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Non-Destructive Estimation of Sapwood and Heartwood Width in Scots Pine (*Pinus sylvestris* L.)

Dirk Bieker and Steffen Rust

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Accurate estimates of the water conducting sapwood area are necessary to scale sapflow measurements to tree and stand level transpiration. We tested a non-destructive method, electric resistivity tomography (ERT), to estimate the area of conductive sapwood in 9 *Pinus sylvestris* L. trees in lower Saxony, Germany. Tomograms were compared to cross-sections stained with benzidine after harvesting. All tomograms displayed a distinct pattern of low resistivity at the stem perimeter and high resistivity in the stem centre with a steep increase in resistivity in between, assumed to indicate the transition from sapwood to heartwood. The tomograms showed a sapwood width 2 cm smaller than the staining method. This indicates that staining methods overestimate the amount of active sapwood because when heartwood is formed, moisture content decreases before extractive contents reach levels visible by staining. The ERT method is a new powerful method for the non-destructive estimation of sapwood and heartwood width.

Keywords non-destructive testing, tomography, sapwood, pine
Addresses University of Applied Sciences and Arts, Faculty of Resource Management, Büsgenweg 1a, D-37077 Göttingen, Germany **E-mail** rust@hawk-hhg.de
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1 Introduction

Whole tree transpiration estimates using sapflow sensors have been widely applied in the past two decades. However, scaling sapflow measurements to whole tree and stand transpiration rates remains problematic, especially in species with deep functional sapwood (Pausch et al. 2000, Cermak et al. 2004). While measurements at several depths provide information on radial sapflow profiles, sapwood area estimates are based on destructive post hoc methods, often confined to increment cores. Reliable non-destructive estimates of the size and distribution of sapwood area at the level of sapflow measurements could improve not only the scaling, but also the positioning of the sapflow sensors.

Scots pine (*Pinus sylvestris* L.) has the widest geographic range of all tree species native to Eurasia and is one of the most important timber species worldwide. Its wide distribution and impact on site and ecosystem hydrology has resulted in a growing number of studies using sapflow sensors to estimate tree and stand transpiration (Cermak 1995, Backes 1996, Sturm et al. 1998, Rust and Lüttschwager 1998). Its sapwood is too wide to be covered by most of the commercially available sapflow sensors and sapwood to heartwood area ratios vary considerably, both within and between stands. Thus, transpiration estimates could significantly gain from information on individual sapwood areas.

In addition, sapwood and heartwood of *Pinus sylvestris* L. are often used for different purposes due to their considerable differences in properties. The non-destructive determination of sapwood and heartwood could help to gain a better understanding of factors that influence their proportion and could therefore support a more effective use.

The higher moisture content of sapwood compared to heartwood in most conifers is well known (Vintilia 1939). While below the fibre saturation point electrical resistivity is primarily correlated with wood moisture, above the fibre saturation point the concentration of mobile ions in the wood exerts the largest influence (Lin 1967, Shigo and Shigo 1974, Tattar and Blanchard 1974, Dixon et al. 1977). Due to the higher water content and the higher amount of ions, the sapwood of *Pinus sylvestris* L. has a considerable lower electric resistivity than the heartwood. During heartwood formation, moisture content decreases before extractive contents (e.g. pinosylvin) reach levels visible by staining (Bergström 2003).

Electric resistivity tomography (ERT) is widely used in material testing, geophysics and medicine to estimate the distribution of specific electric resistivity. Since 1998 (Just et al. 1998), the method has been used for testing standing trees non-destructively, e.g. to detect decay (Dubbel et al. 1999, Bieker 2010), red heartwood in beech (Weihs et al. 1999, Hanskötter 2004) and brown heartwood in ash (Weihs et al. 2005). Recent publications show, that even sapflow can be detected by the electrical resistivity method (Hagrey 2007).

In this study the use of electric resistivity tomography to detect sapwood area in pine is tested and results are compared with area estimates from benzidine stained stem discs. Our hypothesis was that because of higher moisture content sapwood should have a lower resistivity than heartwood. The steep decline in wood moisture from sapwood to heartwood (Rust 1999, Kravka et al. 1999) should help to distinguish the two zones.

2 Material and Methods

Nine *Pinus sylvestris* L. trees (diameter at breast height 24 to 49.5 cm, age 69 to 88 years) growing in a forest near Göttingen (51°27´N, 9°59´E), Germany, were used in this experiment. Measurements were conducted on healthy trees without visible signs of stem decay within two days in September 2006. All but one tree grew in level terrain. Tree no. 6 was placed on a steep hillside.

2.1 Electric Resistivity Tomography (ERT)

A multiplexer with internal power supply (GeoTomMK8E1000 RES/IP, GEOLOG Fuss und Hepp GbR, Germany) and custom-made stainless steel electrodes with a needle diameter of 2 mm were used for the measurements. To analyse a stem cross-section, 24 electrodes were forced through the bark into the outermost wood by hand at constant height (30 cm) above ground. A low frequency current (8 1/3 Hz) was applied and measured in a dipol-dipol-configuration (Reynolds 1997). The software DC2dTree (Günther et al. 2006) was used for tomographic inversion. The entire process including the calculation is completed within 15 minutes per tree.

