JOURNAL OF FOREST SCIENCE, *48*, 2002 (3): 130–140

Estimation of beech tree transpiration in relation to their social status in forest stand

K. Střelcová [1], F. Matejka [2], J. Minďáš [3]

[1]*Technical University, Forestry Faculty, Department of Natural Environment, Zvolen, Slovak Republic*
[2]*Geophysical Institute of the Slovak Academy of Sciences, Bratislava, Slovak Republic*
[3]*Forest Research Institute, Zvolen, Slovak Republic*

ABSTRACT: The results of sap flow continuous measurements by a tree-trunk heat balance method (THB) on beech model trees are analysed in this paper. Experimental research works were carried out in a mature mixed fir-spruce-beech stand in the research area Poľana – Hukavský grúň (φ= 48°39´, λ = 19°29´, H = 850 m a.s.l.) in UNESCO Biosphere Reserve on two co-dominant and one sub-dominant beech trees. A mathematical model of daily transpiration dynamics was proposed for a quantitative analysis of the daily course of sap flow intensity. The model works on a one-tree level and enables to consider the influence of the tree social position in the stand on the sap flow intensity of model beech trees and to express the dependence of sap flow intensity on the tree height and crown projection.

Keywords: *Fagus sylvatica* (L.); heat balance method; mathematical model SVAT; micrometeorological conditions; dendrometric parameters of trees

The climate changes have aroused interest in processes controlling the exchange of water and carbon between vegetation and atmosphere. Atmospheric CO_2 enrichment tends to lower tree stomatal conductance, and this phenomenon reduces tree transpiration rates. CO_2 enriched plants possess a larger leaf area to lose water. It is not known how these competing phenomena influence the depletion of soil water and subsequent productivity of trees when water limits their growth. A key to understand any complex system is the assessment of its components and their accurate quantification by applying suitable methods and techniques. The next step is parametrisation and modelling used to test a new hypothesis and to make predictions for new scenarios.

The measurement and modelling of water consumption by trees in mixed forests with vertical differentiation is much more complicated than in homogeneous forest stands. The amount of water transpired per tree is determined mainly by the green leaf area of the tree and solar radiation incident upon the tree leaves. To measure tree transpiration on a whole-tree level it is convenient to use the tree-trunk heat balance method (THB) that represents direct integrative volumetric measurements of sap flow rate (Čermák et al. 1976, 1982; Kučera et al. 1977; Cienciala et al. 1994).

In recent years, considerable efforts have been made to improve methods for transpiration estimation. Recent mathematical models of water exchange between vegetation and atmosphere take into account the existence of two sources of water: leaf area and soil surface (Choudhury, Monteith 1988; Iritz et al. 1999; Shuttlewort, Wallace 1985; Torula, Heikinheimo 1999; Wallace et al. 1990). Originally, all models based on this methodical approach are designed for the whole canopy. The attempts to simulate the transpiration of an individual plant or tree are very rare. Mathematical modelling of transpiration of an individual plant can be mentioned in this context (Bichele et al. 1980). Consequently, further effort is needed to improve the understanding of interrelations between the water regime of an individual tree and environmental factors.

The aim of this paper is

1. to quantify the amount of water transpired through beech trees of various social position in the forest stand during the day, month and vegetation period,
2. to propose a mathematical model of daily transpiration dynamics working on a one-tree level enabling to consider the influence of tree social position in the stand on the sap flow intensity of model beech trees.

MATERIAL AND METHODS

Site description and plant material. Experimental research works were carried out in a mature mixed fir-

