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Comparison of tree stem diameter variations in beech (*Fagus sylvatica* L.) in Sorø Denmark and in Scots pine (*Pinus sylvestris* L.) in Hyytiälä, Finland

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Tree stem diameter variations were measured simultaneously in beech (*Fagus sylvatica* L.) in Sorø, Denmark and in Scots pine (*Pinus sylvestris* L.) in Hyytiälä, Finland. The variations were detected at two heights on the xylem and the whole stem on both trees. The evapo-transpiration of the forests was measured by eddy-covariance method. The pattern of evapo-transpiration was reflected on the diameter variations in both cases. However, the pattern was clearer in Scots pine than in beech. The amplitude of the variation in beech was 0.02 mm in the case of xylem and 0.03 mm in the case of whole stem measurements. In Scots pine the amplitude of xylem diameter variation was 0.05–0.09 mm depending on the measurement height on the xylem and 0.15 mm on the whole stem. The difference in the elasticity of the wood of the two species was reflected in the amplitudes of the variations. The environmental conditions during the measurement period and the measurement methods were similar at both sites, which made the simple comparison possible.

Introduction

Tree stem diameter changes diurnally due to changes in the water content of the stem (e.g. Kramer & Kozlowski 1979). The amplitude of the variations depends on the rate of transpiration and the elasticity of the shrinking and swelling material (Perämäki *et al*. 2001). In general xylem diameter changes follow the variations in transpiration more thoroughly than the whole stem diameter changes. However, there are only few studies where diameter variations have been measured on both xylem and the whole stem in the same tree. Hellkvist *et al*. (1980) and Sevanto *et al*. (2002) reported simultaneous measurements of diameter changes on xylem and the whole stem for Scots pine. Both found that the amplitude of xylem diameter variations was 0.01 mm of the order of magnitude and the amplitude of the variation of the whole stem was 2–3 times larger than that of the xylem variation.

Pine and beech trees differ from each other e.g. by their growth and reproduction mode and by the structure of sapwood and bark. Pine is an evergreen gymnosperm and the water transporting sapwood consists only of tracheids, whereas beech is a deciduous angiosperm with vessels distributed in a diffuse-porous manner. The wood material of beech is harder and denser than that of pine. Linking the diameter variations to sap flow and water tension requires knowledge about the elasticity of sapwood in radial direction. However, there are no measurements for the modulus of elasticity for living trees. The only values available are given for timber of different moisture contents. Sunley (1974) gives for green timber of beech and Scots pine 6.6–10 MPa and 4.8–8.3 GPa, respectively. Perämäki *et al*. (2001) estimated the elastic modulus of the sapwood of a living Scots pine tree to be 0.02–0.1 GPa. Based on that, the elasticity of the sapwood of a living beech tree would be of the order of magnitude 0.1 GPa. Although these values are not directly comparable they give an idea about the difference in the order of magnitude, which is remarkable. In that light we would expect the diameter variations of beech to be only a fraction of that of pine during the same transpiration rate.

Stem diameter variations have been studied formerly quite widely (e.g. Kozlowski and Winget 1964, Dobbs and Scott 1971, Klepper 1971, Zaerr 1971, Lassoie 1973, Hinckley and Bruckerhoff 1974, Wronski *et al*. 1985, Hellqvist *et al*. 1980, Milne *et al*. 1983, Wronski *et al*. 1985, Herzog *et al*. 1995, Offenthaler *et al*. 2001). However, most of the studies have been made on conifers and only one species at a time has been investigated. In this study we compare simultaneously measured xylem and whole stem diameter variations on a Scots pine and a beech tree, the aim being to characterize the similarities and differences and to explain the observations in the light of environmental conditions and wood structure.

Materials and methods

The measurements were carried out between 31 August and 12 September 2002 at Sorø measurement site in Denmark and at SMEAR II measurement station in Hyytiälä, Finland. At that time the active period of stem growth was over at both sites and the preparation for dormancy had not begun. During the measurement period the sun rose between 5:12 and 5:40 in Hyytiälä and between 5:18 and 5:39 in Sorø and set between 19:36 and 18:57 in Hyytiälä and between 19:08 and 18:39 in Sorø (http://aa.usno.navy.mil/data/docs/RS_OneYear.html). The time difference between Denmark and Finland is 1 hour.

