Stem analysis - The better way to look to intra-tree variability

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ABSTRACT

A comprehensive knowledge of the characteristics of any material is essential to its best utilization. This is especially true for wood because of its cellular nature. Variability of wood parameters in a tree is sometimes a rather nebulous concept since variability is evident within single cells, from early- to latewood, from pith to bark and from stem base to the top of a tree. Comparing data from different heights within a stem is usually referred to as stem analysis. So far, stem analyses have been done using a restricted number of parameters, mostly ring-width, and using a restricted number of samples in longitudinal direction. This study analyses a number of parameters from a single tree. An 81-year old spruce tree was felled and internodial disks were taken from each annual terminal shoot. All tree rings in each disk were measured and a whole-stem analysis was completed for the following parameters: ring-width, mean ring density, percentage of latewood and type of transition from early- to latewood. We have found significant patterns for different parameters. Parameters mainly influenced by the climate during wood formation show more consistent pattern along the stem axis. The strongest signal – expressed in well visible lines parallel to the bark - was seen for the type of transition from early- to latewood. The results give helpful ideas for the discussion of how cores or disks taken at breast height represent the entire tree.

INTRODUCTION

Quality is a subjective expression that must be defined in every context. Usually wood quality is defined in terms of attributes that make it valuable for a given end use. Certain wood characteristics are desirable in one product, but not in another. Wood quality characteristics can be inherent to particular species, but they are also influenced by tree growing conditions. Wood parameters are subject of great variation within trees, a fact that foresters, wood utilization people and researchers have been dealing with for a long time. Variation is evident within single cells, within tree-rings, from pith to bark and from stem base to the top of a tree (Wimmer 1994). Most of the mechanical, anatomical and chemical parameters follow a consistent trend, with some parameters varying only a few percentages, whereas others exhibit a much higher variability. The large within-tree variation was mentioned by Larson (1967) by quoting: "higher variability in wood characteristics exists within a single tree than among trees growing on the same site or between trees growing on different sites". The most discussed source of variation refers to the pith-to-bark trend, also called the juvenile-mature trend.

Variation may also be considered in terms of genetic versus environmental effects, where the smoothed pith-to-bark trend reflects the underlying genetic potential of a tree on a given site (Abdel-Gadir, Krahmer 1993; Yang et al. 1994; Downes et al. 1997). The scatter of points around a smoothed trend indicates the potential of year-to-year variation among the strongest driving factors in wood formation - climate. The variability of certain wood parameters from pith to bark is utilised by dendrochronologists. Most parameters are determined on samples that are taken at breast height, disregarding that significant changes are also taking place with varying stem heights (LeBlanc et al. 1987; Zobel, Buijtenen 1989; Wimmer 1994).

Comparing data from different heights within a stem, which may also include branches or even roots to some extent, is referred to as stem analysis. So far stem analyses have been done for a restricted number of parameters only, mostly ring width, with usually limited numbers of samples taken from several tree heights (LeBlanc et al. 1987; Kramer, Jiménez 1991; Krause 1992; Krause, Eckstein 1992; Payette et al. 1996; Jiménez et al. 2003). Sampling heights are chosen either at fixed distances along the stem (Krause 1992; Krause, Eckstein 1992), or at positions relative to the total tree height (Downes et al. 1997).

The purpose of this study was to perform a complete tree analysis for a set of wood structural parameters by looking at every single tree-ring from every single terminal internode. With qualitative and quantitative analyses this study helps to understand better the phenomenon of within-tree variability.

EXPERIMENTAL METHODS

For this study an 81-year old, dominant Norway spruce tree (*Picea abies* (L.) Karst.) with a straight, undamaged trunk and a regular-shaped crown was selected. The sample tree was felled, cut into short logs and sawn into halves by cutting lengthwise near the pith, ending up in a thick radial orientated board that were always orientated south-east. The flat side of the board enclosing the pith was carefully planned until the pith became visible. This procedure was necessary to accurately identify all internodes. From each terminal shoot we have cut discs 3cm in thickness. In total, 81 sections were obtained, which matched with the number of rings on the disk taken at the tree-base.