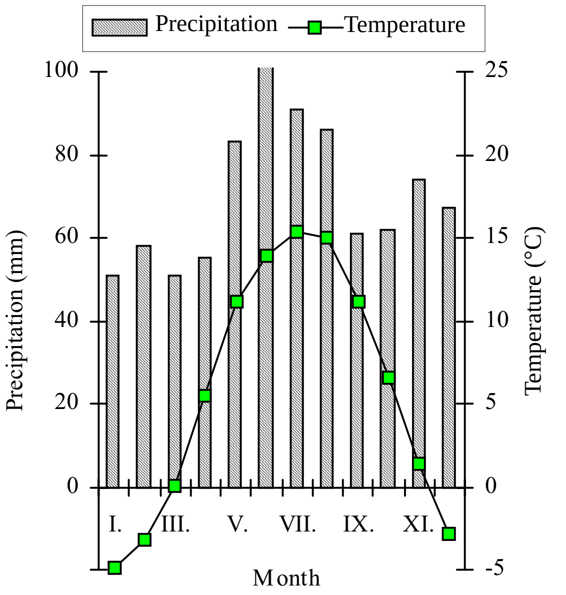


Fig. 1. Climatic diagram for the locality Poľana – Hukavský grúň

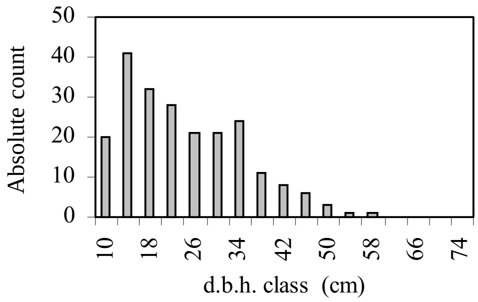
spruce-beech stand (*Abieto-Fagetum*) in the research area Poľana – Hukavský grúň located in the south-eastern part of the Poľana Mts. region in UNESCO Biosphere Reserve (φ= 48°39´, λ = 19°29´, H = 850 m a.s.l.) in Central Slovakia. The investigated stand is located on a slope (5–10°) oriented to the north-east, in a climatically cold area with average (1951–1980) annual temperature of 5.8°C and annual precipitation 853 mm. Walter's climatic diagram for the research plot is shown in Fig. 1. Soil type is Cambisol with 80cm average depth. The stand is about 100 years old with 70% of European beech (*Fagus sylvatica* L.), 20% of Norway spruce (*Picea abies* [L.] Karst.), 3.5% of silver fir (*Abies alba* Mill.) and with single trees of European ash (*Fraxinus excelsior* L.) and sycamore maple (*Acer psedoplatanus* L.). The stand is vertically differentiated, completely closed from the end of May to the end of September, the projected leaf area index (LAI) was 5.89 in June. The size frequency distribution of beech trees is shown in Fig. 2.

Measurements of sap flow rate. The sap flow of model beech trees was estimated by direct non-destructive and continuous measurements by the tree-trunk heat balance method (THB) with internal heating of xylem tissues and sensing of temperature. THB method involves the heating of a xylem segment using 3–5 electrodes inserted in the conductive system. The arrangement of measuring points was as described by ČERMÁK et al. (1976, 1982) and KUČERA et al. (1977). The temperature difference between the heated and unheated part of xylem was monitored by a battery of four copper-constantan thermocouples according to ČERMÁK and KUČERA (1981). The output from the thermocouples was measured using a data logger and the mass flow was obtained by simple calculation based on the differential heat balance equation (KUČERA et al. 1977). There were two measuring points at the opposite sides of the trunk at a 2m height to record possible variations in the sap flow within the stem caused by variability in xylem width. The measuring points were insulated using 30mm polyurethane foam covered with a 0.5mm aluminium shield. The insulation covered about 1 m of the trunk length. The whole installation was covered with plastic foil fastened in a watertight manner to the bark surface above the measuring points. The sap flow instruments were made in Ecological Measuring Systems (Brno, Czech Republic). The measurements of three representative beech trees are presented for the growing season 1996 (from 1 May to 20 October). The mensuration variables of representative trees are given in Table 1.

Measurements of the microclimate. Air temperature, air humidity, global radiation, wind speed and precipita-

Table 1. Mensuration variables of representative trees

Representative tree	Evidence number of tree in the stand	Social position	Height (m)	d.b.h. (cm)	Horizontal crown projection (m^2)
Beech 1	228	co-dominant	37	49.8	69
Beech 2	306	co-dominant	37	44.1	78
Beech 3	301	sub-dominant	32	25.5	19



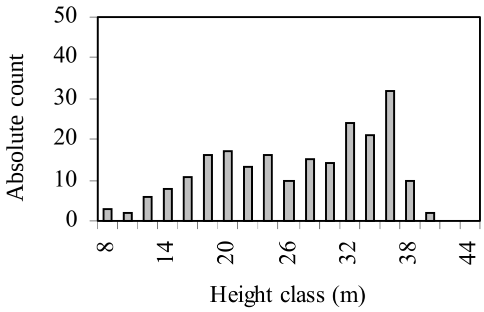


Fig. 2. Frequency distribution of breast height diameters and heights of beech trees in the stand

tion were measured in 10-minute intervals above the investigated stand (34–37 m above the ground) on a meteorological tower using DELTA-T equipment. Soil temperature was measured at a 0.1 m depth. Soil water potential was measured once a week with tensiometers at depths of 15, 30, 50 and 70 cm, at 0.5 and 1m distances from the trunks of representative trees.

Mathematical modelling of transpiration rate. The theoretical analysis of transpiration rates for individual sample trees is based on a mathematical model of plant transpiration in the conditions of soil water deficit (BICHELE et al. 1980). The simulation model was constructed taking into account the most important interrelations in the "soil–plant–atmosphere" continuum (CHOUDHURY, MONTEITH 1988). The idea of the model is based on Darcy's law, continuity equation and the assumption that the effect of plant water reserve on transpiration can be neglected. The forest canopy is divided into one-metre horizontal layers. The sample trees are assumed to have cylindrical crowns with constant leaf area density. Taking into account these simplifications, the relationship between the soil water potential and transpiration can be written for each of the horizontal layers (BICHELE et al. 1980)

$$\frac{1}{-\psi_S} = \frac{1}{-g r_p E - \psi_L} + \beta E \qquad (1)$$

where: ψ_S – soil water potential,
g – gravitational constant,
r_p – internal resistance of trees,
E – transpiration,
ψ_L – leaf water potential,
parameter ß describes the root system of trees and hydrophysical properties of soil (BICHELE et al. 1980).

