ELSEVIER

Journal of Hydrology 168 (1995) 17–27

Journal of Hydrology

[3]

Individual variation of sap-flow rate in large pine and spruce trees and stand transpiration: a pilot study at the central NOPEX site

J. Čermák[a,*], E. Cienciala[b], J. Kučera[c], A. Lindroth[b], E. Bednářová[a]

[a]*Institute of Forest Ecology, Mendel's Agricultural and Forest University, Zemedelska 3, CS-61300 Brno, Czech Republic*

[b]*Department of Environmental Ecology, Swedish Agricultural University, Box 7072, Sodra Ultuna 11, S-75007 Uppsala, Sweden*

[c]*Laboratory of Ecological Measuring Systems, Turisticka 5, 62100 Brno, Czech Republic*

Received 25 May 1994; revision accepted 21 October 1994

Abstract

Transpiration in a mixed old stand of sub-boreal forest in the Norunda region (central Sweden) was estimated on the basis of direct measurement of sap flow rate in 24 large Scots pine and Norway spruce trees in July and August 1993. Sap flow rate was measured using the trunk tissue heat balance method based on internal (electric) heating and sensing of temperature. Transpiration was only 0.7 mm day^{-1} in a relatively dry period in July (i.e. about 20% of potential evaporation) and substantially higher after a rainy period in August. The error of the estimates of transpiration was higher during a dry period (about 13% and 22% in pine and spruce, respectively) and significantly lower (about 9% in both species) during a period of sufficient water supply. Shallow-rooted spruce trees responded much faster to precipitation than deeply rooted pines.

1. Introduction

A new study, NOPEX (NOrthern hemisphere climate Processes land-surface EXperiment), focusing on the interaction between the land surface and the atmosphere and its role in global change is scheduled from 1994 (BAHC Core Project Office, 1993). The experimental area, about 50×100 km^2, is located in central Sweden and is characterized by a patchy landscape, dominated by boreal forests. The central site, where many of the measurements will be made from a 100 m

* Corresponding author.

SSDI 0022-1694(94)02657-2

tower and surroundings, consists of mixed pine and spruce stands. One of the key processes to be studied is the forest evaporation and its control by climatic and physiological factors. Because the processes differ depending on whether the forest is dry or wet it is essential from a modelling point of view to be able to discern the trees from the forest, or vice versa (e.g. Baldocchi et al., 1991). One way of achieving this is to measure the transpiration from the large trees separately by, e.g. the heat pulse method (Swanson, 1970) or by the trunk heat balance method (e.g. Čermák et al., 1982; Schulze et al., 1985; Čermák and Kučera, 1987; Cienciala et al., 1992; Kelliher et al., 1992), while the total evaporation from the forest can be measured by micrometeorological methods.

The aim of the present study is to specify the individual variability of sap flow and probable scaling errors. This is especially important in mixed stands where the different species might change their relative hydrological positions depending on soil water and weather conditions. This also serves to estimate the minimum number of sample trees for measurement of the sap flow necessary to estimate transpiration of the experimental stands with the error acceptable for future NOPEX studies. The study was performed during periods of contrasting water supply and therefore allowed estimates of the impact of drought stress on both transpiration and the error.

2. Material and methods

2.1. The experimental site and environmental conditions

The central NOPEX site (60°5′N, 17°29′E, alt. 45 m) is located at Norunda (near Karlsater) about 27 km north of Uppsala. The natural forest at the experimental plot is about 100 years old (1993). The upper canopy of the stand consisted mostly of Scots pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* (L.)Karst). A sparse lower canopy consisted of many small young spruces growing in spots over the area covered by acidophylous vegetation (*Vaccinium myrtillus*). The deep soil of glacial origin is a boulder to boulder rich sandy till with a significant percentage of large to very large stones. The area is flat and, occasionally, high ground water tables occur in the spring in some places. At Uppsala, the mean air temperature is 5.5°C (1961–1990), the mean annual precipitation (non-adjusted) is 527 mm and the mean Penman open water evaporation is 454 mm (1973–1992). During the growing season, July is normally the warmest and wettest month and April the coolest and driest month (records of Ultuna Meteorological Station).