Measurement sites

Hyytiälä

The SMEAR II measurement station is located in a 40-year-old natural managed Scots pine dominated stand in southern Finland (61°51´N, 24°17´E, 181 m above sea level). The stand is quite homogenous, about 200 m in all directions and about 1.2 km to the north from the station. The terrain is modestly undulate. The dominant stand contains only 1% of species other than Scots pine (e.g. *Betula pubescens* Ehrh., *Alnus incana* L. and *Populus tremula* L.). The height of the dominant trees is about 15 m and the diameter at breast height (1.3 m) is 14 cm. The tree density is about 2000 ha^{-1}, wood biomass 41 t ha^{-1} and the all-sided leaf area index (LAI) is 3.9 m^2 m^{-2} (Ilvesniemi and Liu 2001). The ground vegetation consists of *Calluna vulgaris* L., *Vaccinium vitis-idaea* L. and *Vaccinium myrtillus* L. The parent material of the soil is coarse, silty, glacial till and the soil is a haplic podzol. The annual mean temperature is 3 °C and precipitation 700 mm.

Sorø

The Danish Sorø station is located in an 80-year-old managed beech (*Fagus sylvatica* L.) forest at 55°29´13´´N, 11°38´45´´E. It is elevated 40 m above mean sea level on a flat terrain near Sorø on the island of Zealand. The average height of the beech trees is 25 m. Average tree diameter is 40 cm and the stand density is 430 stem ha^{-1}. The peak leaf area index of the canopy is about 4.75 m^2 m^{-2} at the end of June and the wood increment 11 m^3 ha^{-1} yr^{-1} (1994). There are scattered stands of conifers (mainly Norway spruce (*Picea abies* (L.) Karst.) as well as single trees of other conifers such as European larch (*Larix decidua* Mill.). In total conifers constitute 20% of the area. The soil is a mollisol with a 10–40 cm deep surface organic layer. The annual mean temperature is 8.1 °C and precipitation 510 mm.

Diameter variation measurements

Stem diameter variations were measured using a similar set up at both sites. The sensor system consisted of a framework mounted around the stem and the sensor (LVDT: AX/5.0/5; Solartron Inc., Bognor Regis, West Sussex, UK) was attached to the frame (*see* e.g. Sevanto *et al.* 2002). Two pairs of sensors were installed to each measurement tree: one pair at the base (in Sorø at 3.5–4.0 m and in Hyytiälä at 1.5–1.7 m) and the other higher up in the crown (in Sorø at 9.2–9.5 m and in Hyytiälä at 11.3–11.5 m). In each pair the distance between the sensors was 20–30 cm and the upper sensor measured stem diameter variations and the lower xylem diameter variations. For stem measurements the bark was smoothed and small aluminium plates were glued on opposite sides of the stem. The sensor tip rested on one plate and the frame on the other so that the distance measured was the diameter of the stem (*see* e.g. Sevanto *et al.* 2002). For xylem measurements in the beech tree small holes were made to the bark, phloem and cambium and the aluminium plates were attached directly to the xylem surface. In Scots pine small screws were screwed through the bark, phloem and cambium and the sensor tip and the frame were set to touch the screws. That procedure was used in Scots pine to reduce problems caused by resin leaking between the plate and surface of xylem. Sevanto *et al.* (2001), Perämäki *et al.* (2001) and Sevanto *et al.* (2002) used aluminium plates successfully on the xylem of Scots pine for a short measurement period and the results with the screws are similar. The possible embolization of tracheids near the screws seems not to affect the accuracy of the measurements.

The effect of the thermal expansion of the wood and the frame was taken into account using the procedure of Neher (1993), who reasoned that the thermal expansion of the frame and wood cancel each other, since the expansion coefficient of wood (35×10^{-6} m °C^{-1}) is three times larger than that of steel and the temperature variation in the wood is one third of that of the frame. However, there is uncertainty of the thermal expansion of, especially fresh wood. Irvine and Grace (1997) used a coefficient of -4×10^{-6} m °C^{-1} and Salmén (1990) gives -3×10^{-6} m °C^{-1}. We tried also the values of Irvine and Grace and Salmén, but with that procedure the diameter variation signal of beech was totally and that of Scots pine was almost overcome by temperature because of the small amplitude of diameter variation in autumn. The negative coefficients of Irvine and Grace and Samlén may be a result of measurements where the evaporation of water from the wood has not been taken into account. However, the value of Neher is of the order of magnitude given in tables to dry timber and may be an overestimate. The thermal expansion affects the amplitude of the variation, but since the changes in temperature in Sorø and Hyytiälä were similar, the values are comparable.

