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Long-term measurements of stand water uptake in Swedish boreal forest

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Abstract

Long-term measurements of sap flow were performed to estimate actual transpiration of a mixed pine/spruce sub-boreal stand. There was a variation in water use for the growth periods of 1994–1996 that reflected the hydro-climatic conditions in these years. The variability of water fluxes at tree level was generally high. This forced an application of a ratio 'stand to sample trees' instead of a scaling curve when extrapolating fluxes to a stand level. For about 60-year-old-stand with the leaf area index (LAI) of 4–6 and the basal area of 29 m^2, transpiration reached the maximum of 3.6 mm and the mean of 1 mm day^{-1} for about 180-day long growth period. There were differences in water use for pine and spruce. Quantitatively most important was the difference in spring periods when transpiration of pines only gradually increased to reach proportions correlated tightly with evaporative demand. On the contrary, spruce transpired in accord with the evaporative conditions already at the beginning of the growth period, provided soil moisture was not limiting the uptake. Pine seemed to be more drought-tolerant compared to spruce. Though there were some obvious differences in water use between the two species, the quantitative differences were small with respect to the seasonal water budget The experience with the long-term application of the tissue heat balance (THB) method is discussed. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Sap flow; Transpiration; Pine; Spruce; Drought; Water budget; NOPEX

1. Introduction

During the rotation period of a sub-boreal forest stand, transpiration represents the largest component of a stand water budget The importance of transpiration and herewith the motivation for incorporating transpiration measurements in the large experiments on regional water, carbon and energy exchange as The Northern Hemisphere Climate-Processes Land-Surface Experiment (NOPEX; Halldin et al., 1999) is many-sided. It permits the separation of evaporative components from evapotranspiration measured by the eddy-correlation technique (Grelle et al., 1997). Also, transpiration is directly related to photosynthesis via stomatal/canopy conductance and it can, therefore, limit tree growth. Diurnal courses of tree water uptake reveal the key information on water status of a tree and soil moisture conditions, and they also show the progression and degree of water deficit.

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Transpiration of a stand canopy is estimated on the basis of tree sap flow measurements. There are several techniques used for estimating sap flow (Swanson, 1994). To obtain volumetric quantity, some systems require calibrations as, e.g., the heat pulse (Marshall, 1958; Swanson, 1983) and the heated-probe (Granier, 1987) techniques. On the other hand, their installation is mostly easy and fast. Other techniques based on solving the heat-balance of tissue (THB techniques) in a stem or its segment (Čermák et al., 1973; Kučera et al., 1977; Sakuratani, 1981) do not use any calibration. On the other hand, the installation procedure for THB techniques is usually more time consuming and requires a more devoted handling. The selection of a suitable measuring system may also be determined by tree dimensions, intensity of tree growth, requirements for the length of the measurement period or by working climatic conditions. Similarly, a suitable approach for scaling tree sap flow into the stand transpiration may vary according to plant and stand properties, variability of sap-flow at tree level and the amount of the measured tree samples.

The aim of this paper is to provide a concise summary of sap flow measurements using a THB technique in pine and spruce trees in one stand at the NOPEX central site. We give an overall information of the results from the 3 to 5-year long measurements. We previously analyzed responses to drought on both daily and diurnal resolution and described differences between tree species and age (Cienciala et al., 1997, 1998). Here we focus mainly on transpiration at a stand level, its variability between years and between species. We also discuss the application experience of THB technique including the continuous measurements over a winter period and the items related to sampling strategy in the challenging heterogeneous conditions of a typical grown sub-boreal mixed forest.

2. Material and methods

The detailed description of the NOPEX region can be found in Halldin et al., 1999. The central Tower Site (60°5′N, 17°29′E, alt. 45 m) described by Lundin et al. (1999a), is located in the Norunda Common about 30 km north of Uppsala. Forests in the area are mixtures of Norway spruce and Scots pine with occasional occurrence of birch. They have been managed by forestry practices for over 200 years. Today, the forest is a rich mosaic of stands, which are distinguished by different spruce-pine quotients and age classes. The rotation period for stands in the area is typically 100 years. The soil is deep boulder-rich sandy till of glacial origin. At the site, the soil was podzolized and classified as Dystric Regosols (Stähli et al., 1995).

