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SAPWOOD RINGS ESTIMATION FOR *PINUS SYLVESTRIS* L. IN LITHUANIA AND LATVIA

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ABSTRACT

Pinus sylvestris L. is the predominant tree species used for wooden constructions in the Baltic area. Accordingly, the timber of *Pinus* is the most important object for investigation and dating carried out by dendrochronologists of the Baltic countries. However, the dating of historical *Pinus* is often challenging when the outer sapwood rings are missing in the wood samples. In *Pinus*, sapwood rings increase in number as the tree ages, and therefore calculating the approximate number of missing outer rings from a set range, a technique used for oak, is not possible. In Norway, a simple method for estimating the number of sapwood rings has been developed for some native species of conifers. The aim of this small-scale study was to assess the validity and the practical suitability of the Norwegian method for estimating the number of missing sapwood rings of mostly historical *Pinus* wood samples obtained in the southeastern part of the Baltic region. Our findings indicate that this method is not acceptable for estimating the number of missing sapwood rings for individual trees, but suggest that it may be applicable when dating tree-ring chronologies for a minimum of 20 trees, containing individuals up to 200 years old.

Keywords: Pinus, tree rings, sapwood, heartwood, HAR, dating, Lithuania, Latvia.

INTRODUCTION

Pinus is the main species used as timber in historical buildings in the Baltic States (Läänelaid 2002; Zunde 2003; Vitas 2008). Because of devastating historical events and urbanisation processes, the original historical timber has become a rare find nowadays in the Baltic countries (Läänelaid 2002; Zunde 2016). It is therefore urgently necessary to refine the methodology for obtaining precise dendrochronological information from historical timber in the Baltic countries to enable meaningful analysis of the timber for current as well as future generations of scientists.

One of the main aims of dendrochronology is tree-ring dating. This involves estimation of the year when the last ring of the tree was formed. If the timber sample has a waney edge, the date of the last ring relates to the year of felling, or to the preceding year if it was felled or died at the beginning of the year. However, very often the bark edge in historical samples is missing (Hillam *et al.* 1987). This does not allow the precise date of felling to be established. In this case, dating encompasses the estimation of missing sapwood rings by statistical approximation of the number of missing rings between the heartwood/sapwood boundary and the supposed outermost ring (Kaennel and Schweingruber 1995).

Until now, few studies have dealt with estimation of missing sapwood rings in historical Baltic timber samples (Pukienė and Ožalas 2006). This is mainly because of (a) a lack of knowledge about the potential for estimating missing sapwood rings in the timber species predominantly used in the Baltic States, Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karsten), and (b) the comparatively rare occurrence of historical oak timber (*Quercus robur* L.) in the region.

The timber of *Quercus* was used in the Baltic countries to a much lesser extent, not only because it is less common, but also because of intense

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Quercus trade to Western Europe (Zunde 1998–1999; Wazny 2002). *Quercus robur* L. together with *Quercus petrea* (Matt.) Liebl. were the species most often used for building activities in Western Europe (Hillam *et al*. 1987; Miles 1997, 2006).

In contrast to *Pinus*, estimating the missing sapwood rings in *Quercus* timber is less complicated and has been more successful. Accordingly, estimation of missing *Quercus* sapwood rings is well studied in Europe. Until the middle 2000s, already more than 75 different sapwood estimates have been obtained by researchers in Europe (Miles 2006).

Repeated studies suggest that the number of *Quercus* sapwood rings in most cases corresponds to a number within a set range, which is mainly dependent on the geographical location of the living tree. The number of sapwood rings in *Quercus* decreases in Europe from north to south and from west to east. For example, an estimation range of 10–59 rings is used in northern England, whereas it is between 4–56 in southern England (Miles 1997). In Poland, a sapwood estimate of 9–36 is used (Wazny 1990). In the Baltic countries, the number of sapwood rings of *Quercus* varies from 6 to 18 (Sohar *et al*. 2012; Sohar 2013). Detailed analysis has shown that the age of the tree and the mean ring width are also important variables to be considered in the estimation of *Quercus* sapwood (Hillam *et al*. 1987; Miles 2006).

The probable number of sapwood rings has mostly been presented as a range of estimates with a high (often *ca*. 95%) common confidence level. It should be noted that various techniques have been used to present the sapwood estimates, such as single arithmetic mean, arithmetic mean with standard deviation, skewed mean with standard deviation, range without an arithmetic mean, Bayesian statistical models, etc. (Hillam *et al.* 1987, 2004; Miles 1997, 2006; Gjerdrum 2013).

When all the sapwood rings are missing because of deterioration, decay, or hewing of wood, and in addition the last heartwood ring is not preserved or determinable, reconstruction of the date of felling is not possible. In this case, instead of the actual date of felling, a "*terminus post quem*" or earliest possible felling date is given, or the expression "felled after" is used (Haneca *et al*. 2009). A minimum number of missing sapwood rings are added to the date of the last measured heartwood ring, and the earliest possible date when the timber could have been felled is obtained (Miles 1997; Hillam 2004). Such methods for estimating the missing sapwood rings are useful for oak wood, but they are not directly applicable to the pine wood.

