ABSTRACT

Knowing the mean and the intra-ring density of wood enables to estimate mechanical and physical wood properties, and it provides important climatological information. Many methodological approaches to determine wood density are in use, and they undergo a permanent development and improvement. Goal of this study was to compare two up-to-date non-destructive radiographic techniques - SilviScan (based on X-rays) and Neutron Imaging - in terms of their methodology, the specimen handling, and the generated density data. At the present time, the systems clearly differ regarding their user-friendliness (and thus their suitability) especially for measurements on wooden samples. However, the measurement results of both techniques, i.e. the qualitative and quantitative characteristics of the density profiles, show good to high congruence.

KEY WORDS: wood density, densitometry, SilviScan, neutron imaging, common yew, Norway spruce

INTRODUCTION

Density is a crucial wood property as it correlates with most mechanical but also with other physical properties. The radial density distribution within and across annual rings, together with ring width, is also a basis for tree ring analysis examined on increment cores. Evaluating density profiles for dendrochronological investigations is indispensable, for example, when past environmental conditions have to be reconstructed or the provenance of a wooden piece has to be identified by crossdating. Moreover, density can also provide information about the storage of carbon as a result of growth conditions.

While diverse procedures enable the generation of density profiles from increment cores (e.g. optical methods such as transmission light microscopy, drilling resistance (Rinn et al. 1996), laser-sandblasting method, high-frequency densitometry), the most commonly used are based on radiographic measurements. Two of the most promising and most up-to-date of these non-
destructive techniques are based on X-ray and neutron radiation. X-ray radiography on wood was developed in the 1960s (Polge 1964, 1965, 1966) and is usually based on X-ray film analysed with an optical densitometer. Most of the current investigations still use X-ray film, but problems with non-linearity between the optical and the actual wood density exist. Neutron imaging (NI) is a relatively new non-destructive method working along the same principles as X-ray imaging. NI is more sensitive to hydrogen and therefore particularly suitable for investigating wood or moisture in wood.

As regular users of these and similar techniques, the authors analyse manifold facets of the wooden material structures, depending on the respective question or issue (Evans 1994; Evans et al. 2000, Keunecke et al. 2009, Mannes et al. 2007, Mannes et al. 2009a; Trtik et al. 2007). A good knowledge of the techniques, however, is vitally important to avoid misinterpretation of data. A methodological comparison of techniques may help deepen this knowledge, particularly regarding strengths and weaknesses, sensitivities and restrictions of the methods.

In a prior study (Mannes et al. 2007), a first such comparison was carried out: standard X-ray densitometry and NI were compared with regard to the measurement of tree-ring wood density. The X-ray measurements in that study were performed with “Dendro 2003” (Eschbach et al. 1995). This procedure is somewhat laborious as the samples’ density has first to be calibrated using a calibration wedge, and the information (the transmitted radiation) is stored on a specific film that has to be developed and evaluated. The NI measurements were based on the irradiation of imaging plates, which also have to be read out in several steps.

Both methods have several drawbacks: They are time-consuming and can be subject to quantification errors (as in the case of NI, q.v. Mannes et al. 2009b). X-ray radiography using X-ray film generates analogue data, which have to be converted to digital data for further computational evaluation. It is obvious that such techniques undergo a continuous process of development; in the meantime, advanced techniques are available.

The goal of this present study, therefore, was to determine radial density profiles of wooden samples applying up-to-date versions of both approaches, and to compare them to each other in terms of their methodology, the handling of specimens, and the resulting density data (the latter using basic statistical methods). The neutron measurements were performed at the ICON beamline of the Paul Scherrer Institute (Villigen, Switzerland). Instead of imaging plates, a scintillator – CCD camera system served as the detector. The X-ray measurements (using the SilviScan-3 system) were carried out at CSIRO Materials Science and Engineering (Clayton, Australia), using a two-dimensional scintillation-CCD detector suitable for soft X-rays. Both systems directly generate digital datasets and are clearly improved in their user-friendliness compared to the systems investigated in our prior study.

MATERIAL AND METHODS

Measurement principles

The principle of transmission measurement is valid for both of the analytical techniques employed here: From a radiation source, X-ray or neutron beams are guided to an object. The incoming radiation is attenuated by the object, and the transmitted radiation generates a shadow image registered by a detector system yielding information on the density distribution of wooden samples within the image plane. The beam is aligned parallel to the tangential direction of the wood samples generating radial density profiles; i.e. the density variations result from differences within and between growth rings while the contribution of ray parenchyma is at a rather constant
level. The interaction (e.g., absorption, scattering) between the beam and the object depends on the type of radiation, and also on the object’s elemental composition.