During the study, global short-wave radiation was measured in the open with a pyranometer (Kipp & Zonen CM5, Delft, the Netherlands) and air temperature and humidity, at the height of 10 m with a Rotronic sensor (RS2 Rotronic AG, Bassersdorf, Switzerland). Data on precipitation and open water evaporation (Penman, 1948) were available from May to September 1993 from a meteorological station in Uppsala (Ultuna), about 30 km southeast of the experimental site.

Over two periods of measurement in summer 1993, transpiration was evaluated only on days with relatively fine weather. The first period was under conditions of severe drought in mid-July, when the main experimental days were 16 and 17 July for pine and 19 and 20 of July for spruce. The second period, when the water supply was ample, was later in the year and the experimental days were 28 and 29 August, for both species.

2.2. Measuring and calculating methods

Twelve sample trees were selected for both species and measured with 48 sensors altogether during the first period. Half the number of sensors were used in the second period; only large trees with contrasting sap flow were considered. The appropriate size of sample trees was calculated on the basis of forest inventory data measured at the experimental site and the statistical technique of quantiles of total was applied (Čermák and Kučera, 1990). Sample trees were evenly distributed over the whole range of tree sizes and every sample tree represented the mean tree of the same portion of selected biometric quantity (not the number of trees only). Basal area was applied to such calculations. Good health and symmetrical shape of crowns were the final criteria for selection.

The sap flow rate was measured using the trunk heat balance method with internal heating and sensing (Čermák et al., 1973, 1982; Kučera et al., 1977). A certain part of the lower trunk was heated with the constant power using five stainless steel electrodes inserted in parallel 20 mm apart and approaching the depth of sapwood. Temperature was measured using a battery of eight compensating thermocouples (Čermák and Kučera, 1981). The independent, battery operated six-channel measuring device was applied (model P-6, Ecological Measuring Systems, Ltd, Brno, Czech Republic). Global radiation in the open, air temperature and humidity in midcanopy were measured at the same time. Measurements were taken every minute and stored within data-loggers and averages for 15 min intervals were evaluated.

Two measurement points were installed on the opposite sides of stems (east/west) at breast height of every sample tree to cover the internal variability of sap flow (reflecting different water supply to individual roots around stems). The specific sap flow rate, Q_{wu}, is the variable measured directly and recorded by each gauge; it characterizes the sap flow within a section of tree stems defined by the unit length of their circumference at xylem surface (i.e. at the cambium level), $L_{cu} = 1$ cm. Q_{wu} was scaled up to the tree, Q_{wt} when multiplying the mean recorded data of flow with the stem xylem circumference L_{ct} (cm).

$$Q_{wt} = L^{*}_{ct}(Q_{wuEast} + Q_{wuWest})/2 \tag{1}$$

The sap flow rate data of individual sample trees, Q_{wt} were scaled up to the experimental stand (stand area unit, 1 ha) (Čermák et al., 1982; Čermák and Kučera, 1990) according to the size of trees characterized by a suitable (directly measurable in the field) biometric scaling parameter, SIZE_{tree}. Circumference of stems at breast height, both those of under bark, the xylem, $(\mathrm{CBH})_x$ and stem over bark, $(\mathrm{CBH})_b$, basal area under bark $(A_{bas})_x$ and over bark $(A_{bas})_b$, were the characteristics used for scaling. The scaling characteristic whose results showed minimum variation was applied further. Transpiration of the stand, $Q_{ws} = E_Q$ was calculated for a period of 1 day or longer, i.e. the period over which totals of sap flow and transpiration are equal (to avoid problems with the diurnal time shift of sap flow rate behind actual transpiration). Owing to high variability of transpiration between trees, stand transpiration, E_Q was calculated from the total value of transpiration of the entire set of k sample trees altogether considering the stand density of N (trees ha^{-1})

$$E_Q = \sum_{i=1}^{i=k} (Q_{\mathrm{wt}})_i^* \left[\frac{\sum_{i=1}^{i=N} (\mathrm{SIZE}_{\mathrm{tree}})_i}{\sum_{i=1}^{i=k} (\mathrm{SIZE}_{\mathrm{tree}})_i} \right] \tag{2}$$