Pinus is characterized by a higher number of sapwood rings in comparison to *Quercus* (Gjerdrum 2013). The number of sapwood rings of *Pinus* depends on the cambial age of the tree, *i.e.* the number of sapwood rings increases with the age of the tree (Yang *et al.* 1994; Park 2002; Miles 2006). A comparative study by the Norwegian Forest and Landscape Institute of the number of tree rings in the heartwood and sapwood suggests a certain coherence, named a heartwood age rule (hereafter in the text HAR), *i.e.* the square root of the cambial age minus the square root of heartwood rings equals a constant of *ca.* 3.0 (Gjerdrum 2003, 2013). However, because the total number of tree rings can be expressed as the sum of heartwood and sapwood rings, the HAR formula can be applied for estimating the number of *Pinus* sapwood rings, using the number of known heartwood rings (Gjerdrum 2013:229). According to Gjerdrum (2003), the HAR is constant all over Europe, and it is not dependent on the site conditions.

Thus the HAR is described as a universal and effective tool for the estimation of missing sapwood rings in dendrochronological dating (Gjerdrum 2003, 2013). The estimation of missing sapwood rings of *Pinus* has so far not been performed in the Baltic States. The aim of this small-scale study was to test the validity of the HAR for estimating the number of missing sapwood rings for historical *Pinus* wood samples in the southeast of this region. For this purpose, the number of sapwood rings was also estimated in living *Pinus* trees in Lithuania for different tree age categories.

MATERIALS AND METHODS

The number of heartwood and sapwood rings from living *Pinus* trees in Lithuania and historical material from Latvia was determined and compared during this research. A larger number of previously prepared cores of living *Pinus* were available from Lithuania, whereas a richer collection of various historical *Pinus* samples came from Latvia. Using wood samples from two small neighbouring

Figure 1. Research plots of *Pinus* in Lithuania. The map was created using QGIS 2.18.0.

countries, Latvia and Lithuania, is fully justifiable in this case, because (a) the aim of this research was not to study the relationship between the number of *Pinus* heartwood and sapwood rings, or to analyse the reasons for their disparities, but rather to test the applicability and effectiveness of using HAR in estimating the missing number of sapwood rings in pine timber, and (b) HAR is a formula that can be applied globally (Gjerdrum 2003).

The first part of the research, which was carried out in Lithuania, concentrated on the characteristics of mutual changes in the number of heartwood and sapwood rings in living Lithuanian *Pinus* trees. For this purpose, the heartwood and sapwood rings were separately counted in 1009 living *Pinus* trees from 102 research plots (Figure 1). These trees were cored for dendroclimatological studies in different regions of Lithuania from 1969 to 2017: 1960s – 182, 1970s – 3, 1980s – 37, 1990s – 131, 2000s – 403 and 2010s – 253. The coring was carried out by scientists of the Dendrochronological Laboratory in Kaunas (Lithuania): T. Bitvinskas, J. Karpavičius, V. Stravinskienė, A. Vitas and others. Because the cores collected during Soviet times are mainly from trees less than 100 years old, the recent sampling strategy in the 2000s was designed to sample older trees from mature pine forests in Lithuania. Tree-ring cores were collected using an increment borer, and coring was performed at breast height.

The tree-ring widths were measured using a *Lintab* tree-ring measuring table and *TSAPWin*

software (Rinn 2011). We used cores containing the pith and samples in which the number of missing rings near the pith could be reconstructed using pith indicators (Speer 2010). Sapwood rings for each sample were counted using a stereo microscope and the number corrected when the crossdating indicated missing or double rings. Dating quality control was performed by visual comparison of the ring-width graphs (Eckstein 1987) and statistically using Cofecha (Grissino-Mayer 2001).

Analysis of the estimation of sapwood rings, calculation of the standard error, and approximation of the trend line were performed. The estimated number of sapwood rings for *Pinus* in Lithuania was approximated using a second-order polynomial trendline. The polynomial trendline has shown the highest coefficient of determination (R^2) in comparison to other regression functions, *e.g.* linear, logarithmic, power and exponential approximations. The basic equation to calculate the coefficients of a polynomial trendline is

$$y = (c2 \times x^2) + (c1 \times x) + b,$$

where $c2$ = INDEX(LINEST(y,$x^{(1,2)}$),1), $c1$ = INDEX(LINEST(y,$x^{(1,2)}$),1,2), and b = INDEX-(LINEST(y,$x^{(1,2)}$),1,3).

The number of heartwood rings was calculated by deducing the determined number of sapwood rings from the total number of tree rings in each timber sample. It was possible to estimate the theoretical number of sapwood rings by inserting the number of heartwood rings into the HAR formula (5) (see page 9). We then compared the resulting number with the actual number of sapwood rings counted in the sample to establish if the two numbers matched, and if not, to count the exact difference in units by which the theoretical number was larger/smaller than the real number.

At the same time, the potential influence of the geographical location of the research plots on the number of *Pinus* sapwood rings was also estimated. In order to accomplish this, heartwood and sapwood ring data from living trees from research plots near the northern, eastern, southern and western borders of Lithuania were used and compared. The tree-ring data comprised collections from 10 research plots near the western border of Lithuania (54 pine trees), 30 research plots near the eastern border (372 pine trees), 16 research plots near the northern border (42 pine trees) and 12 research plots near the southern border (128 pine trees). The approximate distance between the southern and northern research plots, and the western and eastern research plots, is 200 km and 300 km, respectively. The research plots were developed in forest stands with different growth conditions.