2.1. Meteorological variables

A continuous climatic data set for the period of May 1994 to May 1997 at the NOPEX central site, where the sap-flow measurements were made, was not available. The data from the central NOPEX site available for this study (SINOP database; Lundin et al., 1999b) included solar radiation and air temperature for a part of the period evaluated here. We, therefore, used air temperature and relative humidity data from a climatic station in Siggefora, about 15 km distant. That station was located above a forest of similar age and structure and the discrepancies of daily average values of temperature and short-wave radiation were mostly below 3% and, therefore, neglected. Daily precipitation data were collected at the site for most of the season; the missing periods were filled with an average of the gauge measurements from three neighboring sites in the region.

To compare evaporative conditions for the measurement periods and years, we used Turc (1961) evaporation (E_{T}; mm day^{-1}), defined for conditions with daily mean air humidity within 50–100% as

$$E_{\mathrm{T}} = \left(\frac{R_{\mathrm{s}}}{41.868 + 50}\right)\left(\frac{0.013T_{\mathrm{a}}}{T_a + 15}\right) \qquad (1)$$

where R_{s} is incoming daily short-wave radiation (kJ day^{-1}) and T_{a} is daily mean air temperature (°C). This formula does not use air humidity, which strongly interacts with transpiration. Hence the estimate is not directly dependent on actual transpiration and can be used as a practical climatic measure of evaporative conditions at the site. See Federer et al. (1996) for a comparison to other estimates.

2.2. Stand description, sap flow and transpiration

The studied stand was 60 years old, with the basal area of 29.3 m^2 ha^{-1} and a maximum stand height of about 23 m. The canopy was closed with occasional openings. The projected leaf-area index (LAI) was about 4–6. The stand was composed of Norway spruce (*Picea abies* (L.); 66% of the stand basal area) and Scots pine (*Pinus sylvestris* (L.); 33%) with a few specimens of birch (*Betula alba* (L.)).

Sap flow rate was measured on 6–12 trees with two measuring points on each. We used the standard equipment from Environmental Measuring Systems (P690.2) which is based on the THB method described by Čermák et al. (1973) and Kučera et al. (1977). Two instruments provided 24 measuring channels distributed between pine and spruce trees. The installation procedure of a 24-channel system usually required 3 working days for a two-man team. This includes tree selection, preparation of stems, installation and insulation of measuring points. Disassembling of the measurement set at the end of a growth season usually required one working day.

Sap-flow measurements spanned into four growth seasons (May 1994–June 1997). We selected a new sample set of trees for each of the seasons 1994–1996 (Cienciala et al., 1999). One set of trees was also measured continuously during a long-term over-winter application from April 1996 to June 1997. The breast height diameter over bark of the measured trees ranged from 16 to 37 cm (Fig. 1).

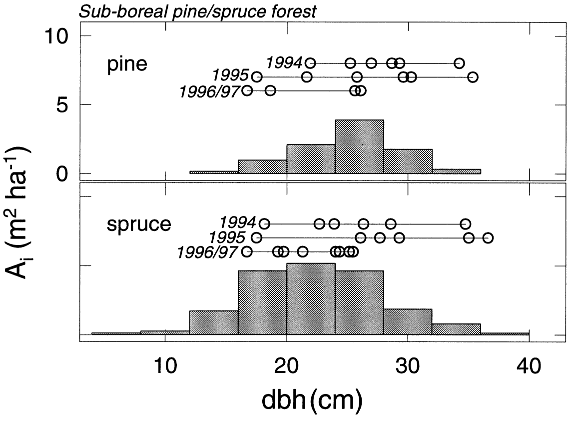

Fig. 1. Frequency distribution of the basal area (A_i) of pine and spruce trees in the studied stand for the range of tree diameters at the breast height (dbh). A_i is used to express the actual share of tree species in the stand. The sample trees (circles) used for sap flow measurements in the individual years.

We tested several approaches for the selection of sample trees. In 1994, the selected trees represented closely the actual distribution of diameters for species. In 1995, tree samples were mostly concentrated among larger trees, which contribute decisively to stand fluxes (e.g. Čermák and Kučera, 1987). In 1996, we avoided any subjective selection and trees were sampled along 1 m wide transect at a random direction.