2.2 Staining and Tomogram Analysis

Trees were felled and stem cross-sections cut in the plane of the tomography were taken to the laboratory and stained with benzidine to delineate the heartwood/sapwood boundary (Rust 1999). This method colours the sapwood red and the heartwood yellow. Sapwood width along two opposing radii per disc was measured to the nearest mm.

For the analysis of the accuracy of the tomograms the centre of the narrow green ring in the tomograms, corresponding to the steep rise in resistivity from sapwood to heartwood, was taken as the heartwood/sapwood boundary. Based on this, sapwood and heartwood area of the cross-sections and sapwood width for eight radii per tree spaced at 45°-intervals were estimated from the tomograms.

All tests were computed with the R statistical programming language (v2.9.2., R Development Core 2009). Linear models were analyzed with the robust package (v0.3-4, Wang et al. 2008).

3 Results

All tomograms display a distinct pattern of low resistivity at the stem perimeter and high resistivity in the stem centre (Fig. 1). The transition between these zones is rather narrow and represents a steep increase in resistivity. The 5% and 95% quantils of electric resistivities of the sapwood of the nine trees were 219 ± 42.5 Ωm and 594 ± 55.5 Ωm. The electric resistivities of the heartwood ranged from the maximum of the sapwood to 1737 ± 393.4 Ωm.

Sapwood width from the tomograms compared well with that obtained by staining ($R^2 = 0.87$, $p < 0.0001$, Fig. 2). Mean sapwood width from staining was 8.1 cm ± 0.6 cm and 6.1 ± 0.5 for the tomograms.

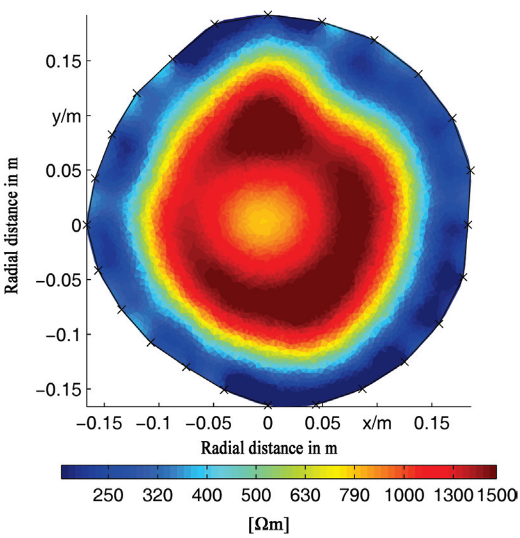

Fig. 1. Representative ERT tomogram of Pinus sylvestris L. Blue indicates low electrical resistivity, red indicates high electrical resistivity.

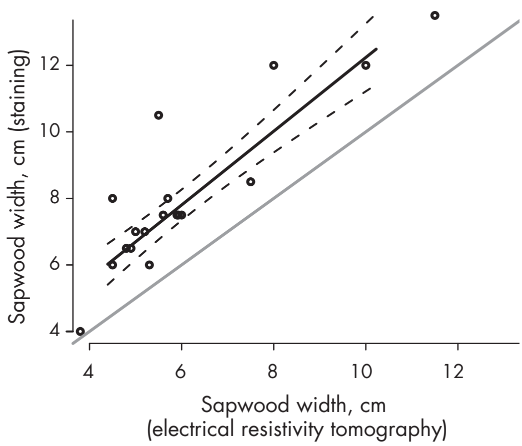

Fig. 2. Sapwood width of Pinus sylvestris L. measured with ERT and benzidine staining. Linear regression and 95%-confidence interval, n= 18; grey line indicates 1:1.

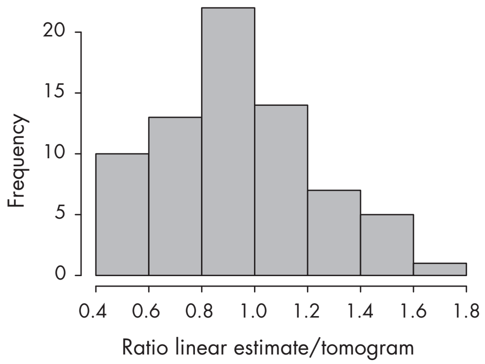

Fig. 3. Frequency distribution of the ratios of sapwood area calculated from single linear estimates of sapwood width and area estimates from tomograms.

The sapwood area calculated from the mean of 8 individual radial measurements in the tomograms did not differ significantly from the mean sapwood area estimated from the tomograms ($p=0.23$). There was, however, a large variation (Fig. 3): estimates from one linear measurement ranged from 43 per cent to 170 per cent of sapwood area as estimated by tomography.