The numbers of sapwood and heartwood rings were also identified and compared from 303 cross-sections of archaeological and architectural *Pinus* timber. These represent different historical structures of the 13th to 18th Centuries investigated in present-day Latvia. Most of the historical timber samples were obtained from the Old Town of the Latvian capital, Riga, where archaeological excavations as well as renovation work on historical buildings, has been most extensive. Old Riga is located by the River Daugava. Because of the shortage of good quality timber, increasingly amounts were imported from outside the present-day territory of Latvia, starting from the 15th Century (Pāvulāne 1975). A large part of the timber used for wooden structures in Riga in the 16th to 18th Centuries was floated down the Daugava River from other countries, mainly from present-day Belarus and the western part of Russia (Pāvulāne 1975; Zunde 1998–1999). For this reason, in Old Riga as well as other population centres along the banks of larger rivers, surviving historical buildings are often partly or fully constructed from timber of unknown geographical origin, and thus with unknown growing conditions. This means that the timber samples for dating with missing sapwood rings can differ because of considerable variation in their provenance.

Considering that HAR is presented as a globally applicable formula (Gjerdrum 2003, 2013), we decided to check its accuracy for the practical reconstruction of missing sapwood rings for randomly selected samples, as described above. For this purpose, we have only used historical timber in which all sapwood rings were present. The heartwood and sapwood rings were counted when measuring ring width, using a tree-ring measuring device together with the *Sakore* dendrochronological data processing software developed at the Institute of Latvian History. The actual number of sapwood rings in each wood sample was compared with the theoretical or estimated number of sapwood rings. The theoretical number of sapwood rings was

calculated from the corresponding number of heartwood rings using the modified HAR formula of P. Gjerdrum. Then, the differences in the absolute numbers between the theoretical and actual number of sapwood rings were calculated, compared and evaluated.

In order to test the appropriateness of Gjerdrum's HAR formula and its practical usefulness for calculating the number of sapwood rings on historical timber in the Baltics, a further derivation of the formula was first undertaken, simplifying the calculation of sapwood rings from a previously determined number of heartwood rings.

In applying the HAR formula for calculating the total number of sapwood rings, Gjerdrum also provides a formula for determining the approximate number of sapwood rings in *Pinus* (A_S) based on a known number of heartwood rings (A_H), namely, if

$$A_C - A_H = A_S \text{ and} \sqrt{A_C} - \sqrt{A_H} = a, \text{ then}$$
$$A_S = a^2 + 2a\sqrt{A_H} + \varepsilon, \quad (1)$$

where A_C is the total number of rings or cambial age, A_H is the number of heartwood rings, A_S is the number of sapwood rings, a is a constant, and ε is an error term (Gjerdrum 2013:229).

Gjerdrum had previously discovered that the value of the constant a is *ca.* 3.0 (Gjerdrum 2003). Using this value, Gjerdrum developed a formula for calculating the approximate number of sapwood rings when the total number of rings of the sample is known (Gjerdrum 2003:419):

$$A_S = 6.0\sqrt{A_C} - 9, \quad (2)$$

where A_S is the number of sapwood rings, and A_C is the total number of rings or cambial age.

In comparison with the first formula (1) for calculating the number of sapwood rings (A_S), the second formula (2) initially appears simpler, but its practical significance is more limited. Thus, if all of the outer rings of a wood sample to be dated survive, then there is generally no need to apply formulas for calculating the number of sapwood rings. Through further derivation of both formulas for calculating the number of sapwood rings, where the constant is first replaced with the symbol a, and then with the ascertained value of the constant, 3.0, two similar pairs of equations were obtained:

$$A_S = 2a\sqrt{A_H} + a^2 + \varepsilon = 6.0\sqrt{A_H} + 9 + \varepsilon \quad (3)$$

$$A_S = 2a\sqrt{A_C} - a^2 + \varepsilon = 6.0\sqrt{A_C} - 9 + \varepsilon, \quad (4)$$

where A_S is the number of sapwood rings, A_H is the number of heartwood rings, A_C is the total number of rings or cambial age, and ε is an error term (Gjerdrum 2013:229).

Thus, of greater practical significance for dendro-dating is formula #3 for calculating the number of sapwood rings, which uses information on the number of heartwood rings in the sample. Here, an unknown has been retained, *i.e.* ε, the effect of errors resulting from a variety of factors, which is unavoidable. In the present study, formula #3 was used, without including a value for the effect of the error ε in calculating the theoretical number of sapwood rings, and this was then compared with the real number of sapwood rings in the corresponding wood sample.

RESULTS

The age of investigated living *Pinus* trees from Lithuania ranges from 34 to 278 years, with an average of 102 years. The majority of trees (62%) are up to 100 years old; 101 to 200-year-old trees comprise 28%, and trees older than 200 years make up 10% (Table 1).