The measurement tree in Sorø was a 22-m-tall beech tree with a diameter of 27 cm at breast height. In Hyytiälä the height of the measurement tree (Scots pine) was 15 m and the diameter at breast height 15 cm. The measurement frequency was min^{-1} at both sites.

Micrometeorological measurements

Evapo-transpiration was measured at both sites using eddy-covariance method and same

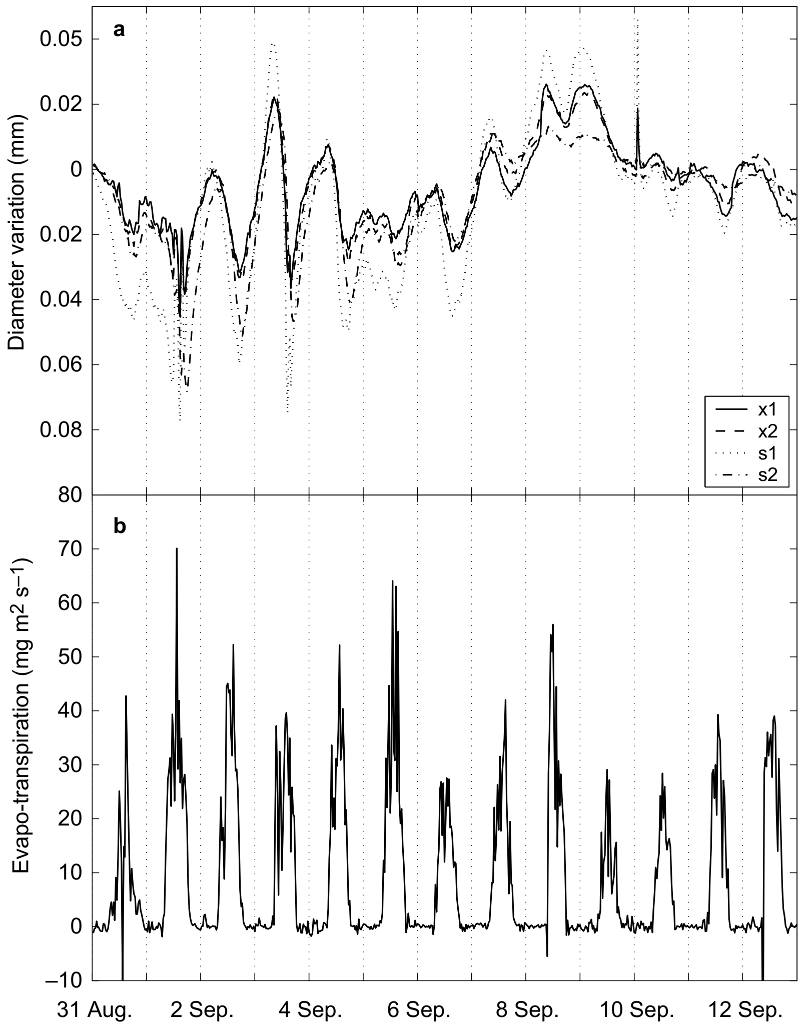

Fig. 1. Stem diameter variations of a beech tree (**a**) and the canopy evapo-transpiration (**b**) in Sorø. The diameter variations were measured on xylem (x1 and x2) and on the whole stem (s1 and s2). The measurement heights were 3.5–4.0 m (x1 and s1) and 9.2–9.5 m (x2 and s2). The diameter is set to zero at the beginning of the measurements. On the *x*-axis time is local solar time.

instruments. An ultrasonic anemometer (Solent 1012R2, Gill Instruments Ltd., Lymington, UK) measured the wind velocity above the canopy with sampling frequency of 20 Hz. A sample of air was taken at the site of the anemometer with the same frequency and analysed using a closed-path infrared gas analyser (LI-COR 6262, Licor Inc., Linclon, NE, USA) for e.g. water vapour concentration. The vapour flux was calculated from the covariance of the instantaneous fluctuations of vertical wind speed and the concentration as 0.5 h averages (*see* e.g. Rannik 1998).

The air temperature was measured in Hyytiälä at 8.4 m and in Sorø at 10 m height with pt-100 type resistance thermometers. The relative humidity was detected by a chilled dew point mirror sensor (M4 Dew point monitor, General Eastern, Woburn, Massachusetts, USA) at the height of 23 m in Hyytiälä and a humidity sensor (HMP 45A, Vaisala, Helsinki, Finland) at the top of the canopy (25 m) in Sorø.