2.3. Assessing the error of estimated transpiration

The error of estimating the transpiration of the stand, was assessed statistically on the basis of variation of the relation of biometric characteristics to daily values of sap flow. The standard error, $\mathrm{SE} = \mathrm{SD}/(n^{0.5})$ was calculated for the whole set of sample trees measured over the given period (certain n) and for each characteristic applied separately. Relative values of SE in per cent of mean were considered. Curves characterizing errors over a range of sample trees were calculated when introducing different n into the above equation. Causes of higher individual variation at the experimental stand, i.e. the presence of stress was evaluated according to: (1) magnitude of transpiration of sample trees; (2) individual variation in transpiration; (3) response of both above-mentioned characteristics of trees after watering the soil; (4) differences in response of deep and shallow rooting species.

3. Results and discussion

3.1. Experimental stand and sample trees

Pine trees were dominant in the stand and created most of its upper canopy. Pine with 386 trees ha^{-1} and 27.9 $\mathrm{m}^2\ \mathrm{ha}^{-1}$ of basal area represented 64% and 80% of the stand, respectively. Spruce with 219 trees ha^{-1} and 6.8 $\mathrm{m}^2\ \mathrm{ha}^{-1}$ of basal area were mostly smaller, more dispersed over the stand and represented 36% and 20% of the stand, respectively (Fig. 1). In contrast to the sparse crowns of the dominant pine, the crowns of spruce trees created most of the lower canopy with their long and denser crowns almost reaching the ground. Twelve sample trees represented the smaller portion of basal area in pine (3.5%) as the dominant species and the larger portion in spruce (12.6%) as the less abundant species. The whole set of sample trees represented 5.2% of the stand area unit (1 ha). Basal area was confirmed as a suitable biometric characteristic for scaling; any more complex characteristics were inappropriate because the individual variation of transpiration caused by other factors was very high.

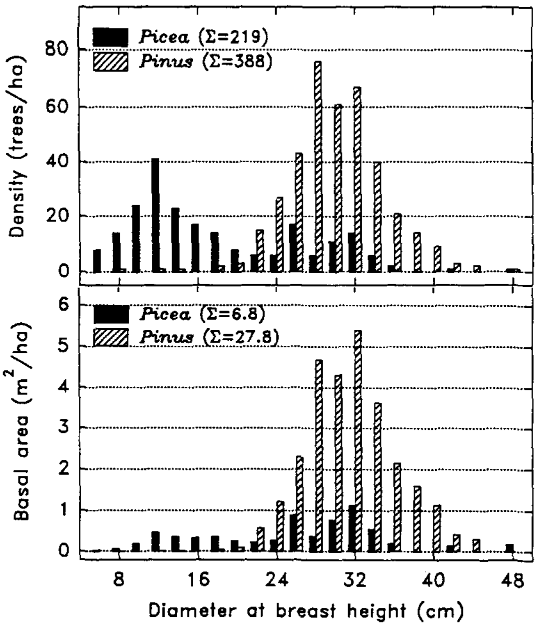

Fig. 1. Distribution of Scots pine and Norway spruce trees at the Norunda experimental old stand. Stand density and basal area.

3.2. Climatic conditions over the growing season

Meteorological conditions occurring during the study period were not typical, if compared with long-term seasonal data. July was much drier and August much wetter in summer 1993 compared with normal. There were only minor differences in climatic conditions between the experimental site at Norunda and the meteorological station at Ultuna, 30 km southeast of the site. Precipitation summarized over 1 month before the period of first measurement in July was only about 40 mm, while over the same time before the second measurement in August it was almost 100 mm. This corresponds to the climatic water deficits of −60 and +30 mm, respectively (thus differing by 90 mm), over the same periods of time (Fig. 2).