The number of sapwood rings of the corresponding *Pinus* samples ranges from 17 to 119, with an average 51 ± 0.5. The standard error of the mean is <1.0 for trees up to 100 years old, except the youngest trees, <30 years old trees for which it reaches 1.5, increasing to 3.2 for trees from 181–190 years old, and ranges from 4.1 to 37.5 for trees older than 220 years.

The coherence between the cambial age of the tree and the number of sapwood rings of *Pinus* investigated in Lithuania is clearly presented in Figure 3. The relationship between the number of sapwood rings and the cambial age of *Pinus* in Lithuania can be expressed as a function, the graphical form of which is a polynomial curve. This explains 98% of the total variation:

$$A_S = -0.0008{A_C}^2 + 0.4702A_C + 13.682, \quad (5)$$

where A_S is the number of sapwood rings, and A_C is the cambial age of a tree. Using this polynomial model, it is easy to calculate that, for example, a 50-year-old *Pinus* tree in Lithuania will have

Table 1. The average number of sapwood rings and the standard error of the mean in different heartwood age groups of *Pinus* in Lithuania.

Number of heartwood rings	Mean number of heartwood rings	No of trees	Mean number of sapwood rings		Standard error of actual sapwood rings, years	Difference, years (E – D)
			actual	HAR estimated		
A	B	C	D	E	F	G
1–10	8	66	31	26	0.7	–5
11–20	15	173	38	33	0.6	–5
21–30	26	193	44	39	0.6	–5
31–40	35	136	47	44	0.7	–3
41–50	45	74	51	49	1.4	–2
51–60	55	71	57	54	1.6	–4
61–70	65	43	58	57	2.2	–1
71–80	75	29	61	61	2.9	0
81–90	85	23	61	64	2.6	4
91–100	96	33	66	68	2.6	2
101–110	105	27	70	70	3.5	1
111–120	116	39	82	74	2.1	–8
121–130	125	33	79	76	2.4	–2
131–140	136	30	70	79	2.6	9
141–150	144	16	68	81	3.1	13
151–160	157	9	72	84	7.5	12
161–170	167	7	66	86	5.5	20
171–180	175	3	50	88	NA	38
181–190	184	2	81	90	NA	10
201–210	202	1	52	94	NA	42
221–230	227	1	44	99	NA	55

NA = not available.

35 sapwood rings, a 100-year-old tree will have 53, and a 150-year-old tree will have 66 sapwood rings on average.

Table 1 shows the mean numbers of heartwood and sapwood rings in *Pinus* trees of different age groups in Lithuania. Although the sapwood range, including minimal and maximal values, is rather wide, the standard error of the mean is less than 3.5 years, when the data of at least 20–30 trees are averaged. However, when the number of investigated trees decreases to less than 10, the standard error increases up to 7.5 years. This shows that high sample replication is necessary to obtain sufficient accuracy.

The relationship between the number of sapwood rings and heartwood rings of *Pinus* in Lithuania is approximated using a polynomial function as well (Figure 4). Compared to the previous polynomial model, the end portion of the curve of this function is lower, demonstrating a relative reduction in the number of sapwood rings in old *Pinus* trees. The function, which is shown below, explains 93% of the total variation:

$$A_S = -0.0023{A_H}^2 + 0.6456A_H + 27.326, \quad (6)$$

where A_S is the number of sapwood rings, and A_H is the number of heartwood rings. This regression model enables us to calculate that a *Pinus* sample containing, for example, 50 heartwood rings will have 54 sapwood rings, a sample with 100 heartwood rings will have 69, and a sample with 150 heartwood rings will have 74 sapwood rings, on average. In Lithuania, the presented equation is valid for *Pinus* trees up to 220 years old.

Nevertheless, it must be remembered that the above-mentioned polynomial formulas apply specifically to *Pinus* in Lithuania, and therefore their use is limited. In contrast to these, Gjerdrum's HAR formula has been characterised as a global formula (Gjerdrum 2003).

The difference between the theoretical number of sapwood rings, calculated using the HAR

formula, and the real number of sapwood rings in *Pinus* from Lithuania was considerable. It ranged from –8 to +55, with a mean value of +8 (Table 1). It is evident that the difference increases in very old trees. For the investigated trees with an average age of up to 200 years, the difference ranges within the acceptable limits of –8 to +9.

Comparison of the mean range of differences between the estimated and actual numbers of sapwood rings for Lithuanian *Pinus* trees growing in geographically opposite regions (eastern/western, and southern/northern), for the *Pinus* trees growing in the eastern and western regions in particular, but also in the northern and southern regions, the theoretical mean number of sapwood rings obtained by applying the HAR formula, was consistently lower than the actual mean number of rings. The difference between the mean estimated and actual number of sapwood rings varied. It was –6.9 in the eastern, –1.5 in the western, –1.0 in the northern, and –5.5 in the southern border regions, which suggests that the development of sapwood rings did not follow the same pattern in these four areas.

The timber samples from historical wood (investigated in Latvia) come from *Pinus* trees that are on average older. These had 28–372 rings, with an average of 128 rings. The majority of samples (53%) contained 101–200 rings. Samples with less than 101 rings formed the second largest group (35%). Samples with 201–300 rings accounted for 11% of the total number, and three samples (1%) had more than 300 rings (Table 2).