The dried disks were sanded with sandpaper grids up to 1000 until individual tracheids became visible. Tree-rings were measured to the nearest 0.01 mm using a LINTAB® measuring device (www.rinntech.de). All ring-width series were cross-dated (Swetnam et al. 1985; Stokes, Smiley 1996) and checked for dating and measurement errors using the COFECHA software (Holmes 1983), followed by a visual checking. On the sanded disks the different parameters were counted and measured, respectively, along the radius from pith to bark in each tree-ring using a precision stereo-microscope that was equipped with a video-system. With this system it was possible to resolve clearly single tracheids. The type of transition from earlywood to latewood was visually assessed by splitting into the categories "gradual", "abrupt" and "compression wood", the latter judged by the shape, i.e. roundness of the tracheids and the entire ring structure. After measuring and counting at the polished surface, x-ray densitometry according to Lenz et al. (1976) was performed; this yielded the usual set of wood density parameter including percentage of latewood. The analysis was done with the Walesch DENDRO 2003 equipment at the WSL, Birmensdorf, Switzerland.

For visualization the data were categorized and indicated with different grey-levels. Each square represents one tree-ring and each plot displays the complete tree-stem for a certain parameter. Missing values generally appear as empty squares. Vertical lines running parallel to the pith indicate cambial rings while tree-rings formed in the same calendar year follow the diagonals running parallel to the stem surface (see figure 1). To visualize the figures of each parameter determined at breast height, graphs of the 5th terminal shoot (white horizontal line in Fig. 2) were plotted. To illustrate the variation from tree-base to top graphs of the 15th cambial ring (white vertical line in Fig. 2) and the calendar ring 1984 (white diagonal in Fig. 2) were also plotted.

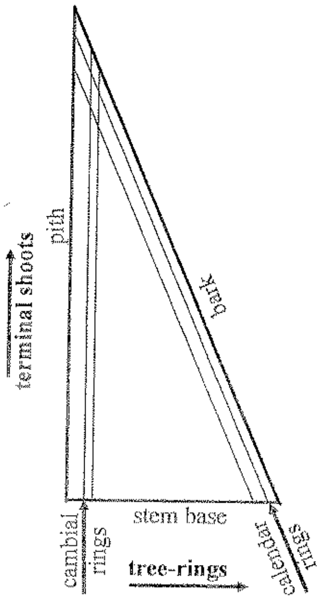

Figure 1: Scheme illustrating the sampling concept with cambial rings vs. calendar rings varying along the radius and tree heights.

A correlation analysis was performed to compare different sampling heights by a sequence of ten rings from each internode. The innermost 15 rings were excluded to account for the juvenility effect. The decadal sequences were either aligned by their cambial rings or by identical calendar years (see figure 2). Correlations were calculated between the 5th terminal shoot and the terminal shoots above, up to the 56th terminal shoot.

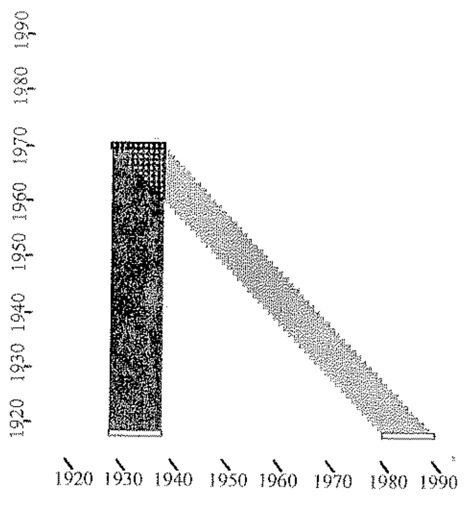

Figure 2: Scheme of data arrangement of the correlation analysis (light grey = available data; dark grey = data set of aligned calendar rings used in the analysis (10 tree-rings); black = data set of aligned cambial rings used in the analysis (10 tree-rings); white lines = place of visualizing trends (from pith to bark - 5th annual terminal shoot (1918); from base to the top cambial ring 15; from base to the top – calendar ring 1984).

RESULTS AND DISCUSSION

Ring-width

Ring width varied between 0.3 and 10.3 mm (mean value: 2.6 mm), a distinct age trend was not present (Fritts 1976, Bräker 1981; Figure 3). Ring-width pattern did not provide evidence for a sharp demarcation between juvenile and mature wood. During the period of accelerated growth (1925 to 1946) the radial age trend was more pronounced in the lower portion of the stem, i.e. from the base up to the annual terminal shoot of 1946. In general, the ring-width pattern of the investigated spruce tree did not match with the ones described by Payette et al. (1996) suggesting a cylinder of higher juvenile growth along the terminal shoots, or by Yang et al. (1994) proposing a conical juvenile wood model.

