial age and for a more accurate dating

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ARTICLE INFO

Keywords:

Larix decidua
European Alps
Sapwood
Felling date
Precise dating

ABSTRACT

European larch (*Larix decidua* Mill.) holds significant importance as a forest tree species throughout the Alps and in certain regions of central Europe. Its extensive use as construction timber has made it a subject of substantial interest in dendroarchaeological studies aimed at understanding the long-term interactions between human societies and forests. Precise dating of felling phases, accurate estimation of the age of harvested wood, and information on the geographical origin of wood play a crucial role when it comes to characterize these interactions. In this study, we compiled a large dataset of *L. decidua* samples from across the European Alps to provide a robust statistical model that predicts the cambial age of *L. decidua* trees based on the number of heartwood rings. By extension, this model can be used to estimate the number of sapwood rings so as to approximate the felling date and to more precisely date archaeological larch timber. The model requires almost complete heartwood sequences (<5 missing rings) to achieve accurate estimations. Our results also evidence that the ratio between the number of sapwood and heartwood rings varies across the Alps. At the same time, the indicator developed in this work is not suitable for a determination of wood origin, raising doubts about the effectiveness of attempts aimed at dendroprovenancing *L. decidua* based on sapwood.

1. Introduction

The general concept of dendrochronology is straightforward and relies on the fact that tree rings visible in the wood of many species serve

as sequential recorders of time. Each individual ring represents the growth that occurred from the beginning to the end of a given growing season for that species in a given area (Manning, 2023), therefore enabling precise dating of wood sequences to a calendar year. Through

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cross-dating with reference chronologies, and provided that the bark is present or the waxy edge is visible on the examined timber (Kaennel and Schweingruber, 1995), the outermost ring can be attributed to the year the tree died, what in many cases corresponds to the felling of the tree. Dendrochronology thus stands as the most accurate absolute dating method in archaeology, allowing the dating of timber with (sub)-annual resolution. In addition, it provides archaeologists valuable insights into the occupation phases of a given site and the origin of wood (dendroprovenancing). These insights, in turn, shed light on the co-evolution between societies and their forest environment, providing crucial knowledge for research (D'Andrea et al., 2023).

In many instances, however, remaining archaeological wood will be squared or eroded, and its outer part (i.e. sapwood and/or bark) will thus often be missing. To accurately determine felling dates, efforts have been made to estimate the number of missing rings, particularly for species with recognizable sapwood (e.g., Hollstein, 1965; Kuniholm and Striker, 1983; Hillam et al., 1987; Wazny and Eckstein, 1991; Lambert et al., 2005; Durost and Lambert, 2006; Sohar et al., 2012; Shindo et al., 2018). Sapwood is the xylem compartment located between the heartwood and the bark, containing reserve materials and ensuring sap and water transport (IAWA, 1964). It is easily recognizable in certain tree species such as oak (*Quercus* sp.), sweet chestnut (*Castanea sativa* Mill.), Scots pine (*Pinus sylvestris* L.), Swiss stone pine (*Pinus cembra* L.) and European larch (*Larix decidua* Mill.). Yet, it is also susceptible to decay due to the absence of toxic extractives which are present in the heartwood of the listed species. When part of the sapwood is preserved, felling dates can still be determined by relying on estimates of sapwood counts, derived from tree-ring records with complete sapwood (Schweingruber, 1988). This estimation requires precise knowledge of the probability distribution and derived statistics of sapwood rings for each studied species. In cases where sapwood is absent due to squaring or removal by wood-destroying insects (Blanchette et al., 1998) or when it is no longer recognizable due to discoloration (Schmidt, 2006), dendroarchaeologists typically define a *terminus post quem* date, that is the earliest possible date of felling. To assess a felling date with a limited number of sapwood rings, several studies have estimated the number of missing rings using the mean width of preserved sapwood rings (Klein et al., 1986; Klein, 1994; Haneca and Debonne, 2012) or the last heartwood and sapwood rings (Gassmann, 1984; Bleicher et al., 2020). More recently, heartwood-based models have been developed for softwood species by which the number of sapwood rings are estimated from the number or width of heartwood rings (Gjerdrum, 2003, 2013; Edvardsson et al., 2022). Such methods are crucial in enabling a more precise dating of archaeological wood in cases where the sapwood is not fully preserved or identifiable.

Likewise, dendrochronology also yields essential information on the provenance of timber (Domínguez-Delmás, 2020): traditionally, tree-ring series from the wood under study are correlated with site or regional ring-width chronologies (Baillie, 1982). The reference chronology that exhibits the strongest statistical match is considered the potential source area of the wood (Eckstein et al., 1986; Wazny, 1992, 2002; Bonde et al., 1997; Haneca et al., 2005; Kuniholm et al., 2007; Daly, 2007; Eißing and Dittmar, 2011; Bridge, 2012). Pattern-matching dendroprovenancing studies can be further enhanced by various scientific techniques including visual, genetic and chemical methods (Dormontt et al., 2015; Van Ham-Meert and Daly, 2023). Among these methods, the number of sapwood rings - which has been demonstrated to vary for certain species depending on the provenance of trees (Hillam et al., 1987; Sohar et al., 2012; Sohar, 2013; Prokop et al., 2017) - represent a cost-effective approach to enhance the accuracy of timber provenance determination. Integrating this information with traditional pattern-matching dendroprovenancing methods can therefore provide more precise insights into the geographic origin of archaeological wood samples.

While estimations of sapwood rings for dating and provenance assessments have traditionally focused on oaks, the most widely studied

species in dendroarchaeology, this study focuses on European larch (*Larix decidua* Mill.). The European larch stands out as a suitable species due to its clear transition between darker heartwood and lighter sapwood, making it easily recognizable. *L. decidua* has been extensively studied in the field of dendrochronology since the 1970s including the European Alps, where it has been used extensively in construction (Boccaleri, 1985; Donati, 1988; Orceel and Orceel, 1988; Büntgen et al., 2004, 2006a; Edouard, 2010; Shindo et al., 2018; Labbas et al., 2022). At the same time, *L. decidua* has also been exported to the Mediterranean basin for various purposes, including shipbuilding (Terrer, 1978; Braunstein, 1988; Guibal and Pomey, 2003; Pignatelli, 2014). Research on tree rings of *L. decidua* also covers various other fields of dendrochronology such as the reconstruction of climate (Serre, 1978; Tessier, 1986; Belingard and Tessier, 1997; Gindl et al., 1999; Büntgen et al., 2006b; Carrer and Urbinati, 2006; Edouard et al., 2009; Nicolussi et al., 2009; Tessier and Edouard, 2010; Saulnier et al., 2019; Esper et al., 2007, 2020), mass movements (Pelfini, 1999; Stoffel et al., 2006, 2010; Corona et al., 2010, 2013) and larch budmoth outbreaks (Pignatelli and Bleuler, 1988; Rolland et al., 2001; Nola et al., 2006; Moser et al., 2010; Saulnier et al., 2017), or the analysis of climate-growth relationships (Motta and Nola, 2001; Johnson et al., 2010; Saulnier et al., 2019). The widespread use of *L. decidua* has resulted in the creation of a dense and multi-millennial network of larch tree-ring series across Europe, at elevations ranging from 500 to 2600 m asl, covering a substantial portion of the species' distribution.