SilviScan uses the well-established X-ray technology to determine density profiles (so called X-ray densitometry). X-ray photons interact with the electrons of atomic shells (the atomic number and the interaction probability are strongly correlated), while neutron radiation, consisting of electrically neutral particles, does not. Instead, neutrons interact with the atomic nuclei and show a high interaction probability for some light elements such as hydrogen.

The degree to which a material attenuates a beam is described by the attenuation coefficient within the linear attenuation law:

\[ I = I_0 e^{-\Sigma z} \]  

(1)

where \( I \) is the intensity of the transmitted beam, \( I_0 \) is the intensity of the incident beam, \( \Sigma \) is the neutron attenuation coefficient of the material (for X-rays, the symbol \( \mu \) is commonly used), and \( z \) is the specimen thickness.

This law is valid for a mono-energetic beam when the sample thickness \( z \) tends towards zero. How to calculate \( \Sigma \) for a material such as wood composed of more than one element and for a facility with a polychromatic spectrum, as well as further theoretical considerations regarding the measurement principle, is described in great detail by Mannes et al. (2009b).

Samples

One yew (\textit{Taxus baccata} L.) and two spruce (\textit{Picea abies} [L.] Karst.) samples were cut from tree disks taken at breast height. Compression wood was carefully omitted. The spruce samples differed greatly in the width of their annual rings. The spruce sample with narrow growth rings is also termed “spruce N” in the following, and the sample with wide growth rings “spruce W”.

The samples were processed to radial sections of 2 mm thickness (tangential) and 7 mm height (longitudinal); their radial length was 80 (yew), 160 (spruce N) and 250 mm (spruce W). Using a twin-blade circular saw, they were cut out of the tree disks from close to the pith to the sapwood.

First the SilviScan, and then a few weeks later the neutron experiments were performed. The equilibrium moisture content of the specimens during the SilviScan measurements was approximately 8 % for both species, and during the NI measurements below this value.

Setup for SilviScan measurements

The measurements were performed at CSIRO Materials Science and Engineering (Clayton, Australia). The SilviScan-3 densitometer uses a copper fine focus tube in point focus mode. The projected source size was approximately 400 \( \mu \)m (horizontal) by 600\( \mu \)m (vertical). The ratio of the distance from the source to the sample to that from the sample to the detector is about 50, giving an apparent source size at the detector of about 8 \( \mu \)m x 12 \( \mu \)m (H x V). The detector is a Photonic Science CCD camera with a 1:1 fibre optic bundle and an X-ray sensitive phosphor coating. The system is periodically calibrated using a cellulose acetate step wedge, taking into account beam hardening (resulting from polychromaticity), pixel response variations and geometric distortion. Densitometry is carried out using an anode voltage of -35 kV and current of 20 mA, and the result for each sample stored as a composite 16-bit image in which the grey scale corresponds with estimated density. Density profiles are reported at 25 micron intervals.

Prior to scanning, the average sample densities are measured gravimetrically (standard procedure for SilviScan analysis) using the conditioned weight and the volume obtained by micrometry. The x-ray density profile average is scaled to match the measured average gravimetric density.
WOOD RESEARCH

For softwoods, the analyses described above can be performed at a rate of 5 - 10 m/day, recording density, tracheid cross-sectional dimensions, ring and ray orientations. In this study, however, only density was analysed.

Setup for neutron measurements

The experiments were carried out at ICON, a NI beamline at the PSI (Villigen, Switzerland) using cold neutrons. An extensive description of the ICON characteristics can be found in Kuehne et al. (2005). The neutrons of this beamline are generated by the Spallation Neutron Source SINQ (for details, see Bauer 1998).

The oven-dry samples were positioned within the path of an almost parallel neutron beam in front of a scintillator – CCD camera system serving as detector. The scintillator, which converts the neutron signal into visible light, was 50 µm thick and was doped with gadolinium as neutron-absorbing agent. Within a light-tight box, a mirror was used to send the emitted light via a 1:1 optical lens-system onto a CCD camera (Lehmann et al. 2007); this allowed storing the images digitally as 16-bit files. The detector had a field of view of 27 mm, thus the samples had to be scanned section by section. The measuring positions were 20 mm apart yielding overlapping areas visible in consecutive images. The exposure time was 150 s and for every section three images were recorded. For data evaluation details (image/scattering correction procedures; calculation of $\Sigma$), see Mannes et al. (2009b). Similar as in the case of SilviScan measurements, the density profiles were calculated using the gravimetrically determined sample densities by adjusting the mean attenuation coefficient $\Sigma$ of the respective specimen to this value.