The reason for the expressed growth reduction after the aforementioned period of rapid growth (1925 to 1946) may be the beginning of severe fluoride air pollution that was present at the growth site at the end of the Second World War. Especially the narrower tree-rings at the outermost part were clearly aligned with calendar-years. The correlation analysis showed significance for the comparison of the same calendar rings (R^2=0.59), but no relationships existed when compared on a cambial ring basis (R^2=0.00). Correlations between ring widths aligned by calendar dates (Figure 3) and the reference, i.e. the 5th annual terminal shoot, showed significance with exception of the terminal shoots (1931, 1937, 1944, 1960 – 1962). This indicates the strong impact of climate on wood formation as described in literature (e.g. Fritts 1976, Schweingruber 1983).

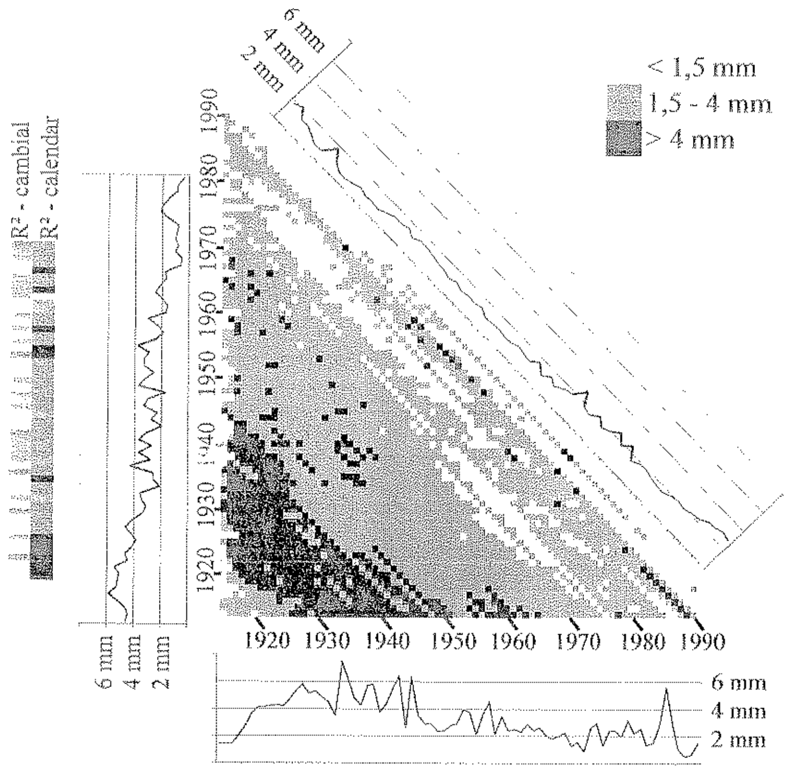

Figure 3:* *Ring-wise data of ring-width (grouped); labelled in different grey levels. The graphs of the 5th annual terminal shoot (1918), the 15th cambial ring and the calendar ring 1984 are given. On the left side the results of the simple correlation analysis are presented (R^2 - cambial = coefficient of correlation across the cambial rings; R^2 - calendar = coefficient of correlation across the calendar rings). The coefficients are labelled in different grey levels (light grey ... $R^2<0$; grey ... $R^2= 0 – 0.4$; dark grey ... $R^2=0.4 – 0.7$; black ... $R^2>0.7$)

Mean ring density

Mean ring density varied between 0.27 and 0.92 g/cm³ (mean value: 0.47 g/cm³). The fast growing period (1925 to 1946) was dominated by lower density (Figure 4). The outermost tree-rings show higher mean ring densities, as frequently reported in literature (e.g. Kollmann 1951; Göhre 1958; Bosshard 1974; Panshin, DeZeeuw 1980).