3.3. Estimated transpiration rates

Diurnal courses of sap flow rate (mean of all sample trees) and radiation show variation under relatively fine, but non-ideal weather conditions (Fig. 3). Sap flow in individual sample trees reflected their different social position within the canopy, where they were shaded by their neighbours, etc. That is why only mean values of a larger set of sample trees weighted by their densities characterize the diurnal course of sap flow rate of the stand, which can be compared with stand transpiration measured e.g. by micrometeorological methods. The time lag of diurnal courses of sap flow rate behind transpiration (Čermák et al., 1982; Schulze et al., 1985; Hatton

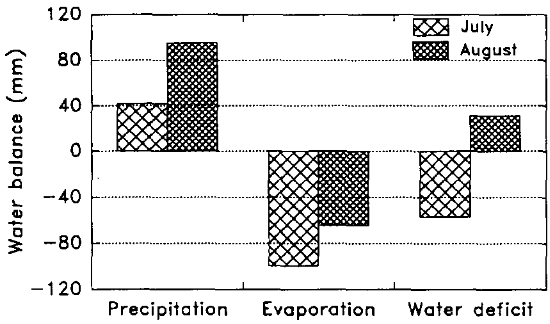

Fig. 2. Precipitation, evaporation and climatic water deficit (precipitation– evaporation) calculated over the period of one month before both study periods in July and August, respectively, using data from the nearby meteorological station at Ultuna.

and Vertessy, 1990), here radiation, reached about 1–2 h. This suggests that a significant amount of water from tissue storage (about 20%) was used for transpiration in morning hours.

Individual variability of the sap flow rate was high in both species (Fig. 4). During the first study period under drought, daily values of specific sap flow rate and data of total sap flow rate in the set of sample trees are given in the Table 1. Mean sample trees of spruce and pine (taken as with DBH u.b. of 27.3 cm) transpired 23.1 l day^{-1} and 13.1 l day^{-1}, respectively, when the Penman open water evaporation estimate was 3.3 mm day^{-1}; transpiration of these species calculated for the stand area unit (1 ha),

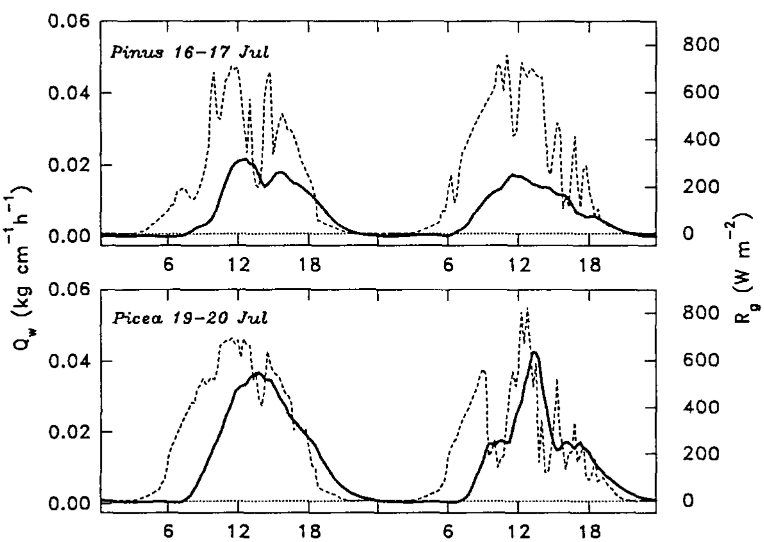

Fig. 3. Diurnal courses of sap flow rate in Scots pine and Norway spruce — mean of all sample trees — and global radiation above the canopy in the Norunda experimental old forest stand, during July 1993. The specific sap flow rate is expressed per radial section of the stem given by the length of its circumference at cambium level, 1 cm.