Precipitation was detected by a rain gauge (AGR-100, Environmental Measurements Ltd., Sunderland U.K.) in Hyytiälä and a rain gauge (Semi-Pro, Pronamic, Silkeborg, Denmark) at 25 m in Sorø. The photosynthetic photon flux (PPF) above the canopy (15 m in Hyytiälä and 25 m in Sorø) was measured with quantum sensors (LI-190SA, Li-Cor Inc., Lincoln, Nebraska, USA). For a more detailed description of the instrumentation *see* Vesala *et al.* (1998) for Hyytiälä and *see* Pilegaard *et al.* (2003) in this issue for Sorø.

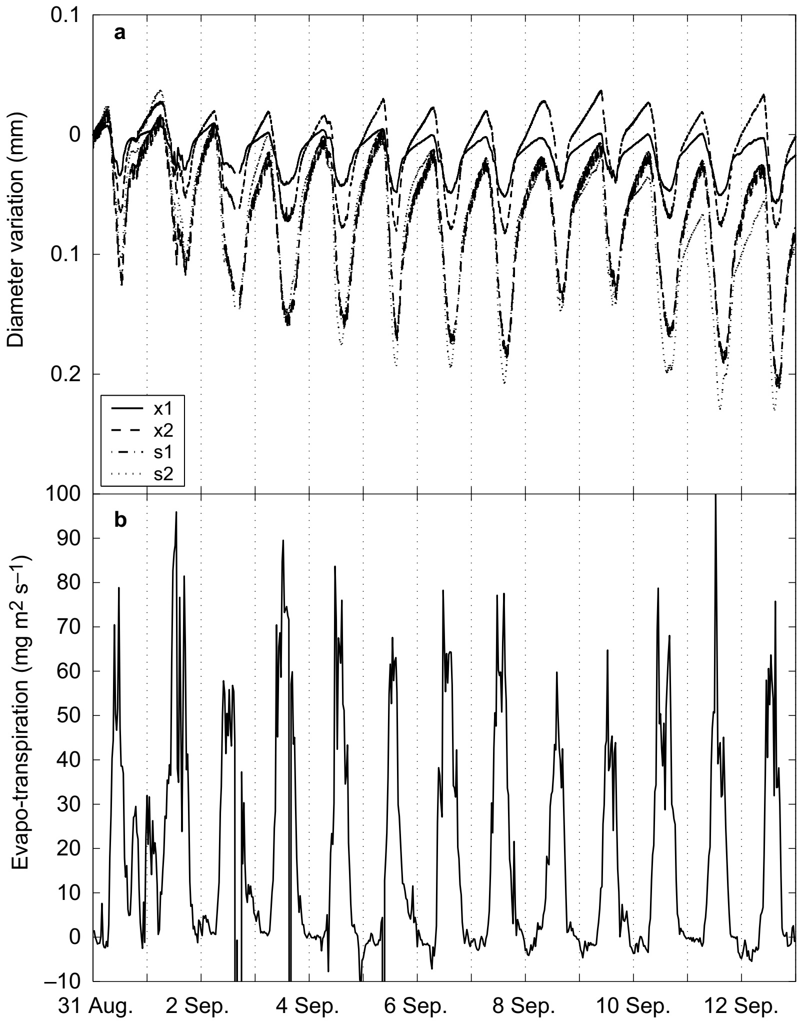

Fig. 2. Stem diameter variations of a Scots pine tree (**a**) and the canopy evapo-transpiration (**b**) in Hyytiälä. The diameter variations were measured on xylem (x1 and x2) and on the whole stem (s1 and s2) at the heights of 1.5–1.7 m (x1 and s1) and 11.3–11.5 m (x2 and s2). The contribution of understorey vegetation to the evapo-transpiration is subtracted from the values according to Sevanto *et al*. (2001). The diameter was set to zero at the beginning of the measurements. On the *x*-axis time is local solar time.