Raw data correction

As a consequence of different climatic conditions during the SilviScan and NI measurements, the samples presumably underwent swelling / shrinkage processes between the experiments, and thus changes in their dimensions and density. To restore the comparability of both techniques’ results, the data first of all had to be adjusted to one another. This was carried out in three steps:

1) The radial profiles were made equidistant (the factor to equalize the total radial length of both data series was determined, and the total lengths of the neutron profiles were adjusted to those of the SilviScan profiles (the NI profiles had to be stretched up to 3 %);
2) The averages of the profiles were equalized (the density of the profiles measured with neutrons was adjusted to that of the profiles measured with SilviScan).
3) Based on Gleichläufigkeit values (Schweingruber 1988), the profiles were spatially synchronized; thus the peak positions were, as far as possible, identical. The definition of Gleichläufigkeit follows in the paragraph below.

Data evaluation and statistics

Besides visual assessment, the data were compared using some basic statistical methods:

Annual ring width

The density maxima and minima in each annual ring were identified. Based on the maxima (i.e., under the assumption that the maximum represents the last-formed cells in an annual ring), the annual rings widths were determined. Using the density value halfway down the slope from latewood to earlywood was also tried but made no significant difference to the findings.
Density distribution
The tabulated density frequencies were analyzed in histograms.

Similarity of data
The degree of similarity between two curves (complete density profiles, density maxima, density minima, annual ring widths) was expressed with Gleichläufigkeit values and correlation coefficients. Gleichläufigkeit for two curves is a standard dendrochronological parameter (Schweingruber 1988) examining the intervals between successive points for an upward or downward trend; it is defined as

\[ G(x,y) = \frac{1}{n-1} \sum_{i=1}^{n-1} \left| G_{ix} + G_{iy} \right| \]  

with

\[ \Delta_i = (x_{i+1} - x_i) \text{ when } \Delta_i > 0: G_{ix} = +0,5; \Delta_i < 0: G_{ix} = -0,5 \]

where \( G(x,y) \) is the Gleichläufigkeit for two whole series \( x \) and \( y \), \( n \) is the number of observations, \( G_{ix} \) and \( G_{iy} \) is the Gleichläufigkeit at moment \( i \) for \( x \) or \( y \), and \( \Delta_i \) is the difference between two successive observed values over the interval \( i \) (\( x_{i+1} - x_i \)). \( x_i \) is the observed value of the series \( x \) at moment \( i \). \( G(x,y) \) can reach a value between 0 and 1; for two curves with identical trends it is 1. To overcome misinterpretation problems due to noise at the growth ring level, the data were smoothed with a 10-point moving average before calculating Gleichläufigkeit. The correlation coefficient, however, was calculated from the unsmoothed data. It is a measure of the linear relationship between pairs of values from two series, and is defined as

\[ r = \pm \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} \]

where \( r \) is the correlation coefficient, \( x_i \) and \( y_i \) are observed values of the series \( x \) or \( y \) at the point \( i \), and \( \bar{x} \) and \( \bar{y} \) are means of the series \( x \) and \( y \).

RESULTS AND DISCUSSION

Comparison of methodology
Appropriate adaptation of the systems for measuring wood density profiles
Growth ring boundaries are not always perpendicular to the wood rays. One big advantage of the SilviScan system is that the measuring direction can be automatically adjusted so that the beam is always parallel with the growth ring boundaries. Failure to adjust the beam correctly causes inaccurate results such as underestimated latewood densities (Fig. 1). At the ICON beamline, such an adjustment is not implemented yet for NI measurements. But in principle it would be possible using an auxiliary CCD camera above the sample as the samples were mounted on a rotating table. For the present study, however, the SilviScan measurements were performed the same way as the NI measurements (i.e. with the beam being perpendicular to the specimen surface, and not necessarily parallel to the growth ring boundaries) to ensure the comparability of SilviScan and NI results.
A further advantage of the SilviScan system is that the sample is automatically moved forward in the radial direction while the transmitted radiation is detected, so that the length of the sample is of secondary importance. At the ICON beamline, no such device is available so that specimens exceeding the detector size have to be scanned in several sections, and the sequences have to be reassembled afterwards.