Due to the high variability of fluxes at the tree level (Čermák et al., 1995), we could not apply a scaling curve for extrapolation the fluxes from tree to stand level. Instead, stand transpiration was estimated from the measured tree sap flow using the ratio of the foliage biomass supported by the set of the measured trees and that of the stand. Foliage mass was calculated using the Swedish biomass functions of Marklund (1988). Marklund's functions were estimated from destructive measurements of tree biomass components using about 500 tree samples for each tree species. The scaling as above weights the differences in mean sample tree diameters when selecting trees in different measurement years. It also accounts for the non-linearity of the relationship between stem diameter and supporting foliage mass, which becomes important when the mean stem diameter of the sample tree set differs from the corresponding mean of all trees in a stand. These calculations were performed individually for pine and spruce according to their respective representation and summed to the actual mixed-stand values. To compare species, transpiration of pine and spruce shares was also scaled so as to represent monospecific stands of either species. This was done by weighting the actual species' basal area representation by the total basal area of the actual stand (29.3 m^2 ha^{-1}).

3. Results and discussion

3.1. Weather conditions

There were some distinct differences in weather conditions in the particular years of the experiment. This was obvious especially for the annual precipitation and its distribution during the growth period (Fig. 2). The growth period was driest in 1994, especially in comparison with the year 1995. The length of the

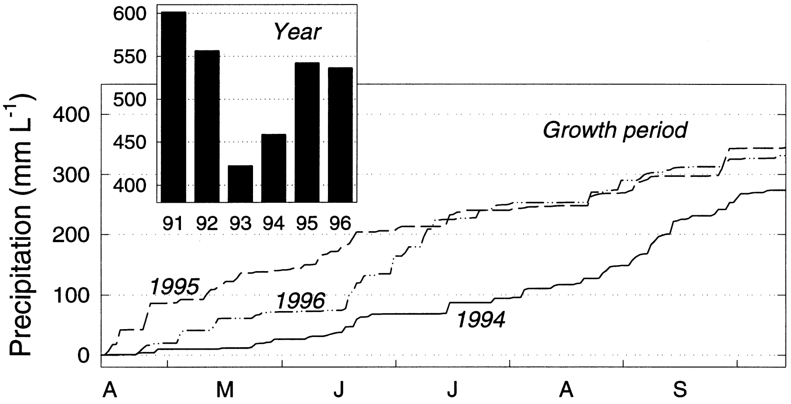

Fig. 2. Annual precipitation during the period 1991–1996 (bars) and cumulative precipitation for the growth periods of the measurement years 1994–1996.

growth season estimated by the threshold daily mean air temperature of 5°C was 178 (year 1994), 190 (1995) and 188 (1996) days. The evaporative conditions also differed between years. Turc equation (E_T; Eq. (1)) was calculated for the shared period of the three growth seasons 1994–1996 ($n = 177$ days; 22 April-15 October). The growth period of 1994 was warmest and the daily mean E_T was 7.3% larger relative to the average daily mean (2.37 mm) for the three growth periods 1994–1996. Similarly, the growth period of 1996 was coldest and the mean daily E_T was smaller by 6.6% relative to the mean of 1994–1996.

3.2. Stand transpiration

The daily stand transpiration (E_Q) typically reached values of 2 mm in spring (Fig. 3). It usually culminated in July reaching about 3 mm day^{-1}, and fell during August and September to about 0.5–1 mm day^{-1}. The maximum value of E_Q was 3.6 mm day^{-1} measured in July. There were several fundamental differences in transpiration between species. (A) Transpiration of spruce started in winter/spring always earlier compared to pine and with full intensity, well correlated to evaporative conditions (Fig. 4 and Cienciala et al., 1998). Pine started to transpire later than spruce and the flux rose gradually across several months. (B) Spruce transpiration was larger than that of pine for most of the season. However, during warm and dry periods, pine transpired more than spruce, indicating a better adaptation to drought. (C) Spruce responded more dynamically to precipitation events as compared to pine (Cienciala et al., 1998).

