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Original article

Estimating missing sapwood rings in three European gymnosperm species by the heartwood age rule

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ABSTRACT

Precise dating of the year of felling is one intended outcome of dendrochronology. However, occasionally some or all sapwood rings might be missing, either due to deterioration or because they were carved off, or for some other reason. Consequently, while heartwood is preserved, sapwood might be fully or partially missing. In such cases, the year of felling must be estimated by adding a suitable number of sapwood rings. A heartwood age rule (HAR) has been advocated for Scots pine and adapted to European larch and Cembra pine, implying a linear relationship between sapwood ring count and the square root of heartwood ring count, largely irrespective of position in the stem. The same rule applied to all observations of a species, irrespective of silviculture, location or fertility of the growth site. Scots pine had twice or thrice as many sapwood rings as Cembra pine, which had 10% more rings than larch. The magnitude of model residuals was proportional to estimated sapwood ring count. Relative residuals were roughly normally distributed. To be applicable in Bayesian modelling in dendrochronology analyses, detailed information on model errors has been provided.

Introduction

Precise dating of the year of felling is one intended outcome of dendrochronology. However, occasionally some or all sapwood rings might be missing, either due to deterioration or because they were carved off, or for some other reason. In such cases, a reliable dating involves the estimation of missing sapwood rings. The traditional approach has been to add the average number of sapwood rings for the species in question, and including an estimated confidence interval calculated from ring count distribution. Log-transformed sapwood ring count has been considered normally distributed (Hughes et al., 1981). When including a priori information, e.g. for diverging ring count distribution or from observing some fraction of the sapwood rings, the confidence interval might be unilateral or narrowed, a technique regularly denoted as Bayesian modelling (Millard, 2002; Haneca and Debonne, 2012). In plant ecology, ring width and sap- and heartwood diameter or area fraction are commonly observed and analysed (e.g. DeBell and Lachenbruch, 2009). Such options for indirect ring count estimation will not be further considered in this paper.

Heartwood formation is directly related to the ageing of trees (Wagenführ, 1989). For Scandinavian Scots pine, the number of heartwood rings has been found to vary in a law-like manner with cambial age: The square root of cambial age minus the square root of heartwood rings equals a constant. This heartwood age rule (HAR) was found to be invariable with cambial age and location in the stem from breast height upwards as well as with growth conditions: rich to poor fertility, marine shore to sandy deposits to alpine stands. Model residuals of the square root transformed heartwood ring count were stationary for all cambial ages and varying growth conditions (Gjerdrum, 2003). The HAR might imply an indirect way to estimate the number of sapwood rings from observed heartwood rings.

The objective of the work presented in this paper has been to verify HAR for predicting sapwood ring count applied for softwood timber over a wider European area. The following gymnosperm species were included: Scots pine (*Pinus sylvestris* L.), European larch (*Larix decidua* Mill.) and Cembra pine (*Pinus cembra* L.). The Cembra pine has been described under different common names; in this paper we just call it after the same Alpine site that lent its name to the Latin nomenclature. These species were chosen for their widespread use in Europe combined with the distinct heartwood likely to be preserved in partially deteriorated wooden artefacts. For each species separately, the work should result in an algorithm for estimating sapwood ring count provided there is knowledge of heartwood rings, and information on the magnitude and distribution of model residuals.

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Materials and methods

Model

The HAR formula (1) (rearranged from Gjerdrum, 2003) has been at the core of the analyses presented in this paper:

$$\sqrt{A_C} - \sqrt{A_H} = a \tag{1}$$

Combining with the generic relation: heartwood ring count A_H plus sapwood ring count A_S equals cambial age A_C, Model (2) and the slightly modified Model (3) were obtained. Model errors are indicated by ε.