To date, two studies (Corona, 1984; Gjerdrum, 2013) attempted to predict the number of rings in larch sapwood. In a pioneering work, Corona (1984) demonstrated that the number of sapwood rings increased with cambial age in 150 *L. decidua* trees from Italian Trentino. Gjerdrum (2013) used a dataset of 369 larch trees sampled in Alpine countries, including Austria, France, Germany, Italy, Slovenia, and Switzerland, with tree ages ranging from 11 to 269 years. The study estimated the number of sapwood rings in *L. decidua* to be around $19 (\pm 7)$. However, in contrast to oak studies, these estimations are based on a relatively limited number of samples and locations across Europe. The small dataset did not therefore allow for an accurate estimation of the number of sapwood rings or the validation of the hypothesis that the number of rings may vary according to ontogenetic or environmental factors. As a result, these limitations still restrict our ability to precisely estimate felling dates of *L. decidua* timbers and/or the inclusion of sapwood ring numbers as an additional marker for dendroprovenancing studies. To address this knowledge gap, we (i) compiled a unique dataset of 1925 *L. decidua* tree-ring series from various locations across Europe, with the aim to provide a more comprehensive and diverse representation of *L. decidua* tree-ring characteristics and to allow for a more robust analysis and estimation of the number of sapwood rings; (ii) grouped the tree-ring series based on their provenance to examine potential regional variability in the number of sapwood rings that could be useful in dendroprovenancing studies; (iii) tested different models to predict felling dates of trees based on the number of sapwood and/or heartwood rings. By applying various models to the dataset, the study also sought to identify the most accurate and reliable approach to estimate felling dates of *L. decidua* trees using their tree-ring characteristics.

2. Material and methods

2.1. Samples and laboratory treatment

In the context of this study, we compiled a database consisting of 1925 samples from both living and dead *L. decidua* trees. All increment cores and wood sections used were collected between 1973 and 2007 and sampled from various ecological contexts within the European Alps (Fig. 1). Unlike archaeological timber, for which the provenance is often unknown, the precise location of each tree is accurately documented. Increment cores from living trees were taken at breast height (1.3 m above the soil surface) using an increment borer. In the case of dead

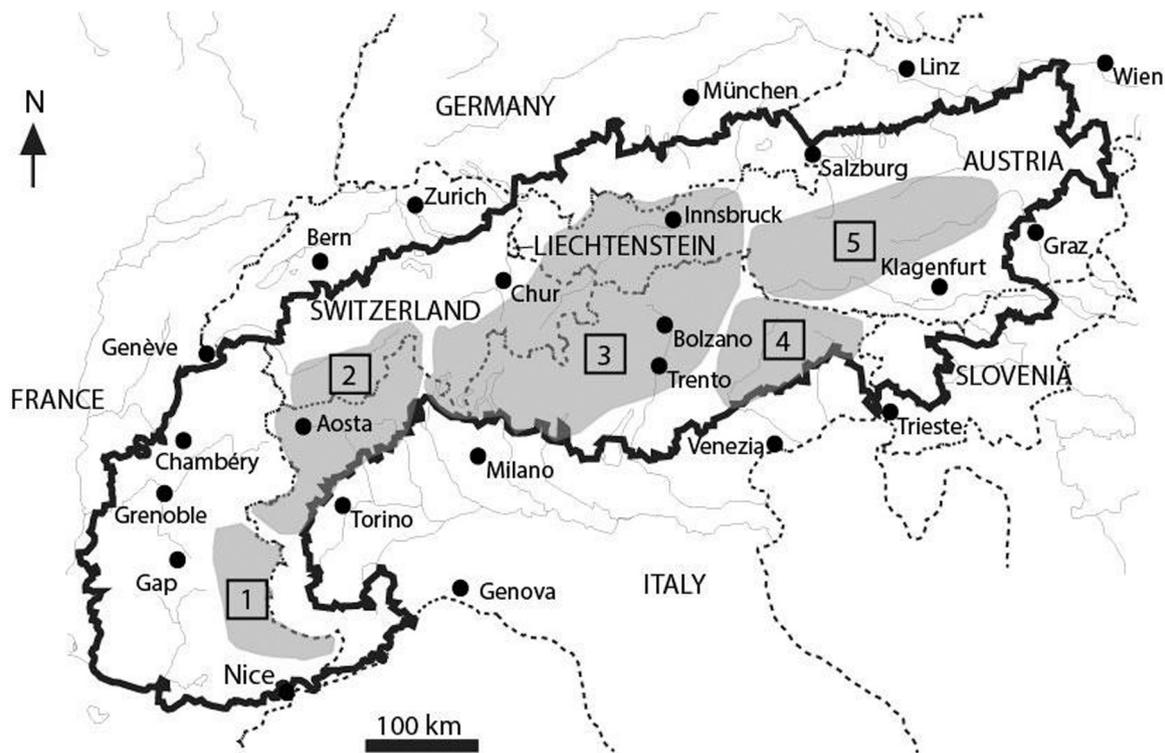


Fig. 1. Geographical distribution of European larch (*L. decidua* Mill.) tree-ring samples from the European Alps. The study area, represented by the European Alps, is delineated with a black line. The five geographical groups, each highlighted in grey, correspond to distinct regions within the Alps where the *L. decidua* tree-ring samples were collected.

wood, thin sections were examined under the microscope along the transverse, tangential and radial planes to confirm the species, following the methodology described by Schweingruber (1978). Once the species was confirmed as *L. decidua*, all samples were sanded or surfaced using a razor blade to enhance visibility of ring anatomy and boundaries. Finally, rings were systematically counted under a binocular (Schweingruber, 1988).

The cambial age (A_c) of each sample was defined as the total number of tree rings counted on the sample, starting from the pith and extending towards the bark. Noteworthy, trees were not sampled at the stem base, and as a result, the number of years (annual rings) it took the tree to grow from seedling to 1.3 m has not been recorded on the sampled cores. Therefore, the age distribution only represents the age of the sampling height, and does not represent inception or germination dates of the trees (Telewski, 1993; Villalba and Veblen, 1997). In addition, in the case of increment cores, and to mitigate the potential bias caused by missing rings near the pith, we only included samples that had five or fewer rings missing towards the pith in our analysis. In addition to cambial age, we also determined the number of sapwood rings (As) and heartwood rings (Ah) on each sample. As ring-width measurements were not recorded systematically by the different contributors of tree-ring material, ring width was not considered as a variable in our analysis.