The difference between the theoretical and real number of sapwood rings for some individual wood samples investigated in Latvia was even larger than in Lithuania, varying from –48 to +53, with a mean value of +5. This confirms that the estimated number of sapwood rings for individual *Pinus* samples using the derived HAR formula can differ greatly from the real number. The most pronounced difference (+53) between the estimated and real number of sapwood rings was seen in the timber sample with the highest total number of tree rings (372); however, a comparatively significant difference was also observed in some samples with considerably fewer rings.

Considering that in some cases the error in the theoretically calculated number of sapwood rings was positive and in other cases negative, the mean value of the difference between the theoretical and real numbers of sapwood rings was lower when applied to a larger number of wood samples. Comparison of the averaged theoretical and the averaged real number of sapwood rings for wood samples divided into sets on the basis of their correspondence to age groups gave the following results: where a set included more than 10 samples, the value of the differences ranged from 1 to 11, but if a set included more than 20 samples then the mean value of the differences exceeded 5 only in one case (Table 2).

As was observed in Lithuania, the percentage of sapwood rings in Latvian *Pinus* timber samples showed significant reduction in proportion to the number of heartwood rings as the trees exceeded the age of 230 years. Accordingly, the results of the study in Lithuania and Latvia show that the mean number of sapwood rings, as calculated from the number of heartwood rings, does not differ from the mean real number of sapwood rings by more than ±9 rings, if this mean value relates to at least 15 to 20 trees (Tables 1, 2). It is evident that the difference between the number of sapwood rings estimated by the HAR equation and the average number of sapwood rings counted is quite small and usually does not exceed 1–9 rings. However, for old *Pinus* trees (>220 years), the discrepancy between the theoretically calculated number of sapwood rings and the actual number of counted increases. For trees older than 300 years, the difference even comprises several decades.

DISCUSSION

The science of dating through dendrochronology has progressed significantly in recent decades. However, the dating accuracy of samples for which the sapwood is incompletely represented remains an important question that needs further attention (Miles 2006).

Sapwood estimation for *Pinus* is less investigated in comparison to the sapwood of *Quercus* in Western Europe. However, *Pinus* is the most important timber material in the Baltic (Läänelaid 2002; Vitas 2008; Zunde 2003), as well as in several other European countries (Houston Durrant *et al.* 2016). Accordingly, it is important to assess the sapwood estimates of *Pinus* in the Baltic countries and to

Table 2. The averaged actual and calculated number of sapwood rings and the difference between them in different age groups of *Pinus* determined in Latvia.

Age class	Number of samples	Mean tree-ring number	Mean number of heartwood rings	Mean number of sapwood rings		Difference, years (F – E)
				actual	HAR estimated	
A	B	C	D	E	F	G
21–30	3	29	9	21	27	6
31–40	4	37	14	23	31	8
41–50	18	45	17	28	34	6
51–60	14	57	24	33	38	5
61–70	12	66	31	35	42	7
71–80	15	77	37	40	45	5
81–90	16	85	42	44	48	4
91–100	25	96	49	47	51	4
101–110	21	105	53	52	53	1
111–120	26	116	61	55	56	1
121–130	23	126	72	54	60	6
131–140	19	135	78	57	62	5
141–150	18	146	88	57	65	8
151–160	13	156	89	67	66	– 1
161–170	6	165	105	60	70	10
171–180	11	175	113	62	73	11
181–190	13	185	114	72	73	1
191–200	10	196	122	74	75	1
201–210	7	204	128	76	77	1
211–220	5	215	131	84	78	– 6
221–230	10	224	144	80	81	1
231–240	1	234	171	63	87	24
241–250	6	246	177	68	89	21
261–270	2	263	195	68	93	25
271–280	2	272	209	64	96	32
301–310	1	309	230	79	100	21
331–340	1	339	265	75	107	32
371–380	1	372	310	62	115	53

understand the geographical differences, if there are any.

This small-scale study was conducted separately on data obtained for tree rings in Latvia and in Lithuania. Our results demonstrate a high variation in the number of sapwood rings in *Pinus* in Lithuania and Latvia. Several explanations have also been proposed by other researchers to explain the variation in sapwood between trees. Firstly, variation is attributed to the genetic inheritance of trees (Paques 2001). There is no consensus on how the site conditions influence the formation of sapwood in *Pinus*. A direct relationship between the number of sapwood rings and the amount of foliage (Berthier *et al*. 2001) and living branches (Kellomäki *et al*. 1999) has been documented. On the other hand, Hillis (1987) found evidence that poor growing conditions may decrease heartwood formation. According to Yang *et al*. (1994), the number of sapwood rings decreases with the height of the stem. The results of our research confirm that the proportion of sapwood to heartwood rings in the *Pinus* trunk can change (decrease) considerably in very old trees. Such a difference can sometimes occur because of the indefinite boundary between *Pinus* heartwood and sapwood. The irregular heartwood/sapwood transition may cross many tree rings, which causes difficulties in the precise estimation of the sapwood rings even in the same tree (Figure 2). The irregular boundary is especially pronounced in the stem disks taken from the stumps of older trees, near the root collar.