$$A_S = a^2 + 2 \cdot a \cdot \sqrt{A_H} + \varepsilon \tag{2}$$

$$A_S = c + b \cdot \sqrt{A_H} + \varepsilon \tag{3}$$

The significance of Model (2) is twofold: simplicity in that it contains only one parameter, and that it relates sapwood rings to the square root of heartwood rings. The expected advantage of (2) and (3) over (1) is the direct estimation from non-transformed values of the dependent variable A_S; the advantage of (3) over (2) is the increased model flexibility in the additional parameter. Parameters estimated independently for each species in three different ways were evaluated: $^{\text{I}}$Parameter a estimated directly from (1), residuals from (2); $^{\text{II}}$Parameter a estimated by non-linear regression from (2); $^{\text{III}}$Parameters c and b estimated by standard linear regression from (3). Residuals were carefully analysed, both natural residuals ε and relative residuals: the quotient of natural residual divided by estimated sapwood ring count, $\varepsilon/\text{Est}(A_S)$. Statistical analyses were performed in the Statistica 64 v.10 software (StatSoft, 2012).

Observations

As compared to the Scandinavian sample of Scots pine supporting the HAR (Gjerdrum, 2003), the number and origin of observations have been substantially increased during the last decade, including observations for additional species and from new European regions (Table 1). The following observation arrangements were applied: cores extracted at breast height of standing trees, cores systematically extracted along felled stems, and ring counts directly at the small end cross-cut of sawlogs. When necessary, samples were treated with a chemical indicator to separate heart- from sapwood (Wagenführ, 1989). In the work presented here, only one observation per tree, which should contain at least 10 heartwood rings, was included in model parameter estimation.

Multiple, along-stem samples consisted of 789 observations along 133 Scots pine stems in the range from breast height to 20 m up from the base. In the same way, 144 cores were extracted along 24 larch stems. These multiple observations per stem were used to verify the along-stem validity of the estimated models. This was done in a mixed linear model (GLM), taking tree number as random effect.

Results

Overall mean observed sapwood ring counts $A_S \pm$ standard deviations were 51.0 ± 15.0, 19.3 ± 7.2 and 28.4 ± 13.4 for Scots pine, European larch and Cembra pine, respectively. For each species, both the mean and the variation increased steadily with increasing heartwood ring count. Observed values, heavily influenced by sampling strategy, deviated significantly both from normal and log-normal distribution for all three species (Shapiro–Wilk's W test, $p < 0.01$, see Stephens, 1974).

Main model

Model (3) performed best for all three species: Model errors were lower and less biased compared to Models (1) and (2). Consequently, only results for Model (3) are presented (Table 2). A prerequisite for the model is that all heartwood rings from the pith outwards have been observed.

Along-stem variation

For Scots pine, any variation upwards in the stem was largely individual for each tree. Scots pine sapwood ring count decreased by 0.7 ± 1.1 rings/m upwards (average ± std.dev.) Similar results were obtained for larch, -0.7 ± 1.5 rings/m.

Residual distribution

Model residuals ε were unbiased, but increased steadily in older samples. Residuals could be made stationary by dividing by estimated number of sapwood rings. Consequently, relative residuals $\varepsilon/\text{Est}(A_S)$ were unbiased and stationary, i.e. invariable with respect to estimated value or heartwood ring count. Relative residuals were roughly normally distributed (Fig. 1). However, the distributions deviated significantly (Kolmogorov–Smirnov test) from the normal

Table 1
Overview of observed samples. Samples taken at breast height (BH), at the top end of sawlogs (random) and/or multiple observations along stems.

Species	Origin of sampled trees	Height in stem	Heartwood rings, range	Sapwood rings, range	No. of trees
Scots pine	Wide variation in fertility, elevation, etc. from polar region through the Alps	BH; random; multiple	9–334	16–126	2738
European larch	Mostly Alpine mountainous, suppl. with northern European plantation trees	BH; random	11–238	5–43	369
Cembra pine	Mostly Alpine mountainous, suppl. with northern European park trees	BH	12–444	3–75	151

Table 2
Estimated parameters and residuals for Model (3).