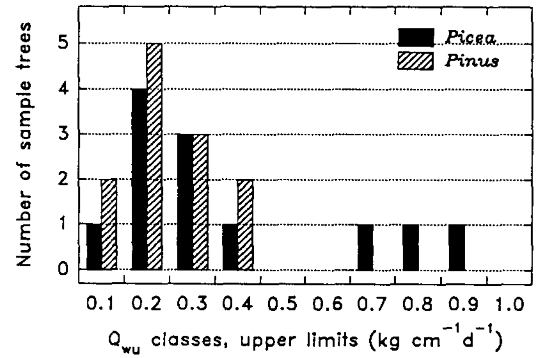

Fig. 4. Individual variation in the specific sap flow rate of Scots pine and Norway spruce trees in the Norunda experimental old forest stand during mean day in July (16–20). The specific sap flow rate is expressed per unit section of the stem, given by the length of its circumference at cambium level, 1 cm.

was in the opposite ratio because that was dependent on their distribution within the stand. Mean daily values of transpiration of spruce and pine thus were 0.22 mm day^{-1} and 0.45 mm day^{-1}, respectively, and the total of the experimental forest stand reached 0.7 mm day^{-1} (Fig. 5).

Transpiration was thus relatively small in both species, about one half of the transpiration occurring under similar weather but non-limited soil moisture conditions; in such cases it was found, usually, that specific sap flow was about $Q_{wu} = 1$ (kg cm^{-1} day^{-1}) (Čermák, 1992) and daily transpiration was also significantly higher (e.g. Molchanov, 1960; Beydeman, 1983; Schulze et al., 1985; Helbig, 1987). Daily sums of sap flow rate in trees are practically equal to daily sums of transpiration for time periods of 1 day or longer. The relatively higher transpiration of spruce trees was evidently caused by the much higher amount of their foliage along substantially longer and denser crowns as compared with the short and sparse crowns of pine.

Table 1
Sap flow rate in sample trees during mean day of the period July 16–20, measured at the Norunda experimental old forest stand near Karlsater in July 1993 and standardized to potential evaporation of $E_p = 4$ (mm day^{-1})

Species	Parameter	Mean sap flow	Standard error in measuring points		Standard error in individual sample trees	
			SE	(%)	SE	(%)
Pinus	Q_{wu}	0.1831	0.0240	13.1	0.0269	14.7
	$Q_{w,sample}$	188.45				
Picea	Q_{wu}	0.3136	0.0755	24.1	0.0691	22.0
	$Q_{w,sample}$	324.02				

Specific sap flow, Q_{wu} kg cm^{-1} day^{-1}, is calculated for the section of xylem given by the radius of the stem and unit length of its circumference of 1 cm. Total sap flow of all sample trees is $Q_{w,sample}$ (kg $(sample\ day)^{-1}$).

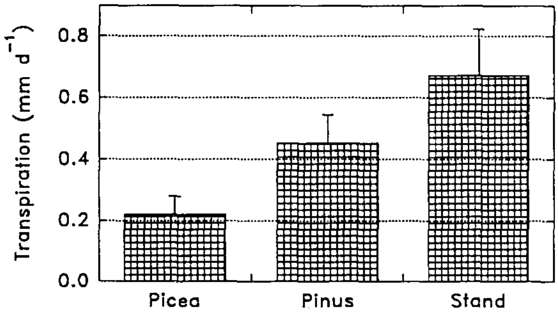

Fig. 5. Transpiration of spruce and pine trees and of the Norunda experimental old forest stand during mean day in July (16–20) under conditions of Penman open water evaporation, E_p = 3.3 mm day^{-1}. Bars represent standard errors of transpiration estimates.

3.4. *Estimating the impacts of drought stress*

The impact of drought stress in July is evident from mean values of transpiration relative to standard potential evaporation from the very same set of sample trees compared with those from wetter August (see Fig. 6). The relative transpiration of pine increased 3.5 times while that of spruce increased 5.4 times after rains.