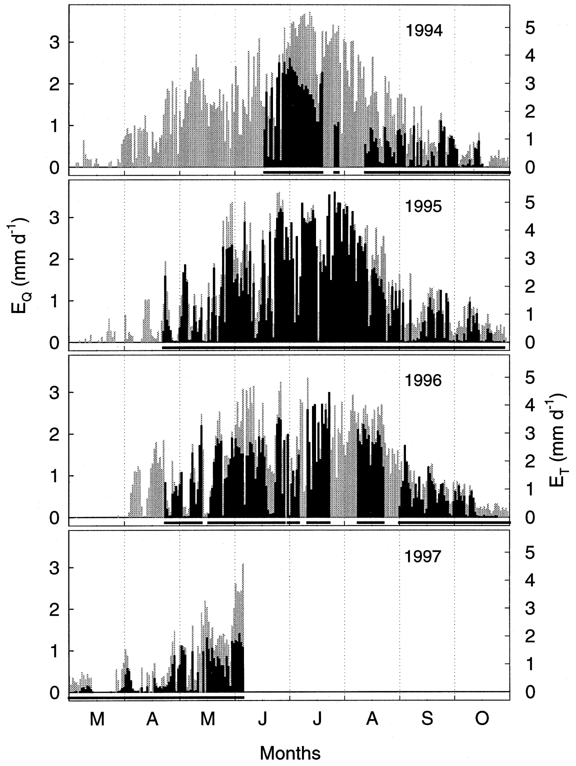

Fig. 3. Actual daily transpiration (E_Q, black bars, left axis) and potential evaporation by Turc (E_T, grey bars, right axis) during the period 1994–1997. A solid line at the bottom of each figure indicates the length of the successfully recorded data for both species.

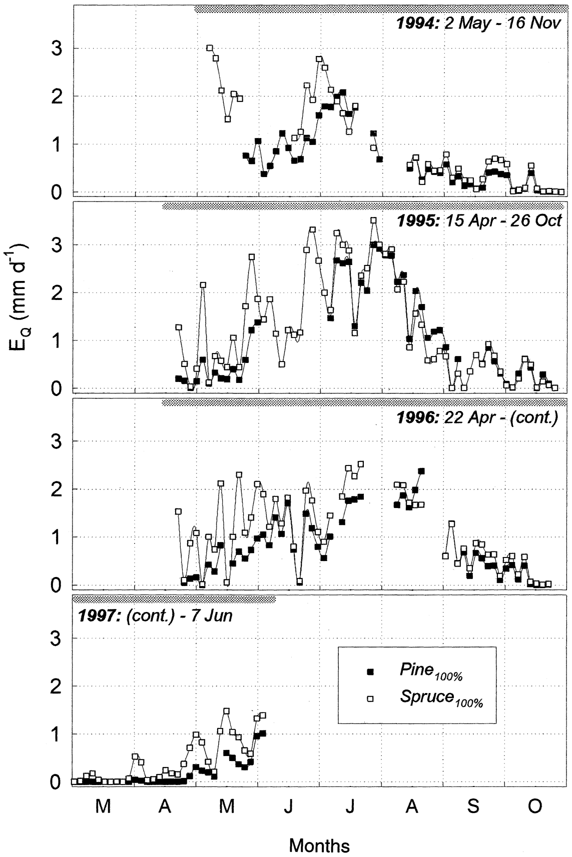

Fig. 4. Transpiration of pine and spruce trees expressed as fluxes corresponding to mono-specific stands with the basal area of the actual mixed stand (29.3 m^2) the data are means of 3 consecutive days.

The flux onset in spring represented quantitatively the most significant difference observed between the species during the experiment. The measurements of soil temperature profile revealed no good support for the hypothesis of soil temperature being responsible for these observations. During the spring time, the temperature gradient is negligible as temperature in different layers reverses. However, a pronounced difference between air and soil temperatures can be critical for both the species. Such situation occurred in 1996, after a particularly cold winter period. The soil at the site was frozen when a large warm front arrived (Fig. 5). Sap flow data indicated a reduction in transpiration for the year 1996 as compared to the previous year: the slope of the regression between transpiration and Turc evaporation (Eq. (1)) decreased (Fig. 6). Also the measurements of CO_2 fluxes and evapotranspiration by an eddy-correlation system in the area showed a similar decrease (Grelle, 1997). The situations with a high evaporative demand when soils are still frozen or have a very low temperature may damage tree foliage. This could jeopardize stability of forest stands on large scales for the areal extend of such events.