Species	Model parameters		R^2	Model residuals, s_ε	Relative residuals		
	c	b			$s_\varepsilon/\text{Est}(A_S)$	Skewness	Kurtosis
Scots p.	22.9	4.16	34.3%	12.17	0.238	0.706	1.420
E. larch	7.38	1.61	28.8%	6.04	0.308	0.722	0.277
Cembra p.	6.50	2.36	61.7%	8.28	0.272	0.577	0.867

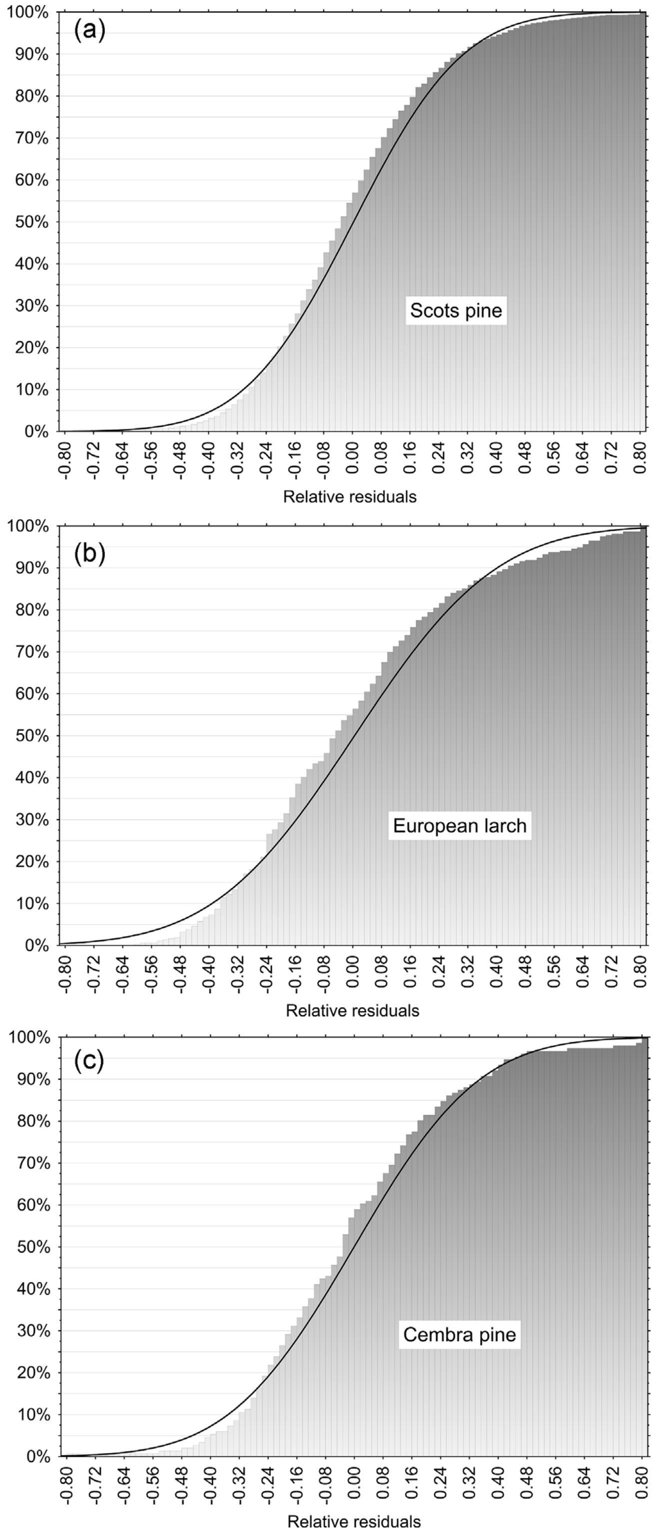

Fig. 1. Cumulative distribution for relative model error $s_\varepsilon/\text{Est}(A_S)$, Model (3). Lines indicate the normal distribution fitted with the model errors given in Table 2. (a) Scots pine. (b) European larch. (c) Cembra pine.

and every other ordinary distribution function. Skewness and kurtosis were positive for each of the three species (Table 2). Three choices for estimating confidence intervals are offered: by applying the selected percentiles (Table 3), by the distribution graphs (Fig. 1) or by generating percentiles from the Johnson distribution with

Table 3
Selected percentiles for relative residuals $s_\varepsilon/\text{Est}(A_S)$, Model (3).