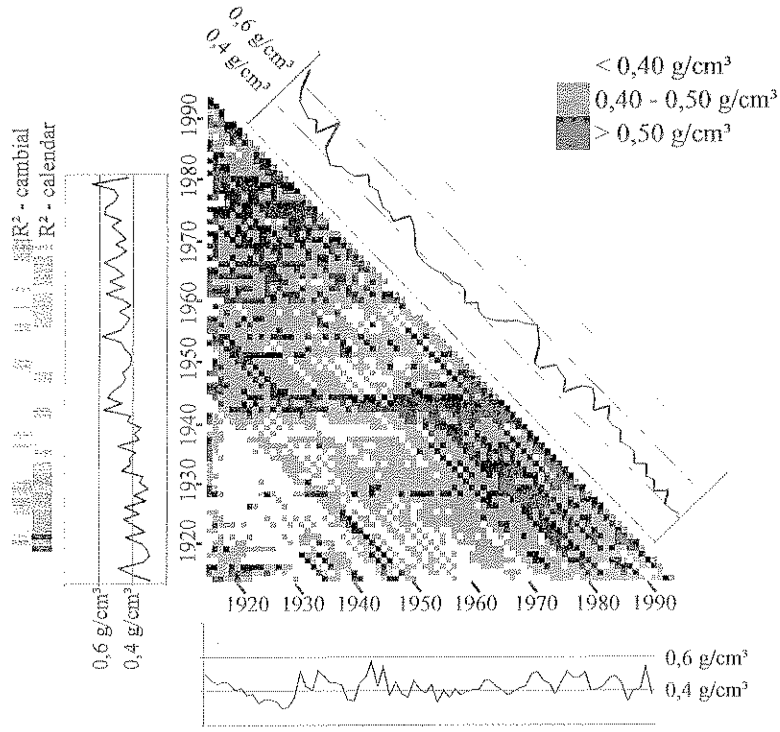

***Figure 4:** Ring-wise data of mean ring density (grouped); labelled in different grey levels. The graphs of the 5th annual terminal shoot (1918), the 15th cambial ring and the calendar ring 1984 are given. On the left side the results of the simple correlation analysis are presented (R^2 - cambial = coefficient of correlation across the cambial rings; R^2 - calendar = coefficient of correlation across the calendar rings). The coefficients are labelled in different grey levels (light grey ... $R^2<0$; grey ... $R^2= 0 - 0.4$; dark grey ... $R^2=0.4 - 0.7$; black ... $R^2>0.7$)*

There are several terminal shoots (1928, 1942-1944) with a generally higher wood density visible as horizontal lines. No definite explanation can be given for this pattern but one might hypothesize that this is related to stem straightness defects, i.e. sinuosity, which is stem waviness or crookedness totally within inter-whorl segments (Doede, Adams 1998; Temel, Adams 2000). However, this phenomenon is most common in Douglas-fir but has not been seen in spruce. In any case it is likely a type of mechanical stabilisation response of the tree. Generally, the wood formed higher up in the stem seemed to have slightly higher wood density. The effect of rapid growth from 1925 to 1946 and the horizontal orientated regions of higher density are masking possible radial trends in wood density as described in Bräker (1981) and Abdel-Gadir, Krahmer (1993). Zobel, Buijtenen (1989) summarized that wood density close to the pith may start a bit higher, followed by a slight decline, before it is again rising in the mature region. These authors also reported slight changes in wood density with height for spruce, while Mitchell, Denne (1997) did not see such a trend.

An expected pattern similarity of ring-widths and mean ring density is in part present in the investigated tree. Downes et al. (2002) summarized that growth pattern and not the rate of growth is the main cause of variation. The pattern of variation of mean ring density show stronger relationships to the percentage of latewood than to ring-width. This strong relationship was confirmed by Wimmer, Grabner (2000). Here, correlation analysis has shown lower significance, compared to ring-width and maximum density (calendar rings R^2=0.11; cambial rings R^2=-0.05). The coefficients calculated for the calendar rings decreased with decreasing proximity to the reference (Figure 4).

Latewood percentage

The percentage of latewood varied between 4 and 94% (mean value: 31.6%). The very high percentages of latewood are found due to existing compression wood (Figure 5). To visualize the amount of latewood-like tracheids, compression wood was not excluded from the analysis. Also the comparison of rings with high latewood percentages with the pattern of visually assessed compression wood as shown in the early- to latewood transition (Figure 6) should be possible. Not all tree rings that visually classified as compression wood showed high numbers of latewood percentage (for example 1951 and 1953). Especially the young tree up to an age of about 30 years was characterized by low amounts of latewood (Figure 5). The same horizontal lines as with mean ring density and maximum density are also seen with the percentage of latewood.