2.2. Statistical analysis

2.2.1. Sapwood characteristics

We first characterized the distribution of sapwood ring numbers within the samples using statistics including the minimum, maximum and mean, as well as the standard deviation.

2.2.2. Age and regional effects

The number of sapwood rings shows a rapid increase in young trees but the shape of the distribution changes as the trees age, revealing a non-linear distribution (Fig. 3B). To identify the main breakpoints in the

growth patterns, we used a segmented regression model allowing for the estimation and inference of regression models between the number of sapwood rings and the cambial age with piecewise linear relationships, using the package segmented in R (Muggeo, 2003). Subsequently, based on the model's results, we classified our samples into three groups, namely young (< 141 years), mature (141 to < 253 years), and old (≥ 254 years) trees. We disregarded trees older than 600 years (Fig. 3B) as they are scarce in the dataset and thus considered as outliers in our distribution.

Regional and local environmental conditions have been reported to influence *L. decidua* wood formation (Schweingruber, 1988; Cook and Kairiukstis, 1992; Saderi et al., 2019). To test for a potential regional effect and to explore the potential for the region of wood origin to be identified wood based on the number of sapwood rings, we categorized the larch populations into five groups based on the bioclimatic characteristics of their respective location: (1) Southern French Alps, (2) West Italian Piedmont and Valais (Switzerland), (3) Trentino – Lombardy – South (all Italy) and North Tyrol (Austria), (4) Italian Veneto and Friuli, (5) East Tyrol and Styria (Austria) (Fig. 1).

Due to significant variations in both (i) the number of available trees in each group (Fig. 2) and (ii) the mean cambial age per group, we introduced a response ratio variable As/Ah representing the ratio between the number of sapwood.

(As) and heartwood (Ah) rings. This approach allows accounting for the group differences and normalizing the data for comparative analysis.

To assess both the age and regional effects, we performed pairwise comparisons on the number of sapwood rings and response ratios using *t*-tests with adjusted *p* values following Holm (1979). In case of variance heterogeneity, we used the Welch-Satterthwaite equation to approximate the degrees of freedom for more accurate results (Sokal and Rohlf, 1995).

2.2.3. Estimation of felling dates

Cambial age and the number of heartwood rings shows a clear linear

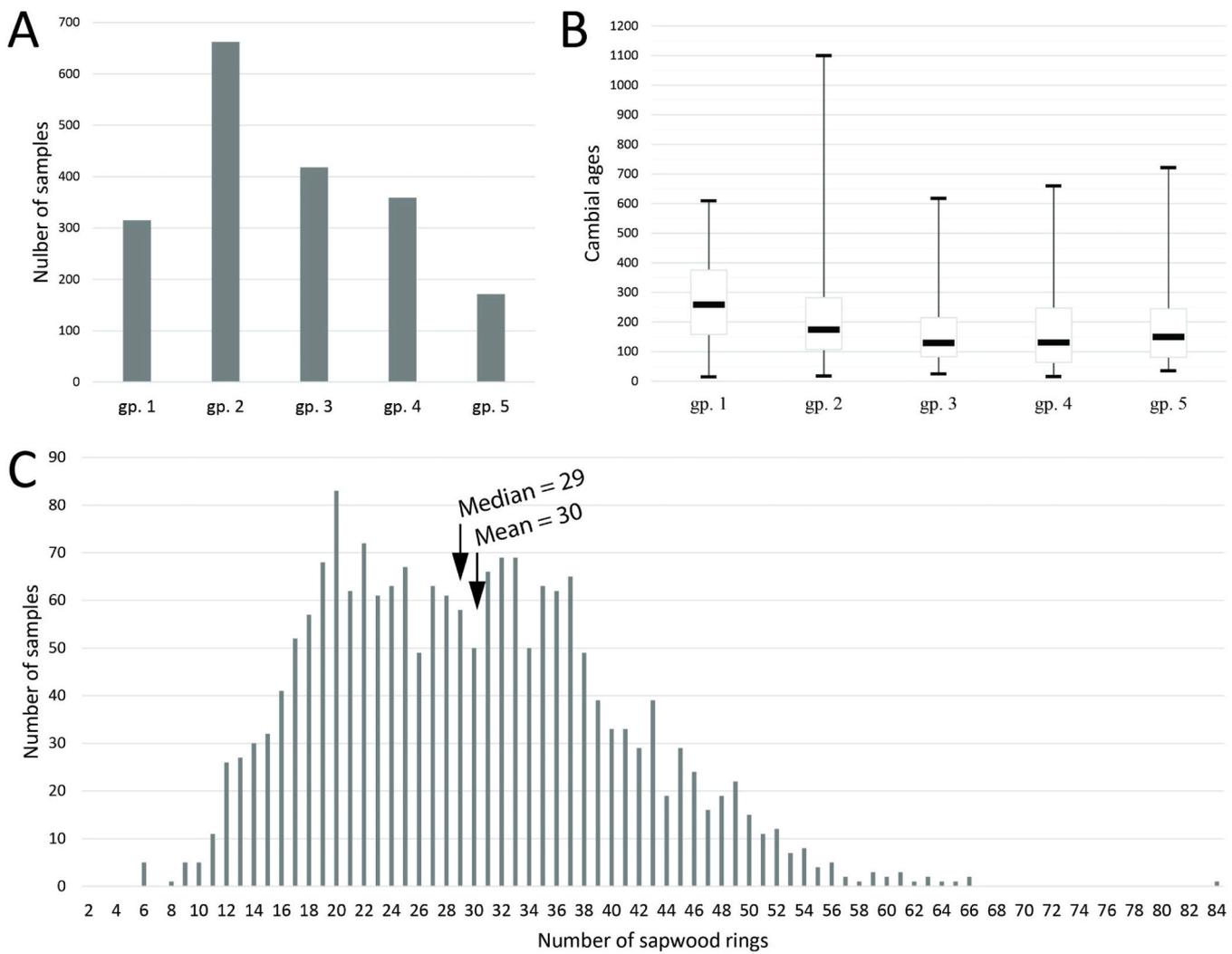


Fig. 2. Number of samples by geographical group (A); box plots of the cambial age distribution for the five geographical groups (B); number of sapwood rings for the entire dataset (C).