Results

The diameter variations had a diurnal pattern and followed evapo-transpiration in both places (Figs. 1 and 2). The shrinkage started in the morning just after sunrise and the swelling began in the afternoon. The shrinkage in Sorø was slower than in Hyytiälä and the diameter was at its smallest about two hours later than the daily maximum of evapo-transpiration, while in Hyytiälä the minimum in diameter and the maximum in evapo-transpiration occurred simultaneously. At both places the evapo-transpiration started at the same time (local time at both sites) because of the sunrise. The pattern of diameter changes in Sorø was not as clear as that in Hyytiälä. This might be due to some problems with the measurement system, especially around 9 September, but since there are no former data for diameter variations in beech we do not know if this is really a characteristic of the variation of that species. The amplitude of the variation in beech was about 0.02 mm for the xylem and about 0.03 mm for the whole stem. In Scots pine there was a difference in the amplitudes of xylem variation according to height. At 1.5 m the amplitude was 0.05 mm on average and at 11 m 0.09 mm. However, the amplitude of the variation of the whole stem was 0.15 mm at both heights.

The variation in the size of the elastic material was calculated by normalizing the diameter variations by the equivalent diameter of

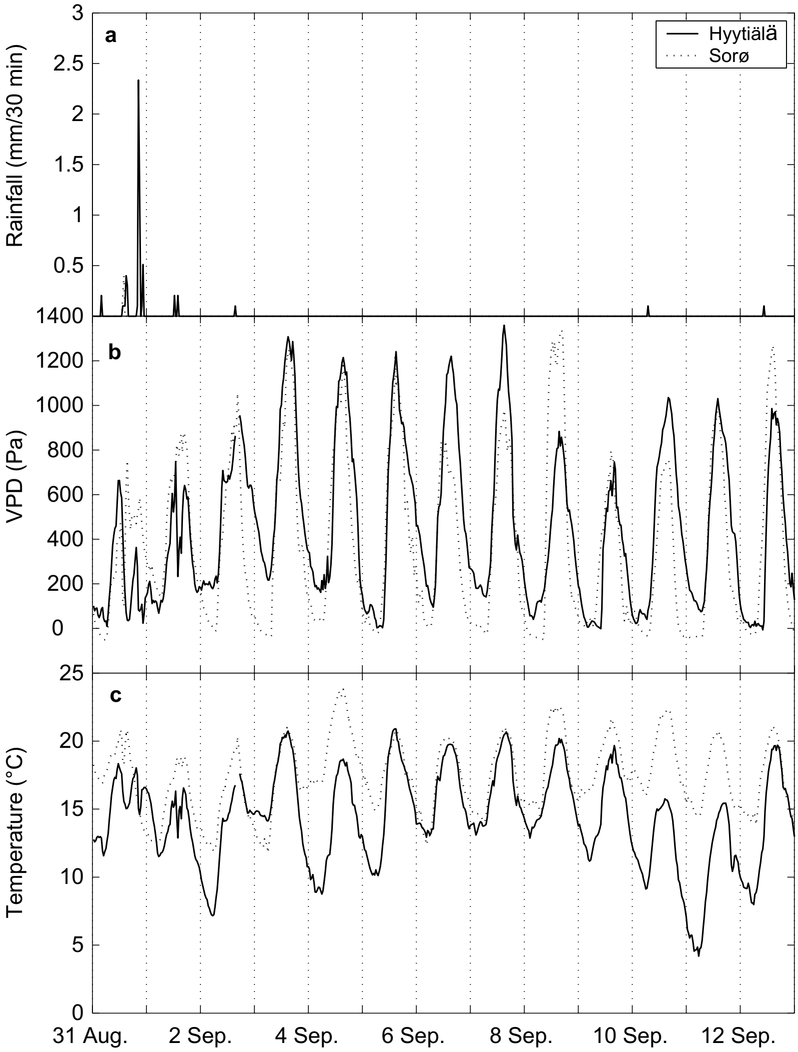

Fig. 3. Rain fall (**a**), water vapour deficit (VPD) (**b**) and air temperature (**c**) during the measurement period in Sorø and Hyytiälä. VPD is calculated from the measurements of relative humidity. In both sites time in local solar time.

the shrinking material. In the case of xylem measurements the values were divided by the equivalent diameter of sapwood and in the case of the whole stem measurements by that of sapwood and bark. In beech, the diurnal variation in diameter was 0.03% for both xylem and whole stem measurements at all heights. In Scots pine the variation was slightly weaker at 1.5 m than at 11 m. The percentages for xylem and whole stem variations were 0.06% and 0.2% for the xylem and 0.2% and 0.3% for the whole stem.