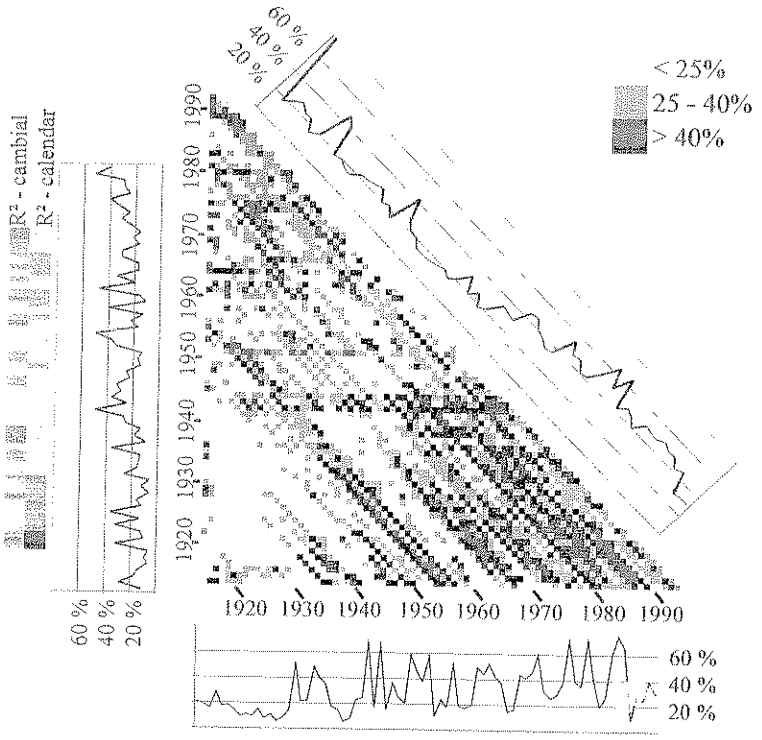

***Figure 5:** Ring-wise data of latewood percentage (grouped); labelled in different grey levels. The graphs of the 5th annual terminal shoot (1918), the 15th cambial ring and the calendar ring 1984 are given. On the left side the results of the simple correlation analysis are presented (R^2 - cambial = coefficient of correlation across the cambial rings; R^2 - calendar = coefficient of correlation across the calendar rings). The coefficients are labelled in different grey levels (light grey ... R^2<0; grey ... R^2= 0 – 0.4; dark grey ... R^2=0.4 – 0.7; black ... R^2>0.7)*

With increasing age the percentage of latewood increased, which was also summarized by Bräker (1981) and Wimmer (1994). Because of the distinct calendar-year pattern, the influence of climate on the percentage of latewood is evident. The reasons for the cessation of earlywood formation and starting of latewood has been debated, however possible influencing factors – including climate - are summarized in Zobel, Buijtenen (1989). The correlation analysis showed weak relationships across stem height for calendar rings and cambial rings, similar to mean ring density (Figure 5). The coefficients of correlation calculated for the calendar rings decreased with distance to the reference.

Early- to latewood transition

Transition from earlywood to latewood appeared to be mainly gradual (Figure 3 E), as stated elsewhere (Liese, Dujesiefken 1986). However, some years clearly showed abrupt transitions seen throughout the stem. This may be indicative for a strong linkage with climate of the year where these rings were formed. Krause (1992) has reported relationships between abrupt earlywood - latewood changes and strong temperature fluctuation, in combination with drought periods in spring and early summer. Compression wood was found in the innermost tree rings along the stem, which was distinct from juvenile wood. Zobel, Buijtenen (1989) have described such associations between juvenile wood and reaction wood. The 1990 tree-ring was found to be thoroughly compression wood in all annual terminal shoots, which matched with a severe clear-cutting activity during the previous winter. Between 1935 and 1949 four years showed a clear compression wood formation in the lower part of the stem. This phenomenon may be attributed to a period of mechanical adjustments of the tree.