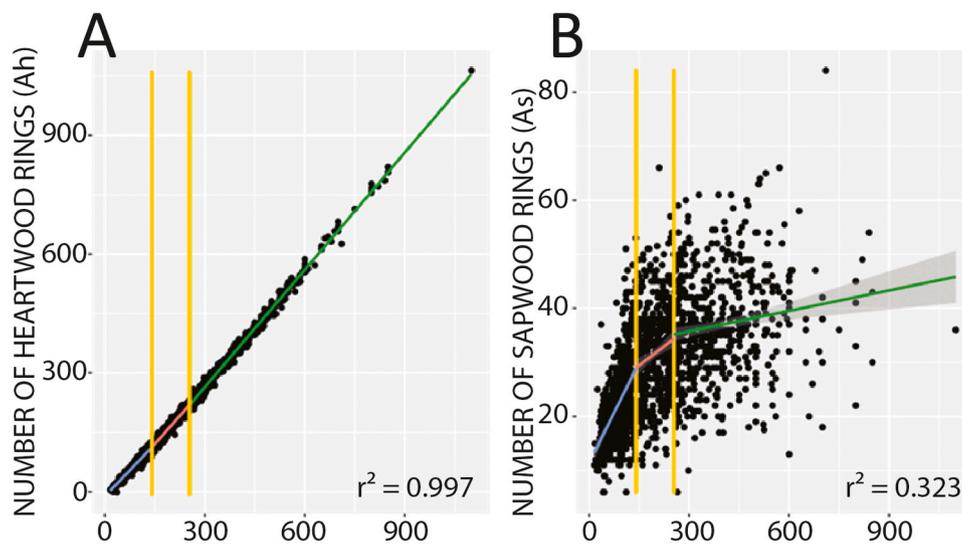


Fig. 3. Relationships between cambial age and the number of (A) heartwood and (B) sapwood rings. Black dots represent the tree-ring series. The two yellow lines mark changes in the linear relationship between the number of sapwood rings and cambial age identified by the segmented approaches, between young and mature trees (141 years) and between mature and old trees (254). Blue, red, and green lines indicate the linear smoothing curves according to age classes, capturing the underlying trends in the data.

relationship (Fig. 3A, $r^2 = 0.997$). Conversely, as shown in Fig. 3B, the relation between cambial age (Ac) and the number of sapwood rings (As) are characterized by a non-linear pattern with high dispersion of the number of sapwood rings (Fig. 3B, $r^2 = 0.323$).

To model relationships between cambial age and the number of heartwood rings in *L. decidua*, we thus employed a linear regression. Yet, due to the non-normal distribution of cambial ages and the number of heartwood rings, a square root transformation (Eq. 1) had to be applied to the data. This transformation helps address the non-normality and meet the assumptions required for the linear regression analysis. The model is represented as:

$$\text{sqrt}(A_c) = a + b \cdot \text{sqrt}(A_h) + e \quad (1)$$

where $\text{sqrt}(A_h)$ and $\text{sqrt}(A_c)$ are the square root of the number of heartwood rings and the square root of the cambial ages (total number of rings) respectively, and a and b are the intercept and the slopes of the regression, and e are the residuals.

Additionally, we tested a diverse set of models to estimate the number of sapwood rings. The models used included extended linear models (Generalized linear models [GLM], Linear mixed models [LMM], Multivariate adaptive regression spline [MARS]) and machine learning methods (Gradient boosting machines [GBM], XGBoost, Random Forest [RF] and quantile regression forest [qRF]). The predictors used in the models included the number of heartwood rings, the regional group and an estimate of the altitude for the original living tree location. As some models only work with numerical independent variables, instead of one-hot encoding, the categorical predictor for the regional group was transformed using the R-package "vtreat" (Mount and Zumel, 2021) to a value of a (cross-validated) one-variable regression model for the number of sapwood rings as a function of the region. Before modelling, all data entries were checked for outliers. Any data entries with an exceptionally high number of sapwood (> 61 rings, $n = 6$) or heartwood (> 563 rings, $n = 26$) rings were removed from analysis. For the LMM the number of heartwood rings was used as a fixed effect and a nesting of the altitude and the transformed value for the regional group as random effects. To develop the machine learning models, we split the data into training ($n = 1112$) and testing ($n = 275$) subsets. The predictive power of all linear and machine learning models was compared with a validation ($n = 75$) subset.

All analyses were performed in R software (version 4.2.2) using the packages "treeclim" (Zang and Biondi, 2015), "FactomineR" (Lê et al., 2017), "lme4" (Bates et al., 2015), "stats" (R Core Team, 2022), "caret" (Kuhn, 2022), "vtreat" (Mount and Zumel, 2021) and "quantregForest" (Meinshausen, 2017).

3. Results

3.1. Number of sapwood ring

The compiled dataset includes 1925 samples with an average cambial age of 205 ± 147 years. The mean number of sapwood rings is 30 ± 11 (min. 6, max. 84) (Table 1 and Table A in the Supplementary Material); the median number of sapwood rings is 29. Sapwood rings

Table 1

L. decidua numbers of sapwood ring for three age classes in each of the five regions of the European Alps investigated.

Sapwood rings	Mean	Median	Min.	Max.	Standard deviation	Upper and lower limit of the 95% standard deviation	Variation coefficient
All ($n = 1925$)	30	29	6	84	11	[29.59; 30.4]	37%
Age classes							
Young ($n = 838$)	23	22	6	53	8	[22.54; 23.46]	34%
Mature ($n = 513$)	32	32	11	66	9	[31.35; 32.65]	27%
Old ($n = 574$)	37	36	6	84	10	[36.31; 37.68]	27%
Regions							
1 ($n = 315$)	34	33	6	66	9	[33.16; 34.84]	26%
2 ($n = 662$)	28	26	6	84	11	[27.30; 28.70]	39%
3 ($n = 418$)	30	30	6	62	11	[29.11; 30.9]	37%
4 ($n = 359$)	29	28	6	61	11	[28.04; 29.96]	38%
5 ($n = 171$)	29	29	9	54	10	[27.74; 30.26]	34%

and cambial age variables do not follow a normal distribution.

3.2. Age and regional variability

The mean number of sapwood rings in mature (32 ± 9) and older (37 ± 10) trees is higher than in younger (23 ± 8) trees. Pairwise comparison confirmed an age effect in the mean A_s/c ratio with significant differences between the age classes (Fig. 5 and Table 1). Based on the increase in the number of sapwood rings as a function of age, we argue that samples with less than 23 sapwood rings most likely originate from young larch trees (<141 years) For example, in the actual dataset, among the 577 trees with less than 23 sapwood rings, there are 463 young, 73 mature and 41 old. Conversely, samples with 37 or more sapwood rings are likely from old larch trees aged 254 years or older. This is again confirmed by the number of trees among the 497 with more than 37 sapwood rings: 57 young, 158 mature and 282 old.

Differences in the number of sapwood rings between age groups are also observed at the regional scale (Fig. 4 and Fig. A in the Supplementary Material), with notable variations in group 4. The number of sapwood rings in young trees within this group is 22 ± 6 , while in mature trees, it increases to 34 ± 8 . Interestingly, this specific region (group 4) also exhibits the highest mean number of sapwood rings (40 ± 9) in old trees. (Table A in the Supplementary Material).