There are indications, however, that the difference can be considerably influenced by certain

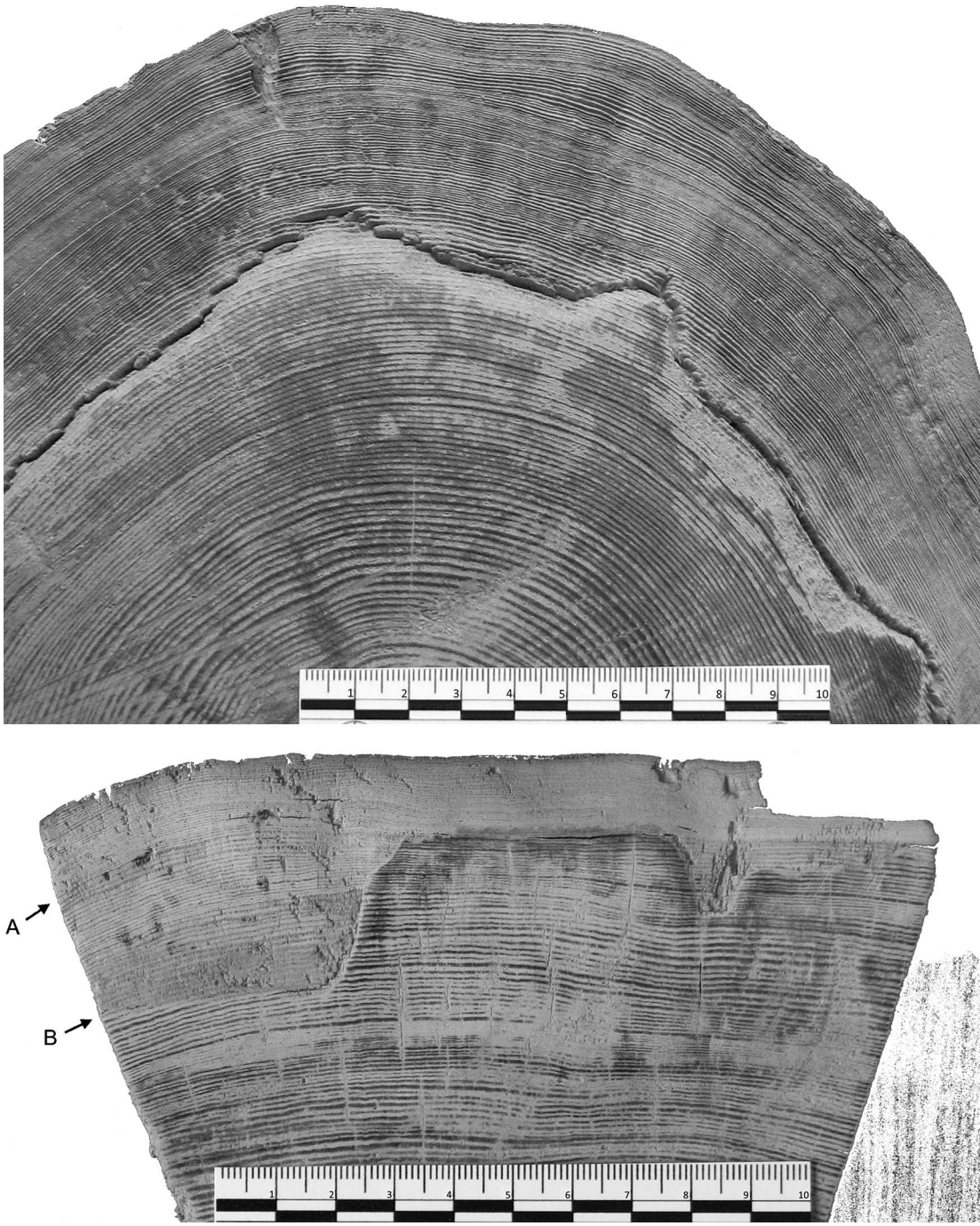

Figure 2. Two cross-sections of *Pinus* historical timber from Latvia showing the irregular borderline between heartwood and sapwood. Upper image: sapwood is not decomposed and sapwood-heartwood boundary rings is marked on surface. Lower image: sapwood rings are decomposed so the boundary with in-tact heartwood is easily recognizable. Note the difference in number of tree rings in sapwood between positions A and B on the lower image. [Photo by M. Zunde.]

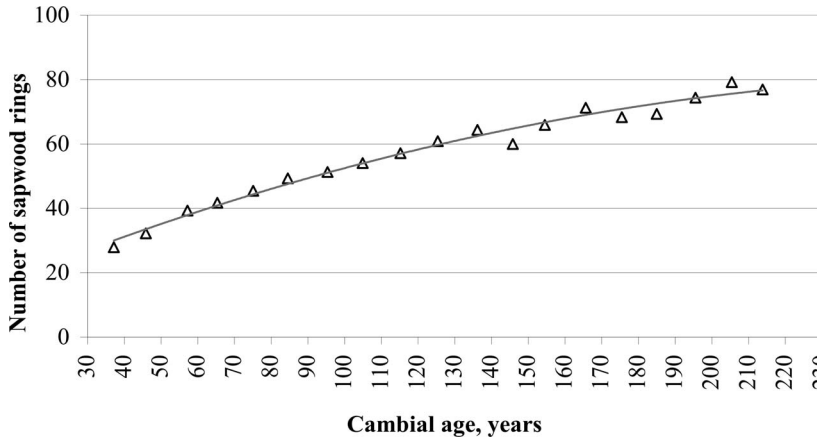

Figure 3. The average number of sapwood rings of *Pinus* in Lithuania and polynomial trend line.