The above results cannot be taken as an absolute measure of the level of water stress, since the increased sap flow itself is not evidence that transpiration reached its potential. Watering can release only the supply-limited portion of the stress, probably affecting one of the most important hydraulic resistances in the soil–tree–atmosphere continuum located in the soil just outside the roots or in the soil–root interface as the root shrinkage (Williams, 1974; Bowen, 1985; Orlander and Due, 1986). However, watering cannot increase transpiration above limits given by possibly changed properties of tree conductive systems that may affect water demand in the long-term (Čermák et al., 1993). Any damage to the conductive systems of trees, hypoxia or drought stress in soils can decrease transpiration significantly. Such impacts may occur in different trees or in their parts (e.g. individual large roots) at different times; this increases the individual variability (Čermák, 1986; Čermák and Kučera, 1990).

In contrast to the usually deeper root systems of pine, spruce is generally known as a shallow-rooting species. Henderson et al. (1983) found the highest density of spruce roots in the upper 10–20 cm of soil, decreasing to zero at 60 cm. This corresponds with tree water uptake. Even when a hydraulic lift may operate between roots growing at different depths (Caldwell and Richards, 1989), they cannot grow deeper, since spruce is more sensitive to flooding (De Bell et al., 1984; Levan and Riha, 1985). If the supply of water to the roots were increased by raising the level of the water table, larger changes in transpiration of deeply rooting pine should be expected.

3.5. *Individual variability in transpiration and scaling error*

When measuring 12 trees of each species under water stress, the scaling error of transpiration estimates for the stand was lower in pine, around 15% and higher in

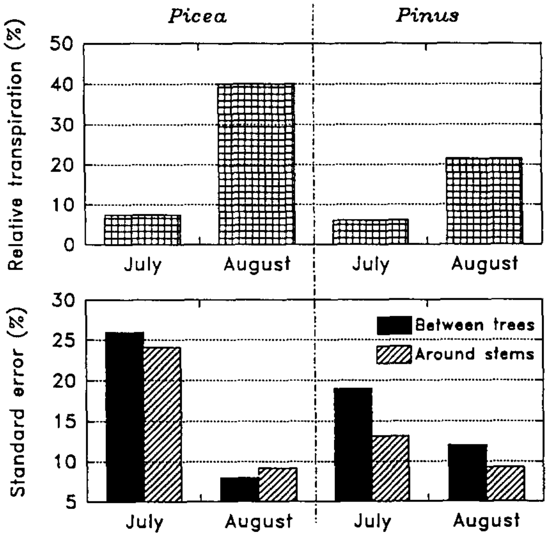

Fig. 6. Sap flow rate or daily transpiration of Norway spruce and Scots pine, relative to Penman open water evaporation and its variation within trees, (i.e. reflecting different water supply to individual roots around stems) at the experimental old stand during dry and wet periods in summer 1993. Standard error is expressed in per cent of mean.

spruce, about 22% (Fig. 7). There were very small differences in errors when calculated for 12 trees of each species or when separately taken at 24 measuring points for the same set of trees (see Table 1). Watering the soil contributed substantially to decreasing the variability of the sap flow within trees (reflecting different water supply to individual roots around stems situated in soils with different water contents and/or potentials) in August by about and 31% and 62% of the original values in July in pine and spruce, respectively (see Fig. 6). If the above

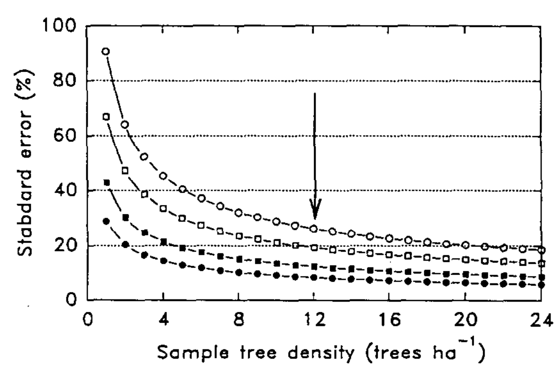

Fig. 7. Standard error of specific sap flow rate for the set of sample trees composed of the different numbers of samples of Scots pine and Norway spruce in the Norunda experimental old stand, during July 1993. (Specific sap flow rate, Q_{wu} kg cm − 1 day^{-1} is expressed for the segment of xylem given by the length of its circumference at the cambium level, 1 cm.)

variation was calculated for the same set of 24 trees with an ample water supply, the relative standard error decreased to about 9% in both species. This is similar to observations of other authors (e.g. Diawara et al., 1991) who found that a set of ten sample trees provides an estimate of mean sap flow density with a confidence interval lower than 10%.