Results of the pairwise comparisons confirm substantial variations in the A_s/c ratio between regions, particularly between groups 1–2–3 and 4–5, as illustrated in Fig. 6. Notably, significant differences are observed when comparing group 1 to groups 4 and 5, group 2 to groups 4 and 5, and group 3 to group 4, respectively, as presented in Table 2. For eastern populations, the A_s/c ratio is consistently higher than 0.2, suggesting a relatively higher number of sapwood rings in relation to cambial age. In contrast, the western population consistently exhibits an A_s/c ratio below 0.2, indicating a lower number of sapwood rings with respect to cambial age. These findings highlight regional disparities, with eastern populations showing a more pronounced sapwood ring formation relative to their cambial age compared to the western populations.

3.3. Cambial age estimation

The linear model applied on the training dataset provided very significant results ($R^2 = 0.993$, $p < 0.001$, Fig. 7A, RMSE=0.34, initial variable ranging from 3.5 to 32.6). The resulting equation for the model can thus be expressed as follows:

$$\text{sqrt}(A_c) = 1.80 + 0.95 * \text{sqrt}(A_h) + e$$

The prediction of cambial age based on the results of model 1 applied to the verification dataset provides a correlation between predicted Ac and real value of Ac of about 0.995 (Case studies at the end of the Supplementary materials). This high correlation indicates that the model's estimations align closely with true cambial age values, further affirming its accuracy and predictive capability.

Estimating sapwood ring numbers with extended linear and machine learning models does not yield significantly different results than the simple linear model, even when incorporating additional information on

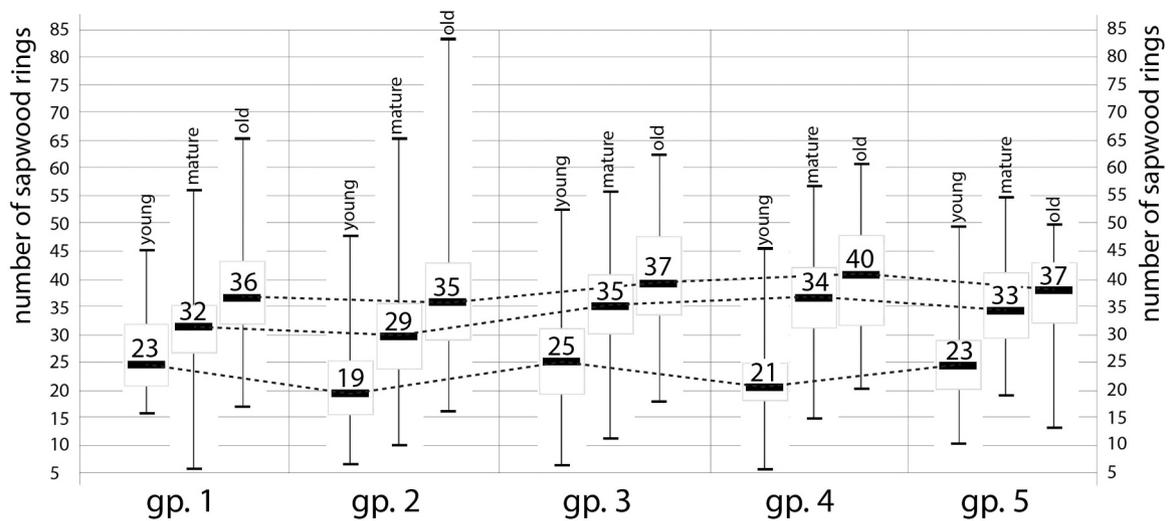


Fig. 4. Box plots of the number of sapwood rings for young, mature, and old *L. decidua* trees in each of the five regions of the European Alps. Each box plot shows the minimum, maximum, median, as well as the first and third quartiles (25th and 75th percentiles) of the cambial age for each region (gp.1-gp.5). To enhance readability, we added the numerical value of the median in each box plot.

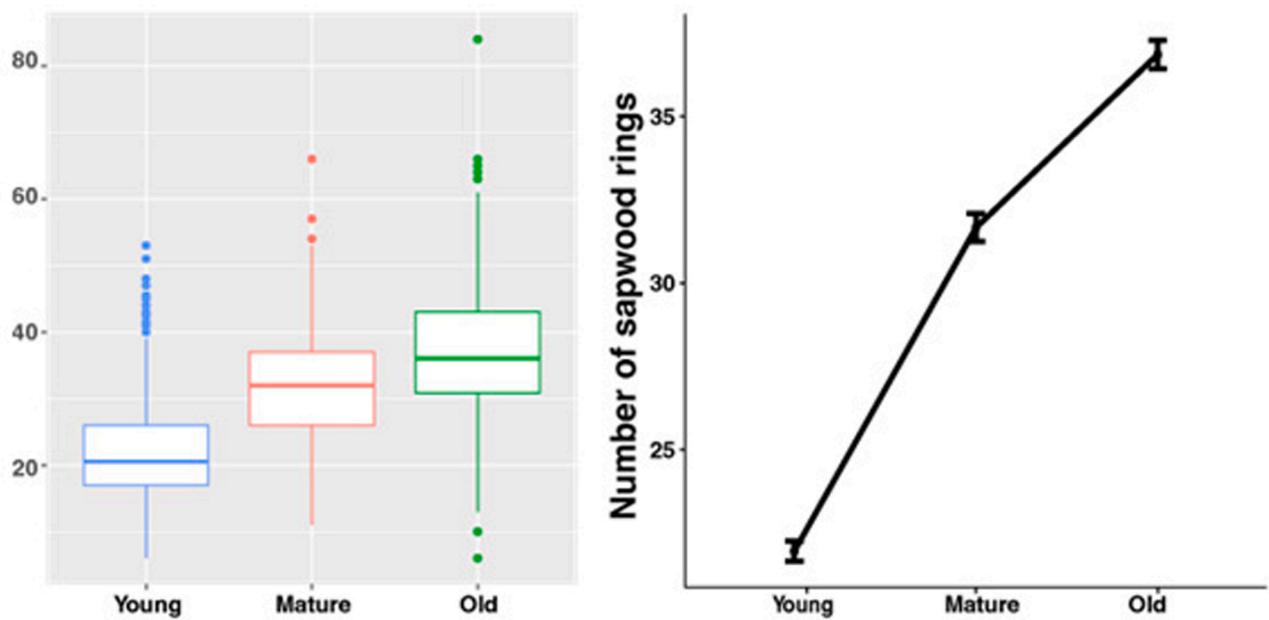


Fig. 5. Boxplots (left panel) and pairwise t-test (right panel) results with adjusted p-values (Holm, 1979) for the number of sapwood rings among the three age class groups of trees.

regional groups and estimated altitude. When re-predicting on the training (T) or predicting on the independent validation (V) data sets, the different models show similar prediction intervals (PI) at the 95% confidence level (Fig. 8), which indicates a good generalization of the models and no significant overfitting. The extended linear model, particularly the Linear Mixed Model (LMM), showed the best performance (Fig. 8A, C). The LMM yielded higher mean ranges of the PI for the different age classes: young (T: 26.3, V: 26.1), mature (T: 31.6, V: 30.1), and old (T: 35.7, V: 32.8). These findings suggest that incorporating additional variables through extended linear and machine learning modelling does not significantly alter the overall predictive performance as compared to the simple linear model. The asymptotic relationship observed in Fig. 3B remains consistent across approaches.