The two systems differ with respect to the handling of the measurements since one system is specialised for this kind of experiment while the other was conceived for a different purpose. SilviScan was designed and constructed for the determination of density (and other properties) within wood samples, thus the measurements as well as the data collection and evaluation is less intricate and time consuming than with the NI setup. The NI setup at the ICON beamline was designed for micro-tomography and the data acquisition had to be slightly adjusted for the measurement of density profiles. Sample positioning and data acquisition (longer exposure time, acquisition in sections) require more time. The data evaluation is also more time consuming, because the image data have to be normalised and the effects of neutron scattering have to be corrected (Mannes et al. 2009b). By developing an experimental setup and routine for this kind of measurement, the handling could be simplified and the time required could be significantly reduced.

Comparison of data

Visual assessment

The visual agreement in pattern and level over the entire data range of both density curves (SilviScan and NI measurements) was good for all three specimens. A representative section of the yew density profile is shown in Fig. 2. In particular the moving averages show a high degree of congruence. The noise in the lower density range is clearly higher than in the upper one; the NI curve is slightly less noisy. The latter phenomenon has already been observed by Mannes et al. (2007); they explained it with scattering artefacts.
Fig. 2: Radial density profiles of the same specimen section, determined by SilviScan and by NI.

An even higher congruence is obvious for the widths of annual rings (Fig. 3; mean values: yew 1.66 mm, spruce N 1.33 mm, spruce W 4.57 mm). The profiles determined with SilviScan and NI exhibit a high synchronicity. Resulting from annual maximum peak to maximum peak measurements, the signal noise within the annual rings, is not reflected in these curves.

Fig. 3: Annual ring width of the yew and the two spruce specimens, determined by SilviScan and by NI.
Density distribution

To evaluate if both techniques differ regarding their sensitivities for different density levels, the distribution has been analyzed over the density classes in histograms (Fig. 4). Due to the higher earlywood than latewood percentage in a growth ring, the distribution is generally shifted to the lower density classes. This shift is more pronounced for the spruce samples due to their higher earlywood percentage compared to yew. The deviation between both methodological approaches illustrated by the histograms seems negligible, and can probably be ascribed to the results of the different climatic conditions during the measurements and to the preparatory data correction.

![Fig. 4: Histogram of density classes, as measured by SilviScan and by NI.](image)

Calculated similarity of data

The mathematical evaluation of data similarity confirms the visually assessed high congruence between SilviScan and NI measurements. Tab. 1 summarizes the correlation coefficients and Gleichläufigkeit values for the parameters density, density maxima, density minima, and annual ring width.
Tab. 1: Correlation coefficients and Gleichläufigkeit for (sequential) density data and annual ring width determined by SilviScan and by NI.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Density</th>
<th>Density maxima</th>
<th>Density minima</th>
<th>Annual ring width</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yew</td>
<td>Spruce N</td>
<td>Spruce W</td>
<td></td>
</tr>
<tr>
<td>r (n)</td>
<td>0.802 (8063)</td>
<td>0.753 (45)</td>
<td>0.911 (45)</td>
<td>0.996 (45)</td>
</tr>
<tr>
<td>G (n)</td>
<td>0.683 (8063)</td>
<td>0.902 (45)</td>
<td>0.772 (45)</td>
<td>0.900 (45)</td>
</tr>
</tbody>
</table>

r - correlation coefficient, G - Gleichläufigkeit, n - number of considered values

The highest similarities were measured for the annual ring width, demonstrating the suitability of both measurement techniques for dendrochronological applications. The correlation coefficients for density are slightly lower for spruce, and even smaller for yew, than for the annual ring width. The agreement between both methods in measured density maxima and minima is still good. However, the agreement between spruce density minima (which are clearly lower than yew density minima) is somewhat smaller.

If the samples had been measured at the same room conditions (and thus with the same shape and dimensions), greater similarity would have been expected.

CONCLUSION

With respect to the obtained results, i.e. density profiles, the two methods prove to be equivalent. The methods differ mainly in the handling and the time required to obtain the final results. In this regard, SilviScan has a clear advantage over NI, owing to the fact that the SilviScan system was specially developed for the kind of experiment performed within the scope of this work. The NI setup needed corrections for the measurements and the evaluation of the resulting data was also more time consuming and intricate. The advantage of the NI system is its flexibility, which allows the utilisation for diverse applications including computed tomography, the qualitative and quantitative assessment of dynamic processes (e.g. water transport by diffusion), etc. SilviScan on the other hand is a ready-to-use solution for the determination of density profiles and tree-ring analysis, as well as the determination of the microfibril angle and other parameters within the sample.

ACKNOWLEDGEMENTS

The authors would like to thank Dr. Britta Eilmann (Swiss Federal Institute for Forest, Snow
and Landscape Research WSL; research group: Forest Dynamics) for her advice regarding basic statistical evaluation commonly used in dendrochronology.

REFERENCES