4. Conclusions and recommendation

Transpiration of Scots pine and Norway spruce as the main canopy species in an old forest stand can be estimated easily on the basis of measurement of sap flow rate. For this, the method of heat balance with internal sensing and heating which is designed for large trees, does not require any additional measurement and calibration is probably among the best at present. The advantages of the sap flow approach are: simplicity, fast installation, low cost (no additional constructions such as towers or masts are necessary) and capability to work independently (battery operated system) in any field conditions. Different species and trees of any size and social position within stands can be studied simultaneously. Results may be interpreted in terms of behaviour of both foliage and root systems. The occurrence of stress conditions and their causes may be specified better. The error in estimating the transpiration is rather low under adequate water supply and higher under drought stress. It can be decreased significantly by increasing the number of sample trees.

For the period of very intensive studies as planned in the NOPEX programme, measurement of the sap flow rate should start in spring as early as possible after snow melt, when sufficient soil water after winter may be expected. This would allow better assessment of potential transpiration and the level of drought stress (if any) over the growing seasons. To achieve reasonable precision of transpiration estimates at the stand level, six to 12 trees of every species per unit of stand area should be measured. Data of transpiration measured with other independent methods, e.g. the Bowen ratio method, eddy correlation method, estimates of soil water depletion and data obtained with the tree sap flow rate measurement approach, should be compared to get the maximum information about the ecosystem under study.

References

BAHC Core Project Office, 1993. Biospheric aspects of the hydrological cycle (BAHC). The operational plan. Rep. No.27, IGBP Global Change, Stockholm.

Baldocchi, D.D., Luxmoore, R.J. and Hatfield, J.L., 1991. Discerning the forest from trees: an essay on scaling canopy stomatal conductance. Agric. For. Meteorol., 54: 197–226.

Beydeman, I.N., 1983. On Water Consumption by Plants in Different Natural Zones of the USSR. Nauka, Novosibirsk (in Russian).

Bowen, G.D., 1985. Roots as component of tree productivity. In: M.G.R. Cannell and J.E. Jackson (Editors), Trees as Crop Plants. Institute of Terrestrial Ecology, Huttingdon, UK, pp. 303–315.

Caldwell, M.M. and Richards, J.H., 1989. Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots. Oecologia, 79: 1–5.

Čermák, J., 1986. Short- and long-term response of transpiration flow rate in full-grown trees to water stress. In: Proc. 18th IUFRO World Congress, Whole-Plant Physiology Working Party (S 2.01–15), 7–21 September 1986, Ljubljana, Yugoslavia. Yugoslav IUFRO World Congress Organizing Committee (Editor), Plesko, Ljubljana, pp. 187–193.

Čermák, J., 1992. Transpiration of trees and its importance in forest ecology. Assoc. Prof. Thesis, Agricultural University, Brno (in Czech).

Čermák, J. and Kučera, J., 1981. The compensation of natural temperature gradient in the measuring point during the sapflow rate determination in trees. Biol. Plant. (Praha), 23(6): 469–471.

Čermák, J. and Kučera, J., 1987. Transpiration of fully grown trees and stands of spruce (*Picea abies* (L.) Karst.) estimated by the tree-trunk heat balance method. In: R.H. Swanson, P.Y. Bernier and P.D. Woodward (Editors), Proc. Forest Hydrology and Watershed Measurements, Vancouver, Canada, August 1987. Publ. No. 167, IAHS, Wallingford, UK, pp. 311–317.

Čermák, J. and Kučera, J., 1990. Scaling up transpiration data between trees, stands and watersheds. Silva Carelica, 15: 101–120.