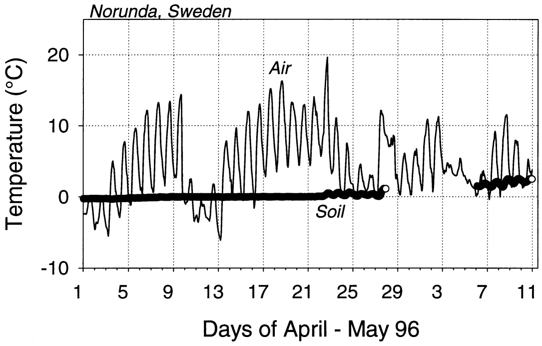

Fig. 5. Actual values of air and soil (15 cm depth) temperature during spring 1996: air temperature reached over 10° during the day while soil was still mostly frozen.

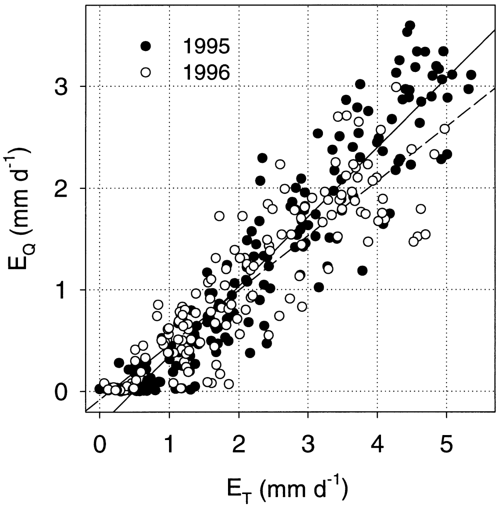

Fig. 6. Scatter diagram of daily stand transpiration and evaporation of Turc and the regression lines for 1995 (filled symbols, solid line) and 1996 (open symbols, dashed line). The regression slope decreased for 1996 (see text).

The measured fluxes were used to for the estimation and functional parameterization of canopy conductance from the Penman–Monteith equation. This was required to analyze and quantify transpiration deficit, i.e., water quantity that is demanded but not available for a given tree/stand canopy. This procedure was performed first with a daily time step (Cienciala et al., 1997) and later with an hourly resolution and separately for pine and spruce (Cienciala et al., 1998). Provided the parameterization period is not limited by soil drought, the fitted conductance functions can be applied in the Penman–Monteith formula to calculate potential transpiration (water use) for drier periods. Comparing the actual water use and the potential transpiration enables quantification of 'transpiration deficit' for these cycles. Unfortunately, this approach does not reveal the actual mechanisms controlling tree fluxes under drought or under high evaporative conditions. In the stomatal/canopy conductance (g_c) models (e.g. Lohammar et al., 1980), vapor pressure deficit dependence has the form of an exponential decay. This function mimics the transport limitations to g_c, which arise either due to the actual lack of water in the soil or due to the resistance to flow along the pathway. These factors do not accommodate water transport in the required rate and this makes the uptake/transpiration flux to depart from the rates that would correspond to the actual evaporative conditions. The mechanisms of these limitations are related to water potential in trees and indirectly to water potential in soil. These tensions are the actual limiting factors that shape the diurnal water uptake curve that we measure as sap flow rate. A correct treatment of tree water uptake in the models with a detail temporal resolution, therefore, requires an application of non-steady state models that include capacitance term(s).

The analyses of transpiration deficit revealed large differences in transpiration for individual years. In 1994, seasonal transpiration deficit was at least 20% (Cienciala et al., 1997). In the following year, however, fluxes were higher and better correlated to evaporative conditions. For example, the Turc potential evaporation (Eq. (1)) explained 79% versus 90% of the variation in daily water use in 1994 and 1995, respectively. The analyses performed with hourly resolution showed that the limitations to sap flow were also frequently pronounced in 1995, but the magnitude of transpiration deficit was mostly negligible for seasonal water budget. The responses to drought were species-specific with pines being generally less sensitive to water deficit. However, the quantitative differences in transpiration deficit for pine and spruce were not large for the studied period (Cienciala et al., 1998).