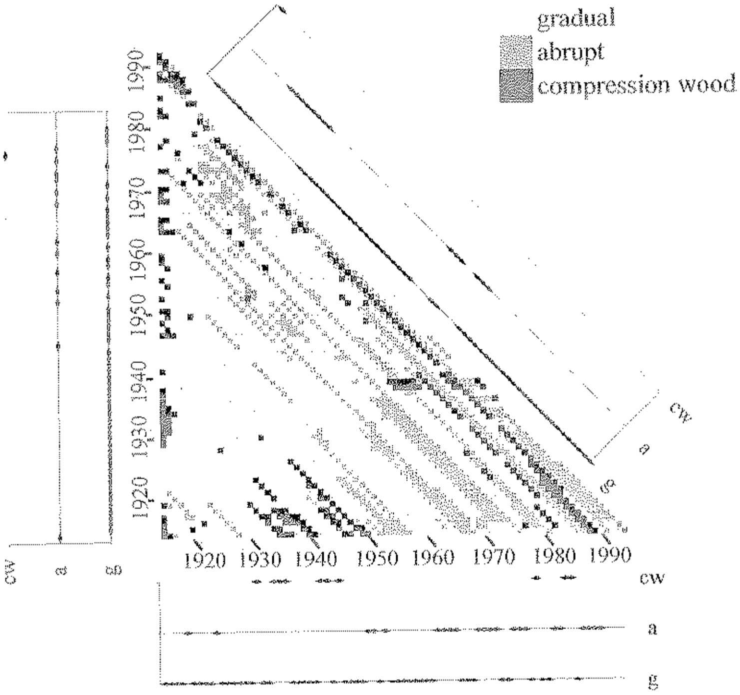

Figure 6: Ring-wise data of type of transition from early- to latewood; labelled in different grey levels. The graphs of the 5th annual terminal shoot (1918), the 15th cambial ring and the calendar ring 1984 are given. (g ... gradual, a ... abrupt, cw ... compression wood)

Demarcation of juvenile wood

Comparing all described parameters of this single spruce tree no general pattern for juvenile wood was found. Downes et al. (1997) described four possible patterns of variation, mapped onto conical shapes: cylindrical symmetry, conical symmetry, general linear and general non-linear. All presented parameters (ring-width, mean ring density, percentage of latewood and transition from early- to latewood) did not show clearly the demarcation between juvenile and mature wood. But these parameters presented a strong alignment with calendar-years along the annual terminal shoots as described by the conical-symmetry-model. Abdel-Gadir, Krahmer (1993) summarized: "The change from juvenile wood to typical mature wood is neither sharp nor the same for all intra-ring characteristics."

Evaluating sampling strategies

To evaluate the significance of sampling at breast height a correlation analysis was performed. The ring-width pattern of the 5th annual terminal shoot showed significant correlations with the ring-widths of the internodes above, if aligned by calendar years (see figure 2 and 3). Averaging the correlation coefficients of the 52 terminal shoots above the reference (5th terminal shoot) by calendar rings resulted to R^2=0.59. Due to expected influences of the root system on ring-width below breast height the lower terminal shoots were excluded. The results of the calendar ring comparisons were: for mean ring density R^2=0.11 and for the latewood percentage R^2=-0.07. It can be concluded that cores taken at breast height represent the annual pattern of wood formation of the whole stem for the climate induced parameters (ring-width).

In wood quality studies measurements are often done at defined tree ages (= cambial rings). The correlation coefficients for the cambial rings, averaged across the 52 terminal shoots above the reference, were non-significant. Climate (=calendar rings) had a higher impact on ring pattern than cambial age, as already discussed (e.g. Fritts 1976, Bräker 1981, Schweingruber 1983). Therefore, due to the different pattern for each of the parameters, no general recommendation for an optimal sampling point to study wood quality can be given.

CONCLUSIONS

A whole-stem analysis using each terminal shoot was helpful to visualize the variability within a stem. Dendrochronologists looking for the sampling that represents best the climate-growth relationships, as well as people who are into wood quality asking for the best way to represent the entire tree, may learn a great deal about within-tree variability from such whole-stem analysis. The studied parameters showed different trends with increasing age. It was not possible to determine a general pattern for juvenile-mature wood appearance that would be valid for all observed parameters.

To answer the questions about best sampling points at the tree, dendrochronologists may still stay with their breast height as a good choice enclosing almost all available tree-rings and most of the year-to-year variations. For wood quality studies this study has no general recommendation for the best sampling point as it depends on the parameter investigated.

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