Extracting prediction intervals for machine learning models can be challenging; using a variant of the Random Forest algorithm, the

Quantile Regression Forest (qRF) (Meinshausen, 2006), is considered useful in the context of this research. To find the best model parameters, we conducted a 10-fold cross-validation. The results obtained from the qRF show slight improvements in the estimation of the mean number of sapwood rings and narrower prediction intervals (PI) (Fig. 8B and D) compared to the LMM, while remaining otherwise similar for the three age classes: young (Training: 17.4, Validation: 20.8), mature (Training: 25.8, Validation: 27.9), and old (Training: 27.8, Validation: 28.0).

The prediction interval is an indicator for the reliability of the predicted number of sapwood rings and shows the upper/lower limit of the range sapwood ring numbers for the selected confidence level. Here, the 95%-PI generally widens with increasing heartwood ring numbers (Fig. 8), showing that the estimation of sapwood rings is less reliable for older trees. Yet, we observe that the ratio between cambial age and the prediction interval is higher for young trees (25–30.5%) but decreases

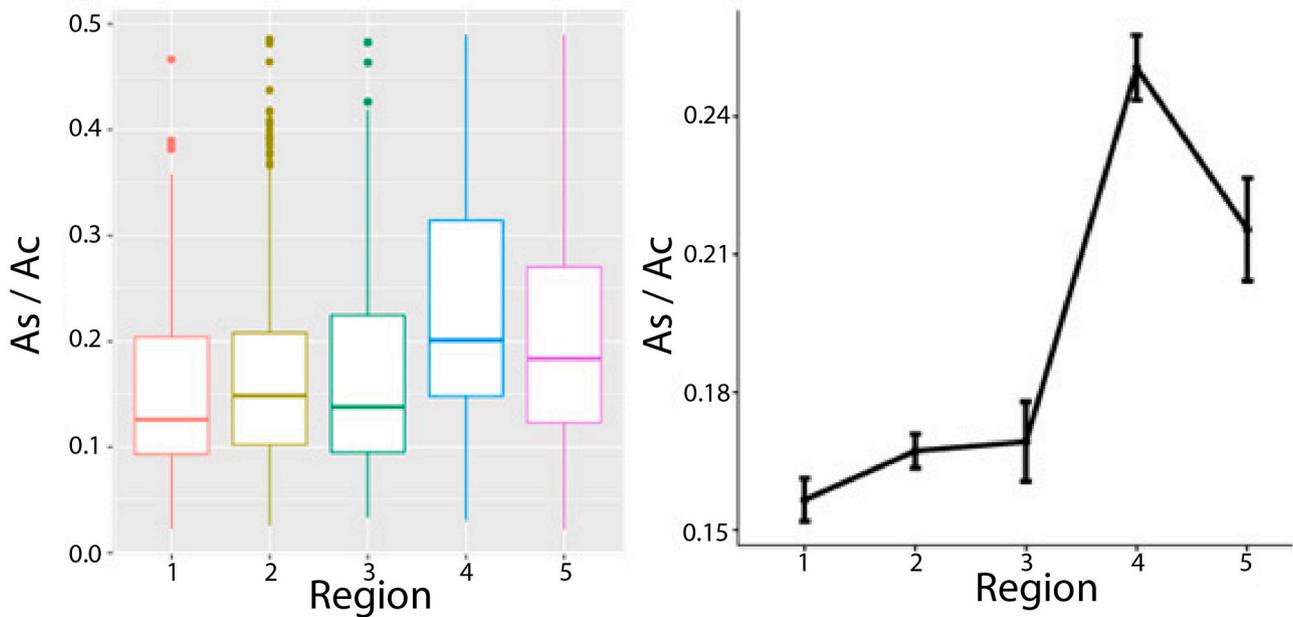


Fig. 6. Boxplots (left panel) and pairwise t-test (right panel) results with adjusted p-values (Holm, 1979) for the response ratio (Sapwood ring / Cambial age or As/AC) according to the regional origin of trees.

Table 2
One-way ANOVA and pairwise t-test results.

Variables	Group	Oneway anova (Welch correction)			Pairwise t-tests	
		f	p value	signif.	p value	signif.
Regional provenance	GRs 1-2	36.706	< 2.2e-16	***	0.75344	
	GRs 1-3				1.00000	
	GRs 1-4				< 2e-16	***
	GRs 1-5				2.5e-05	***
	GRs 2-3				1.00000	
	GRs 2-4				< 2e-16	***
	GRs 2-5				0.00063	***
	GRs 3-4				2.4e-11	***
	GRs 3-5				0.01216	.
	GRs 4-5				0.08183	.
Age groups	Young-Mature	986.06	< 2.2e-16	***	< 2e-16	***
	Young-Old				< 2e-16	***
	Mature-Old				< 2e-16	***