ecological factors. For example, if HAR is characterised as a universal formula, the application of which produces an accurate estimate of the number of sapwood rings regardless of growth conditions of the sampled trees (Gjerdrum 2003), why were considerable differences between the mean estimated and actual number of *Pinus* sapwood rings observed in four regions of Lithuania, and how can they be explained? Characteristically, the most pronounced differences in mean values were not observed in those research plots where the trees had varied differences (both positive and negative) between the estimated and the actual number of sapwood rings, as is the usual case, but in particular research plots near the border, where the differences were similar: either only positive, or only negative in all, or almost all, trees. Such exclusively positive or negative differences between the theoretical and actual number of sapwood rings between the trees of the same forest stand might be interpreted as being caused by their relatively young or, by contrast, very old age. On the other hand, at least in theory, the change in the number of *Pinus* heartwood and sapwood rings in these tree stands can also occur because of particular environmental factors. In this case, the similar patterns of differences observed in the proportion of the *Pinus* heartwood to sapwood rings in two or more tree stands can be explained more precisely by the influence of certain ecological factors in these tree stands, rather than their geographical location. This issue should be explored further in new studies on a larger scale.

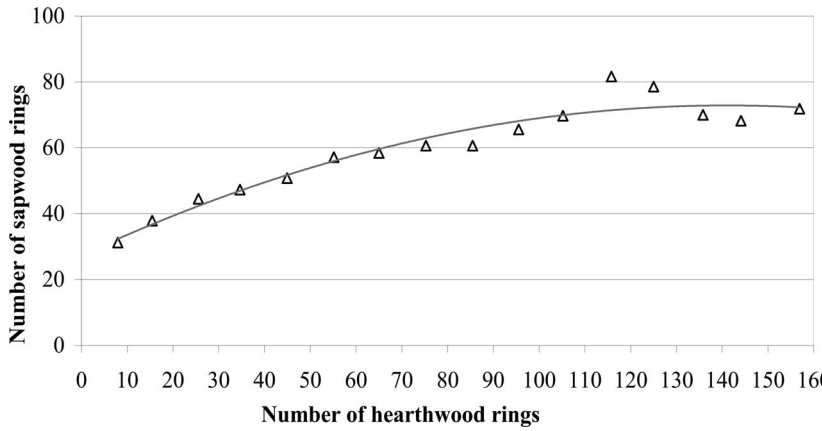

Figure 4. Relationship of the average number of sapwood and heartwood rings of *Pinus* in Lithuania and polynomial trend line.

So far it has been ascertained that in trees with relatively small crowns, the heartwood rings are narrower and the sapwood is smaller (Gjerdrum 2003). It would, however, be necessary to establish if, and to what extent, the narrow sapwood in such trees is determined by the annual radial increase or decrease in the number of rings.

Consequently, and as confirmed by the results of this study, high replication is necessary to adequately estimate the number of *Pinus* sapwood rings, just as it is necessary in estimating the number of missing sapwood rings in *Quercus* timber samples (Hillam 1987; Miles 1997, 2006). For example, Miles (2006) defined the need for 250 samples to avoid bias in producing sapwood estimates for *Quercus*, but groups of between 17 and 25 samples produce a felling date of five years. In our study, it is likewise concluded that the mean value of the theoretical number of *Pinus* sapwood rings, when applied to at least 20 trees, no longer shows such widely differing changes in the proportion of heartwood to sapwood rings as may appear with individual trees because of the different factors mentioned above.

In Lithuania, where the analysed wood samples were more homogeneous, *i.e.* they had been obtained (a) in greater numbers, (b) from relatively younger trees, more similar in age, (c) from known locations in the country, and (d) at breast height on the trunk, a relatively smaller difference was observed between the theoretically calculated and the real number of sapwood rings. Characteristically, negative values of the difference were more frequently obtained than in Latvia. We consider that this results from the greater heterogeneity of the historical wood studied in Latvia (especially in Riga where large amounts of timber were used that had been floated to the city from *Pinus* forests with heterogeneous characteristics located at great distances) as well as to the possible effect of variation among the wood samples in terms of the height on the *Pinus* trunk. This difference points to the differential reaction of the trees to the influence of certain factors, as was found in the Lithuanian study. It also suggests that the HAR formula cannot be used to determine with high precision the proportion of heartwood to sapwood rings in *Pinus* trees of different ages and with different growth conditions, contrary to the description of the formula. It should be remembered that the HAR formula was found to be invariable with cambial age and location in the stem from breast height upwards as well as with growth conditions, *e.g.* rich to poor fertility, marine shore sandy deposits to inland sandy deposits, and lowland 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, 2013).