Considering the quantities of the measured transpiration as a component of a stand water budget suggests several important observations. During the growth periods of 1994–1996 there were about 72 ($\pm$1.5 SE) days with precipitation event. Already for a very modest interception capacity of 1.0 mm, only 200 (year 1994) to 270 mm (year 1995) of precipitation remained available for the total plant water uptake. But interception capacity is likely higher and a considerable amount of water is also evaporated from a soil surface and ground floor (see Grelle et al., 1997). Therefore, the amount of available water during a growth season either does not meet the demand of trees or this demand is very tightly balanced. This also suggests that the importance of soil water capacity in these ecosystems is critical. Large quantities-about 40% of precipitation occur outside the period of growth season and soil compartment, therefore, acts as an important buffer and a reserve for tree transpiration during a growth period. The tight demand/supply water balance with trees transpiring practically all available water thus strongly indicates that water is one of the critical constrains to tree growth in the region. The long-term field irrigation experiment in southern Sweden supports this conclusion: a monospecific stand of Norway spruce always grew significantly more relative to non-irrigated one and this was true also during relatively humid years (Nilsson and Wiklund, 1992). Moreover, that experimental area was located in a considerably more humid region compared to the NOPEX area.

3.3. Methodological notes

The strategy for the selection of tree samples was changed during the experiment, as more information became gradually available. In 1994, we aimed at covering the frequency distribution of tree diameters in order to construct a scaling curve applicable for extrapolating fluxes from a tree- to a stand level. The results from 1994 showed that the variation of fluxes at tree level was too large for a reliable fit of the scaling curve. Therefore, in 1995 we selected more trees in the upper diameter classes. This was to accommodate a more accurate fit for the scaling curve in that diameter range, which contributes decisively to stand fluxes. However, the heterogeneity of tree level fluxes remained high and forced the application of a sample trees-to-stand ratio when calculating stand-level fluxes. For this, we applied circumference and the supported needle biomass for individual species as an integrated biometrical parameter for scaling. Also, we abandoned any subjective tree sampling and in 1996/1997 applied the selection of trees for sap flow measurements along a randomly chosen 1 m wide transect. With a given sample size (12 trees), the measured set reassembled the actual ratio of species in the stand.

Our experience strongly supports the use of two measuring points on the opposite sides of a tree trunk. For moist conditions, a difference between the fluxes measured at two points on the same trunk was typically about 30% for pine and spruce trees, but it occasionally reached above 50%. For drought conditions, the variability along the stem circumference may still increase (e.g. Čermák et al., 1995). Since the soil at the site is extremely heterogeneous with many large stones, the root distribution becomes uneven. This also contributes to the large variability of sap flow rates along the stem circumference.

The most frequent cause for a failure of the equipment at the site was lightning. This was the almost solely responsible factor for the data loss in summer periods of 1994–1996 (Fig. 3).

There was no significant change of the correlation between measuring points in the measured trees for the years 1996 and 1997. We observed a slightly increased growth of the tissues next to the electrodes, approximately 2 mm after the annual cycle. This effect was not dependent on heat application: the testing set of electrodes that were not used for measurements affected tissues similarly. Hence, the measurement over the winter period did not confirm concerns associated with a continuous 12-month use of a measuring point in one tree. Thus a good strategy for long-term sap flow measurements may be setting-up the measurements at the end of a growth period. The measuring points can be in operation for one year, covering one winter and the following growth period. This ensures that the physiologically interesting occasional warm spells in the winter period and early onsets of the growth season will be monitored.

4. Conclusions and recommendations

1. Maximum daily transpiration rates are in the order of 3.5 mm in June/July, while more typical rates are in the range 1–2 mm during the growth season.
2. The winter measurements showed that transpiration could commence early in spring when the root zone may still be mostly frozen after a cold winter.
3. Stand transpiration exhibits relatively large inter-annual variability both relative to atmospheric forcing and in absolute numbers. The reason for this is that the transpiration is closely balanced by the water input to the soil during the growth season.
4. The two species, pine and spruce, respectively, exhibit distinctly different seasonal patterns; pine respond more slowly to the atmospheric forcing in spring while spruce is much more responsive. After mid-summer, the two species generally show a similar response although during drought, spruce is more sensitive to soil water deficits.
5. Different methodological approaches have been tested and scaling to stand level using tree foliage mass relative to stand foliage is recommended in this type of mixed stands. With respect to the heterogeneous conditions at the site, the set of 12 trees appeared to be the minimum reasonable sample size to extrapolate tree fluxes into stand transpiration and monitor simultaneously two tree species. It is also recommended that the sensors in the THB method should be installed in the trunks in late autumn and then be measured during a complete annual cycle.

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