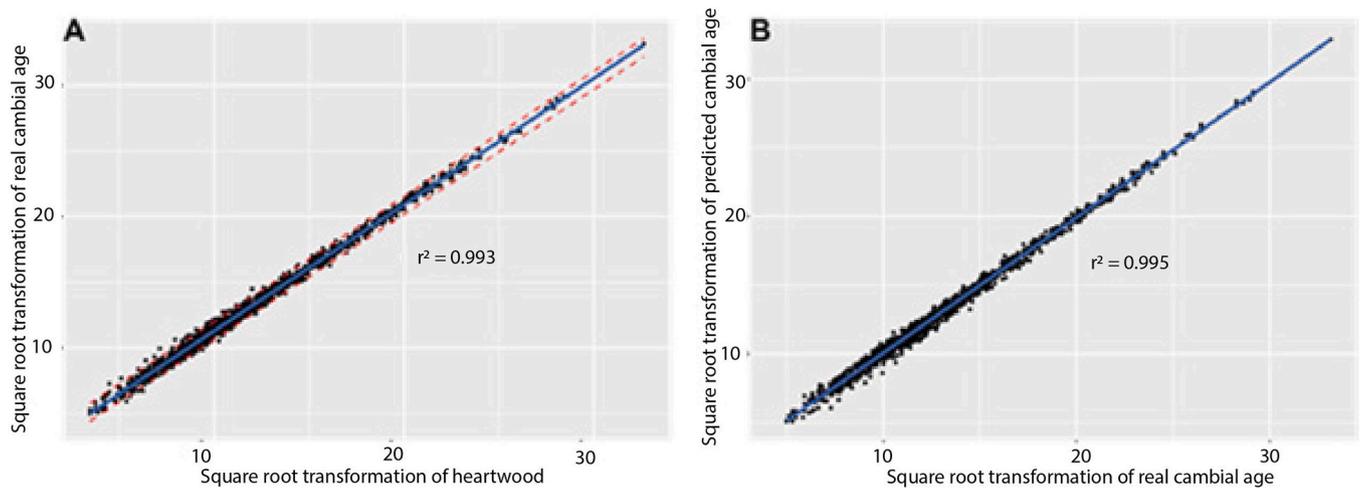


Fig. 7. Results of linear model 1: (A) Regression of cambial age (Ac) against the number of heartwood rings (Ah). (B) Biplot of real cambial age (Ac) against predicted cambial age based on the linear model. Black dots represent individual samples. Blue and red dotted lines represent the linear regression line fitted to the data and the confidence interval of the linear regression, respectively. Pearson r squared correlation values are given for each model.

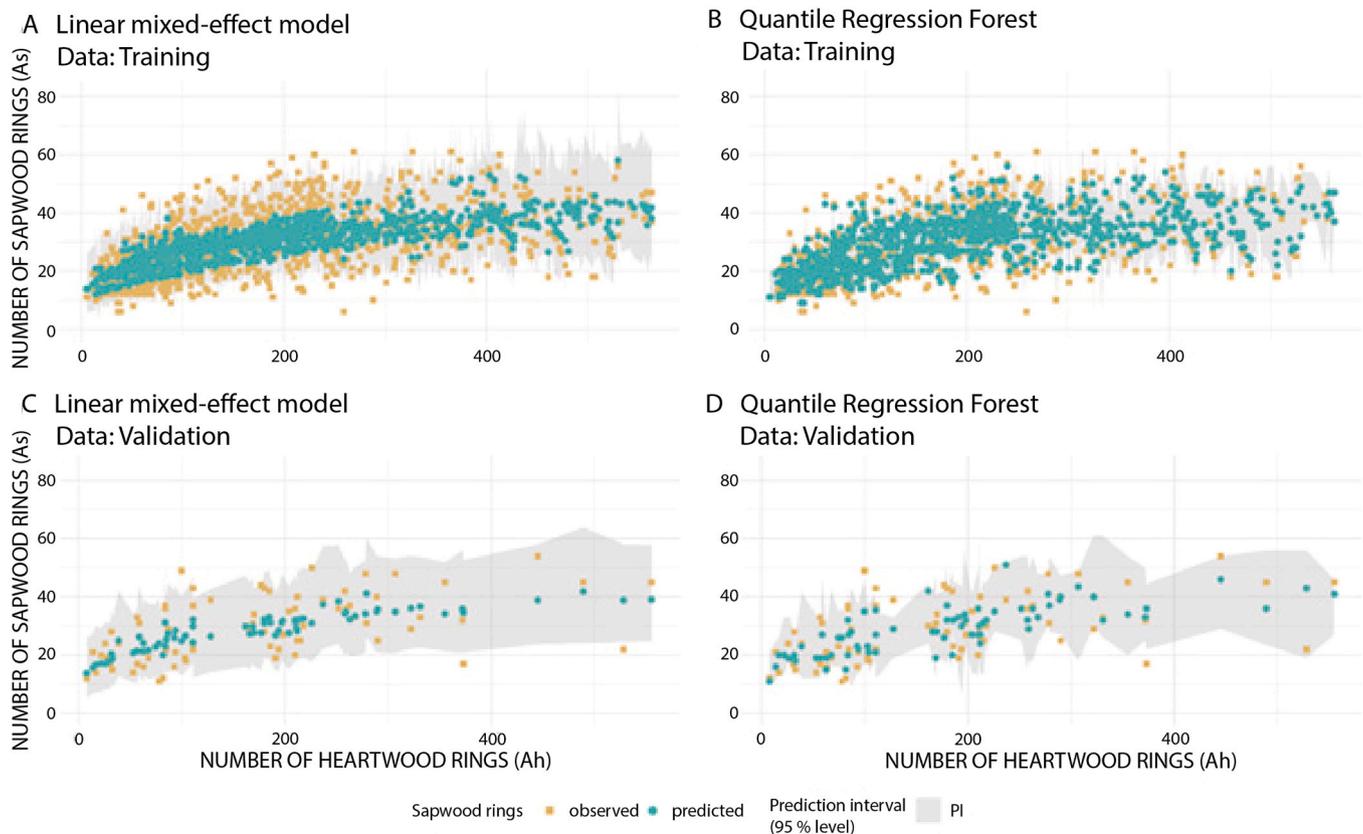


Fig. 8. Prediction intervals (PIs) of the number of sapwood rings at 95% level for both the Linear Mixed Model (LMM; panels A, C) and the Quantile Regression Forest (qRF; panels B, D). The PIs are shown for re-predicting on the training data in panels (A, B) while panels (C, D) show the results for prediction on the independent validation data. The PIs slightly widen with increasing numbers of heartwood rings, especially when re-predicting on the training data.

for mature (~13.1%) and old (~8.3%) age classes. In general it is possible to use the limits of the PI for number of sapwood rings at a selected position of number of heartwood rings to get a range for the expected cambial age, but a widening interval indicates higher uncertainty when trying to estimate in a next step the felling date based on these predictions and their respective PI-Range.

4. Discussion

Progress in the development or improvement of reliable sapwood statistics is of paramount importance for an accurate dating and age estimation of archaeological and historical artifacts (Edvardsson et al., 2022). Notably, the characteristics of larch sapwood in our study significantly differ from previous research focused on *L. decidua* trees. We observe a mean number of sapwood rings of 30 ± 11 , while Gjerdrum (2013) reported a mean of 19 ± 7 for *L. decidua* sapwood rings. We hypothesize that these differences result from different tree ages included in both datasets. Indeed, our results clearly show that the number of larch sapwood rings increases with age, but also that the rate of increase varies according to a tree's cambial age. Gjerdrum's dataset included trees with ages that ranged from 16 to 269 years; that dataset therefore included trees with substantially lower mean ages than in our study. Consequently, Gjerdrum's results align more closely with the statistics we obtained for younger trees (23 ± 8 , Table 1).