Species	2.5%	5%	Median	95%	97.5%
Scots pine	−0.399	−0.342	−0.023	0.431	0.528
E. larch	−0.467	−0.423	−0.042	0.641	0.699
Cembra p.	−0.437	−0.389	−0.029	0.460	0.725

Table 4
Parameters in the Johnson distribution for relative residuals $s_\varepsilon/\text{Est}(A_S)$, Model (3).

Species	Type	Γ gamma	Δ delta	Λ lambda	Ξ xi
Scots p.	2 – SU	−1.621	2.618	0.478	−0.340
E. larch	3 – SB	1.575	1.458	2.419	−0.658
Cembra p.	2 – SU	−2.265	3.329	0.693	−0.537

parameters listed in Table 4. The Kolmogorov–Smirnov *D*-statistics for the Johnson distribution were in the range 0.01–0.03 and the Liliefors $p \geq 0.78$ for each species, indicating a suitable fit.

Discussion

Sapwood ring count increases steadily with age, but at a different rate for each of the three investigated species. Thus, both the average and the distribution of sapwood rings depend on the distribution of cambial age in a sample. Consequently, conformity in sample age is necessary for a successful direct use of such information in dendrochronology investigations. This might be the case when the investigated objects consist of a combination of complete rings sets, which can be extrapolated to others partly missing some or all sapwood rings (Haneca and Debonne, 2012).

Under other circumstances, the approach described in this paper might be advantageous. The increase in sapwood rings was found to be proportional to the square root of heartwood ring count and largely invariable with height in stem (Table 2), as predicted by the heartwood age rule (Gjerdrum, 2003). Nevertheless, the advantage of Model (3) over (2) also indicated some discrepancy with the HAR.

The same Model (3) proved to be the best for each species. Even so, for a given number of heartwood rings, the magnitude of the estimated sapwood ring count varies: Cembra pine is 10% higher than larch, and Scots pine is two or three times higher than Cembra pine and larch.

Sapwood estimates can only be obtained from samples where all heartwood rings are available, i.e. from the pith to the sapwood border. Explained variance R^2 varied from 29% for larch to 62% for Cembra pine. For larch this small figure can be attributed to the generally few sapwood ring number and corresponding low variation found in any sample, and for Cembra pine the closer correlation related to the quite wide age range in the observations (Table 1). Relative model residuals were of the same magnitude, between 0.24 and 0.31 (Table 2), implying that natural model residuals were twice as big for Scots pine compared to the other two species, for similar number of heartwood rings. The physiological transformation from sapwood to heartwood in a stem is known to be somewhat less regular close to the base (Gjerdrum, 2003), and so samples lower than breast height should be avoided, if possible.

The advantage of stationary residuals could be obtained by dividing with estimated sapwood ring count. Unfortunately, these relative residuals did not comply directly with the normal distribution or any other widely used distribution functions. Higher order moments: skewness and kurtosis, were both significantly higher than zero (Table 2), indicating a tail to the right (positive skewness) and a narrow peak and wide tails (positive kurtosis). In order to provide information for establishing confidence intervals in various situations, various statistics are given: separate graphs for each species (Fig. 1), selected percentiles (Table 3) and parameters for fitted Johnson distribution (Table 4). For more rough estimations, the normal distribution might be adapted.

The substantial number and variation in origin of investigated trees, in particular for Scots pine, the wide span in cambial age, and the conformity in results between the three species should indicate a high reliability for the reported results.

Conclusions

It is clearly demonstrated that the number of sapwood rings increases steadily with heartwood ring count, and, consequently, with cambial age for the three European gymnosperms Scots pine, European larch and Cembra pine. Even if based on the idea of the heartwood age rule, the conformity to this model is not complete. The models for sapwood ring count estimation and residual distribution should be useful tools in dendrochronology analyses.

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