Accordingly, our results show that if the number of heartwood rings is known, then the mean number of sapwood rings can be calculated fairly accurately for large numbers of *Pinus* timbers cut at the same time. Hence, if the precise date of the last heartwood ring has been established for at least 20 structural timbers of *Pinus* from a major structure, Gjerdrum's HAR formula can be used to calculate the approximate date of the structure even in cases where the sapwood rings of the timbers have been removed almost entirely. In practice, this can be done by first determining the mean absolute date of the last heartwood ring in contemporary architectural elements of the same building, and then adding the mean number of sapwood rings, estimated by HAR as

$$D_t = \Sigma^n{}_{i=1} D_{Hi} n^{-1} + \Sigma^n{}_{i=1} A_{Si} n^{-1},$$

where D_t is the theoretical date of the building, D_H is the absolute date of the last heartwood ring of the architectural element, A_S is the theoretical number of sapwood rings in the architectural element estimated by the HAR formula, n is the number of contemporary architectural elements in the wooden construction, i is the serial number of the architectural element, from 1 to n.

The results of this study permit the conclusion that the error between the theoretically calculated mean number of sapwood rings and the real number of sapwood rings for more than 20 *Pinus* trees does not exceed the error in calculating the number of sapwood rings for *Quercus* samples (Sohar *et al.* 2012; Sohar 2013). However, for *Pinus* trees older than 300 years, the difference already comprises several decades (Table 2, Figure 5). Hence, we question the suitability of HAR for the calculation of the sapwood amount for very old *Pinus* trees.

For the present, there are no conclusive results on sapwood longevity and heartwood formation rate of *Pinus.* It is necessary to explain that

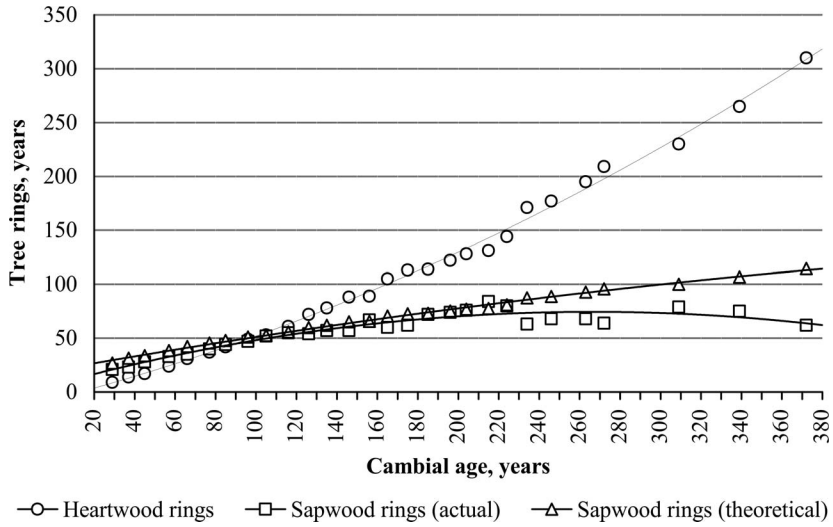

Figure 5. The actual (counted) and theoretical (estimated according to HAR) averaged number of sapwood rings and the corresponding number of heartwood rings.

sapwood longevity is sapwood lifespan expressed in the number of rings (years). Park (2002) describes that, for example, old Korean pines have 70–80 sapwood rings on average, *i.e.* the number of sapwood rings is nearly stable for *Pinus* older than 150 years. Thus, the sapwood ring number is related to heartwood formation rate and sapwood ring longevity. Our investigation indicates that the average sapwood longevity in Lithuania is *ca*. 78 years.

Questions not addressed in our study and requiring further attention include (a) the influence of growing conditions on sapwood formation, (b) the effect of the stem height on the number of sapwood rings and its conformance to the HAR formula as well as establishment of the precise age at which the development of heartwood rings starts, and (c) how this age differs between trees. Although these results are preliminary and are based on a limited number of trees, it is expedient to pursue the investigations in a dedicated study. However, such studies will also encounter the problems relating to poor growing conditions of trees on wet sites, including very narrow and missing tree rings.

CONCLUSIONS

Our investigations indicate that calculation of the number of sapwood rings for individual *Pinus* samples using the derived HAR formula of Gjerdrum can be inconclusive, especially for old (>220 years) *Pinus* trees. The sapwood estimation bias in historical timber increases because the source location of the wood and the height on the tree trunk from which the sample has been taken are unknown. So far, the results indicate that the proportion of heartwood to sapwood rings in different *Pinus* growth locations might be influenced by local ecological factors. To test this hypothesis and explore the related questions, it is necessary to conduct in-depth studies on a larger scale. However, our present results show that the mean number of sapwood rings can be calculated fairly accurately for large numbers of *Pinus* timbers. If the precise date of the last heartwood ring has been established for at least 20 timbers of *Pinus*, Gjerdrum's HAR formula can be used to calculate the approximate date of the structure even in cases where the sapwood rings of the timbers have been removed almost entirely. Hence, we question the suitability of HAR formula for the calculation of the sapwood amount for individual *Pinus* trees, but we support it for a group of at least 20 timbers.

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