The evapo-transpiration was slightly higher in Hyytiälä than in Sorø during the measurement period (Figs. 1b and 2b). This might be due to that there is no understorey vegetation in Sorø while that is quite dense in Hyytiälä. However, the contribution of the ground vegetation to evapo-transpiration was estimated using a linear regression with PPFD (*see* Sevanto *et al.* 2001) and subtracted from the data.

The measurement period was fairly dry at both sites. The total rainfall was 12 mm in Hyytiälä and the heaviest rains occurred on 31 August and 1 September. In Sorø it rained only on 31 August and the total rainfall was 0.6 mm (Fig. 3a). The water vapour deficit (VPD) had a similar diurnal cycle at both sites being highest in the middle of the day (Fig. 3b). That also reflects the relatively dry non-rainy conditions. The air temperature was slightly higher in Sorø than in Hyytiälä (Fig. 3c). In Sorø it varied between 12 and 24 °C (average 17.4 °C) whereas in Hyytiälä the lowest temperature was 4.2 °C and the highest 20.9 °C (average 14.2 °C).

Discussion

The diameter variations followed the pattern of transpiration in both beech and Scots pine. However, the amplitude of the changes was smaller in beech than in pine and there was also a remarkable difference in the amount of the shrinkage relative to the amount of sapwood as expected because of the difference in the elasticity. The results are similar to those reported earlier for different species (*see* e.g. Hellqvist *et al.* 1980, Milne *et al.* 1983, Hinckley and Bruckerhoff 1974). Also, Sevanto *et al.* (2001) measured diameter variations on several Scots pine trees in the same stand and linked the variations with changes in evapo-transpiration. The variations were similar in all trees. This and the measurements on the beech tree suggest that a similar link can be found also in beech. According to Irvine and Grace (1997) and Perämäki *et al.* (2001) water tension inside the stem can be calculated from xylem diameter variations using Hooke's law. Applying this to the average xylem diameter variations in the crown gives an average tension of 0.1 MPa for both trees (modulus of elasticity for beech 0.1 GPa and for Scots pine 0.06 GPa (Sunley 1974)). The value is quite low as compared with measured daytime leaf water potentials (*see* e.g. Whitehead and Jarvis 1981 and Hinckley *et al.* 1981), but taking the uncertainty of the elasticity, the season and the measurement heights into account makes it reasonable.

The evapo-transpiration was slightly higher in Hyytiälä than in Sorø. The leaf area indexes of the forests and the weather conditions were almost the same, which suggests that the evapo-transpiration should be of the same order of magnitude, since according to Kramer and Kozlowski (1979) the species composition of the forest has only a modest effect on the water loss summer time. The major difference between the stands (despite different tree species) was the amount of understorey vegetation and the slight difference in the evapo-transpiration may be due to an under-estimation of the contribution of that in Hyytiälä. However, the rainfall was also larger in Hyytiälä, which increases the amount of evaporation. In the light of tree stem diameter variations, this means that during the measurement period the conditions were well comparable and the results reflect differences in the behaviour of different species more than differences in the environmental conditions. However, the Scots pine tree was of the average size of the trees in the Hyytiälä stand while the beech tree in Sorø was a suppressed one and their contribution to the transpiration of the forest is different. If we measured diameter variations on an average beech tree, we would probably find the diameter variation larger and hence the water tension higher as well. Also the delay in the shrinkage in diameter in Sorø may be due to the shading.

The structure of the sapwood of Scots pine is more homogenous than that of beech. This makes the point-like measurements of diameter variations more suitable for the evaluation of transpiration and water tension of the whole trunk in Scots pine than in beech. The possible existence of compression or tension wood and the position of branches are more critical to the diameter variations in beech than in Scots pine. Furthermore, the regular growth of pine trees makes the installation of the sensors to comparable sites on the trunk easier in Scots pine than in beech. The reason for the uneven pattern of the diameter variations in beech may also be one of these. However, this method could probably be used as a non-destructive tool for detecting the active xylem area in beech, which is needed in some types of sap flow measurements e.g. the Granier-method (Granier 1987).

Conclusions

Diurnal variation of stem diameter of beech and Scots pine has a similar pattern that follows transpiration. The major differences between the species are in the amplitude of the variation and the contribution of the xylem and whole stem to the changes. However, the measurement period was quite short and the measurements were made on only one tree of each species and on one angular direction at each height. For beech, especially, measurements to different directions of the stem at the same height are needed in order to determine the true nature of the variations unquestionably. Although the data is limited, some generalizations can be made since the measurement system has proved its potential in former studies.

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