Čermák, J., Deml, M. and Penka, M., 1973. A new method of sap flow rate determination in trees. Biol. Plant. (Praha), 15(3): 171–178.

Čermák, J., Ulehla, J., Kučera, J. and Penka, M., 1982. Sap flow rate and transpiration dynamics in the full grown oak (*Quercus robur* L.) in flood plain forest exposed to seasonal floods as related to potential evapotranspiration and tree dimensions. Biol. Plant. (Praha), 24(6): 446–460.

Čermák, J., Matyssek, R. and Kučera, J., 1993. Rapid response of large, drought stressed beech trees to irrigation. Tree Physiol., 12: 281–290.

Cienciala, E., Lindroth, A., Čermák, J., Hallgren, J.E. and Kučera, J., 1992. Assessment of transpiration estimates for *Picea abies* trees during a growing season. Trees, 6: 121–127.

DeBell, D.S., Hook, D.D., McKee, Jr., W.H. and Askew, J.L., 1984. Growth and physiology of loblolly pine roots under various water table level and phosphorus treatment. For. Sci. 30(3): 705.

Diawara, A., Lousteau, D. and Berbigier, P., 1991. Comparison of two methods for estimating the evaporation of a *Pinus pinaster* (Ait.) stand: sap flow and energy balance with sensible heat flux measurements by an eddy covariance method. Agric. For. Meteorol., 54: 49–66.

Hatton, T.J. and Vertessy, R.A., 1990. Transpiration of plantation *Pinus radiata* estimated by the heat pulse method and the bowen ratio. Hydrol. Process., 4: 289–298.

Helbig, A., 1987. Use of lysimeter measurements for estimation of the evapotranspiration of pine forest by Bagrov's method. In: R.H. Swanson, P.Y. Bernier and P.D. Woodward (Editors), Proc. Forest Hydrology and Watershed, Vancouver, Canada, August 1987. IAHS–AISH Publ. No. 167, IAHS–AISH, Wallingford, UK, pp. 357–363.

Henderson, R., Ford, E.D., Renshaw, E. and Deans, J.D., 1983. Morphology of the structural root system of Sitka spruce. 1. Analysis and quantitative description. Forestry, 56(2): 121–135.

Kelliher, F.M., Kostner, B.M.M., Holliger, D.Y., Byers, J.N., Hunt, J.E., McSeveny, T.M., Meserth, R., Weir, P.L. and Schulze, E.-D., 1992. Evaporation, xylem sap flow and tree transpiration in a New-Zealand broad-leaved forest. Agric. For. Meteorol., 62(1–2): 53–73.

Kučera, J., Čermák, J. and Penka, M., 1977. Improved thermal method of continual recording the transpiration flow rate dynamics. Biol. Plant. (Praha), 19(6): 413–420.

Levan, M.A. and Riha, S.J., 1985. Response of root systems of northern conifer transplants to flooding. Can. J. For. Res., 16: 42–46.

Molchanov, A.A., 1960. Hydrological Role of Forests. Acad. Sci. USSR, Moscow (in Russian).

Orlander, G. and Due, K., 1986. Location of hydraulic resistance in the soil–plant pathway in seedlings of *Pinus sylvestris* L. grown in peat. Can. J. For. Res., 16(1): 115–123.

Penman, H.L., 1948. Natural evaporation from open water, baresoil and grass. Proc. R. Soc. London, Ser. A, 193: 120–145.

Schulze, E.-E., Čermák, J., Matyssek, R., Penka, M., Zimmermann, R., Vasicek, F., Gries, W. and Kučera, J., 1985. Canopy transpiration and flow rate fluxes in the xylem of the trunk of *Larix* and *Picea* trees — a comparison of xylem porometer and cuvette measurements. Oecologia (Berlin), 66: 475–483.

Swanson, R.H., 1970. Sampling for direct transpiration estimates. J. Hydrol. (Dunedin), 9: 72–77.

Williams, J., 1974. Root density and water potential gradients near the plant root. J. Exp. Bot., 25: 669–674.