4.1. Age-dependent number of sapwood rings

The age-related trend sapwood ring numbers observed here – but also reported in other studies (Hughes et al., 1981; Corona, 1984; Sohar et al., 2012; Gjerdrum, 2013; Jevšenak et al., 2019), may be attributed to the tree's physiological mechanisms. The primary function of

sapwood in a tree is to conduct water from the roots to the crown, ensuring a continuous supply of water to the foliage (Gartner, 1995). As a tree grows and increases its foliage, a strong correlation emerges between the amount of foliage and the area of sapwood required to supply water to the expanding canopy. Yet, maintaining sapwood incurs certain efforts for the tree: living parenchyma cells in the sapwood consume significant amounts of energy for maintenance. Therefore, if the amount of sapwood exceeds the water demands of the foliage, there may be an energy-saving strategy for the tree to convert excess sapwood into heartwood (Taylor et al., 2002). This physiological mechanism may also explain the strong correlation between cambial age and the number of sapwood rings in young *L. decidua* trees with rapid growth and expanding foliage which becomes weaker as the tree ages and foliage expansion stabilizes.

4.2. Sapwood rings as a proxy for provenancing?

Several studies provide evidence that sapwood ring numbers may vary depending on environmental factors (Wrobel et al., 1993; Rybníček et al., 2006). In this study, we hypothesize that the geographical origin of the analyzed trees, including differences in elevation, may significantly influence sapwood ring numbers (Auer et al., 2007). This hypothesis is supported by observations that trees growing in resource-limited environments – such as high altitudes – may allocate fewer resources and energy to sapwood production and maintaining (Galván et al., 2012). Similarly, differences could arise from the strong topographic and bioclimatic gradients experienced by *L. decidua* trees in the European Alps (Saulnier et al., 2011) or in response to varying severity of larch budmoth outbreaks in space and time (Saulnier et al., 2017). The difference in larch sapwood ring numbers observed between the populations located in the West and East is not related to altitude,

which is comparable between the regions, except possibly for those growing in region 5 (the easternmost one) where trees were sampled at lower altitudes. We can also exclude that it results from age-related effects since the response ratio analysis removes the increasing trend in sapwood ring numbers and allows for a more accurate comparison across different populations. The difference rather tends to confirm the existence of a latitudinal gradient that would apparently be comparable to the longitudinal gradient reported in northern Europe for deciduous oak trees, and used for dendroprovenancing studies (Hillam et al., 1987; Sohar et al., 2012; Sohar, 2013; Prokop et al., 2017).

However, our results should be interpreted with caution when used to pinpoint the origin of *L. decidua* wood for several reasons: (i) the alpine latitudinal climate gradient is considerably weaker than the pronounced contrast that exists between the oceanic (west) and continental (east) synoptic systems in Northern Europe; (ii) within the Alps, climate is more controlled by altitude than by east-west gradients, rendering an estimation of dendroprovenance based solely on sapwood ring numbers more difficult. In addition, (iii) genetics, the impact of local recurrent disturbances (such as larch budmoth outbreaks or geomorphic processes), may influence sapwood ring patterns in *L. decidua* trees (Wagner, 2013). Finally, (iv) the network of reference chronologies available to trace the origin of timbers and to validate provenances estimated from sapwood ring numbers is much sparser for *L. decidua* than it is for oaks.

4.3. Estimation of felling dates

Until now, dendroarchaeologists estimated the felling date of larch timbers with incomplete sapwood with the help of sapwood statistics. Our study confirms that this approach is generally appropriate but not always the most accurate due to significant variations in the number of sapwood rings throughout the life of trees. Our research also demonstrates that a more accurate prediction of the felling date can be obtained based on linear models which robustly estimate the number of sapwood rings from the number of heartwood rings (see Table B in Supplementary material). The sole limitation of this model is that the heartwood must be complete or have less than five missing rings towards the pith. This holds particularly true for planks and highly squared pieces like furniture and artworks, very frequently encountered in dendroarchaeological studies, for which our sapwood ring estimation method cannot be used. Conversely, many Alpine structures are constructed from logs that are slightly squared and have well-preserved piths. For material of this nature, our method works very good and allows accurate estimation of sapwood ring numbers and, consequently, tree felling dates.

To address the issue of timber with incomplete or missing heartwood, we also developed some more sophisticated models based on the number of sapwood rings. As the relationship between sapwood and cambial age is non-linear, we considered heartwood, altitude and regional factors as regressors in the models. Yet, our efforts to use more complex extended linear and machine learning models resulted in only marginal improvements in model accuracy. For instance, incorporating altitudinal data did not increase model performance, thus contradicting our assumption of temperature-dependent sapwood formation (Galván et al., 2012). For now, from a practical point of view, we therefore recommend adding 19 years to the date of the last heartwood ring preserved, that is larch minimum sapwood rings according to the full dataset (mean number of sapwood ring is 30 ± 11), associated with the words “felling *Terminus post quem*”, i.e. a date from which the tree may have been felled.

5. Conclusions

Our study explored the use of sapwood variations in *L. decidua* trees from five different regions within the European Alps and three age classes to estimate felling dates of archaeological timber and to trace the

provenance of trees. To improve the assessment of timber felling dates, we propose a simple linear model based on the number of heartwood rings, which proves to be more efficient than the conventional approach used in dendroarchaeology which has hitherto solely relied on sapwood statistics (see “Table B: Cambial age estimation for samples with 1–300 heartwood rings” and “Case study” in Supplementary material). For dendroprovenancing, and despite the fact that our study shows that it is theoretically possible to use the variations in sapwood ring numbers to trace the origin of larch timbers across the European Alps, we urge for caution when linking an archaeological wood of unknown origin to one of the five regions solely based on sapwood ring numbers. To address the remaining challenge of *L. decidua* dendroprovenancing more completely, we propose three potential strategies for future research. Firstly, study variability related to sampling height in archaeological/historical timber because cambial age is not the same towards the base or the top of the tree. Secondly reducing age variance within regions through a careful selection of samples from living trees could lead to more precise estimations. Thirdly, the relationship between sapwood ring width or sapwood width and the number of sapwood rings should also be considered as a potential proxy in future studies. Additionally, further research could incorporate other dendrochronological techniques, genetic analysis, or consideration of local disturbances to improve the accuracy and robustness of dendroprovenancing efforts with *L. decidua* wood. Collaborative efforts to expand the network of reference chronologies for *L. decidua* would also be valuable to validate the sapwood approach.

Funding

This research was funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2150 ROOTS-390870439.

Declaration of Competing Interest

Corresponding authors, on behalf of all the authors, declare not any financial and personal relationships with other people or organizations that could inappropriately influence our work. Generative AI was not used in our scientific writing.

Data Availability

Data will be made available on request.

Acknowledgements

Christelle Belingard, Françoise Serre-Bachet, Lucien Tessier and Carlo Urbinati collected many larch data we've used here and thus contributed to the success of this study. We thank the two anonymous reviewers for their pertinent advice, which helped to improve the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.dendro.2023.126150.

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