The inner zone of high resistivity is not homogeneous, though. In the centre of most of the tested trees the there is an area of relatively low resistivity. This area coincides with the pith of the trees (Fig. 4).

4 Discussion

The sapwood width measured with the staining method was about 28% ± 3% higher than that measured by ERT. This is even more than the difference between computer tomography and staining of 17% found by Rust (1999). Therefore it is likely that ERT-results display the physiological active sapwood, whose width is over-estimated by staining. But the sharp boundary between low and high electric resistivity is not just an effect of the higher water content in the sapwood. Other parameters related to heartwood formation like resin content (Tattar and Blanchard 1974) and pit closure (Du 1991) increase electric resistivity as well.

The strong differences in wood moisture content between sapwood and heartwood that can be found in pine and other conifers allow the accurate estimation of the different zones. However, most central European hardwoods do not have such strong contrasts between sapwood and heartwood, which might limit the possibilities of ERT.

The location of the pith of the trees corresponded closely to the spot of relatively low electric resistivity in the tomograms (Figs. 1 and 4), confirming results of Shigo and Shigo (1974), who found a good correlation between relative low electric resistivity and the pith of a stem.

Even the decentral pith in tree no. 6, which was placed on a steep hillside, was depicted in

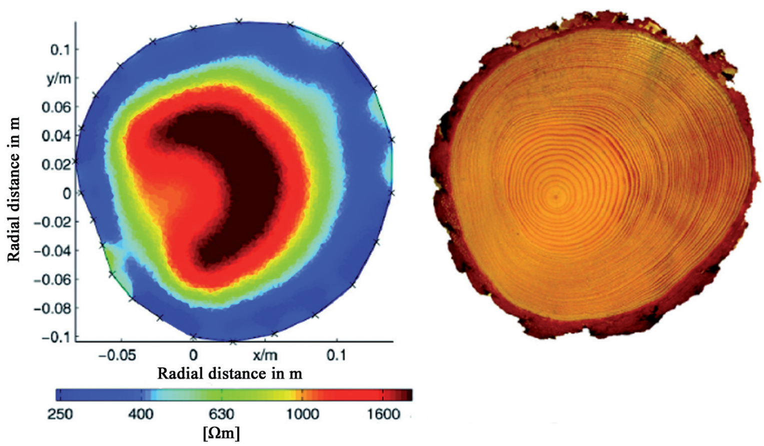

Fig. 4. Tomogram and stem cross section with decentral pith of *Pinus sylvestris* L.

the tomogram (Fig. 4) which indicates that ERT is able to show reaction wood.

The growth rings next to the pith are made of juvenile wood, whose anatomical and physical properties differ considerably from the properties of mature wood: specific gravity is lower, moisture content higher, fibres are shorter, cellulose content is considerably lower (Knigge and Schulz 1966), lignin content (Zobel and Sprague 1998) and earlywood percentage are higher than in the surrounding mature wood.

A variation of electrolyte concentration from the stem centre to the heartwood/sapwood border might also explain the relative low electric resistivities around the pith. Helmisaari and Siltala (1989) found increasing concentrations of Ca, Mg, Mn and Zn towards the pith of *Pinus sylvestris* L. while concentrations of K and P decreased. Bieker and Rust (2010) could show that increasing concentrations of K and Mg decrease electric resistivities in the heartwood of *Quercus robur* while wood moisture content remained constant.

Further investigations are needed to clarify the factors causing the relative low electric resistivities around the pith of *Pinus sylvestris* L. and other conifers. The variation of wood moisture content in stem cross-sections of different species and the influence of electrolytes that could be found for oak trees indicate that tomograms have to be interpreted carefully and species specific influences have to be considered.

Estimates of sapwood area, which are necessary for the up-scaling of sap flow measurements to higher levels, often are one of the main sources of errors (Hatton et al. 1995, Köstner et al. 1998, Bovard et al. 2005). With sufficient sampling, in our case eight linear measurements per tree, sapwood area can be accurately estimated using linear methods. That many measurements, however, render the tree useless for further sapflow and also many other measurements. Estimates of whole-tree transpiration based on fewer or just one linear measurement are prone to large errors (Fig. 3).

Although the strong correlation between wood moisture content and electric resistivity allows the exact localisation of sapwood, the extrapolation from single sapflow measurements to tree or stand level is not possible, because of the large radial and circumferential variability of sapflow, even within areas of similar wood moisture content (Cermak et al. 2004). But with non-destructive measurements of sapwood area, sapflow sensors can be placed in parts of the stem that are most suitable. Installing sensors partly in heartwood can be avoided and representative points of measurement can be selected.

Thus there are many applications for a fast and non-destructive method for the detection of sapwood area in experimental plant physiology, e.g.:

– Guide the positioning of sapflow sensors (Nadezhdina et al. 2002)
– Scaling of sapflow density or velocity to tree and stand level
– Calculation of specific hydraulic conductance (Rust 1999, Cruiziat et al. 2002)
– Monitoring of heartwood formation
– Monitoring of heartwood/sapwood relationships

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