Transpiration E depends on stomatal resistance and atmospheric factors according to Penman–Monteith equation (MONTEITH 1973)

$$\lambda E = \frac{\Delta r_b R + \rho c_p D}{\Delta r_b + \gamma (r_b + r_s)} \qquad (2)$$

where: λ – latent heat,
R-P – difference between net radiation R and soil heat flux P,
Δ – temperature derivative of saturated vapour pressure,
ρ – density of dry air,
c_p – specific heat of air at constant pressure,
D – vapour pressure deficit,
r_b – boundary layer resistance,
r_s – stomatal resistance between the whole layer of leaves and atmosphere.

Stomatal resistance is considered as a function of solar radiation intercepted by leaves Q_L and leaf water potential ψ_L (MATEJKA, HUZULÁK 1995). This relationship is expressed in the form

$$r_s = r_0 \left(1 + \frac{n}{Q_L}\right) \exp(-\mathrm{m}\,\psi_L) \qquad (3)$$

where: r_0 – minimal stomatal resistance that corresponds to the conditions of high irradiation of leaves and to sufficient moisture content of soil.

Relationships (1), (2) and (3) form a system of three equations with unknown variables ψ_L, r_s and E that can be considered as a mathematical model describing the response of transpiration from sample trees to changes in soil, plant and atmospheric parameters.

Input data of the model can be divided into two groups involving the characteristics of soil, trees and atmosphere:

1. Directly measured data: global radiation, net radiation, wind speed, air temperature and humidity, tree height, crown projection, leaf area index and soil water potential.
2. Values calculated from directly measured data: boundary layer resistance, stomatal resistance for each of the horizontal layers of leaves.

The resistances r_b and r_s were calculated according to the procedure recommended by CHOUDHURY and MONTEITH (1988). The parameters r_0, m and ß were determined from experimental data obtained for the analysed beech stand.

Running the model, the system of its governing equations (1), (2) and (3) was numerically solved for ψ_L, r_s, E in each of the horizontal layers of leaves, then the values of E were summarised to obtain the transpiration of the whole sample tree.

The measurements of global radiation, wind speed, air temperature and humidity above the canopy carried out in 15-minute intervals during the day 6. 1. 1996 were used as meteorological model inputs.

RESULTS AND DISCUSSION

Environmental conditions during the growing season

Average annual temperature (5.3°C) and precipitation total (921 mm) in 1996 were normal in comparison with long-term average. The weather was fairly typical of this location during the year and growing season. From the physiological point of view, the growing season was favourable (Fig. 3). High average temperature in May (dT = +1.7°C) was compensated by a sufficient amount of precipitation (177% of the long-term average). Warm and humid May led to the earlier start of phenological phases "growing and developing leaf" (on 9 May) and "physiologically adult leaf" (on 16 May) than in other years. The phase of the physiologically adult leaf lasted for 134 days, which is important for the amount of transpired water and production of trees. Leaf development started in the lower parts of adult beech tree crowns and proceeded toward the top of the crowns. This phenomenon is also described in other papers (MC GEE 1986; ŠTEFANČÍK 1995).

Weather conditions and soil moisture content have a strong influence on the amount of transpired water. Daily meteorological characteristics (global radiation, air and soil temperature, vapour pressure deficit, potential evapotranspiration) and soil water potential were presented by STŘELCOVÁ and MINĎÁŠ (1998).

The average air temperature values gradually increased (including short interruptions) from the beginning of the growing season and culminated in the first decade of June. With the formation of the west zonal air circulation in the second half of June and with its prevailing influence in July and partially in August, the average daily air temperatures dropped below the values recorded at the beginning of June. At the turn of August and September we recorded a sharp longer-lasting decrease in air temperature caused by the cold north-west advection. Daily averages of soil temperature at the depth of 10 cm showed a considerably smoother course than daily averages of air temperature and in summer the values ranged from 8 to 10°C.

Precipitation events were relatively frequent and uniformly distributed in time. Larger differences were recorded for precipitation amounts higher than 5 mm. This value can be considered as a benchmark limiting value when the penetration of precipitation water into the soil is assessed. Precipitation amounts measured in July and August were relatively low (besides small exceptions); it was reflected by the soil water potential values that gradually decreased from –100 hPa at the beginning of July to –800 hPa at the end of August. Frequent precipitation events at the turn of August and September resulted in the water re-saturation of soil and return of the soil water potential value to –100 hPa.

Taking into account the relationship between air temperature and potential evapotranspiration (PET), we calculated potential evapotranspiration according to TÜRC (1961). PET values usually range in the interval from 0.5 to 4 mm. Average saturation deficit values (dE) show a very good coincidence with the seasonal PET course. The trend of soil water potential values at various depth of soil was similar (Fig. 4). A decrease in the soil water potential in June was most significant at the depth of 30 and 50 cm as a result of water depletion by root desuction and intensive transpiration. Soil water potential decreased below –400 hPa in the second decade of June after a drought period. In spite of this fact the limiting soil water conditions for tree transpiration in June and July were not observed. According to PAPRITZ et al. (1991) beech transpiration is reduced when the soil water potential is lower than –700 hPa. Such low values (–750 hPa) were recorded in the second decade of August.

Tree sap flow rates during the growing season

To compare the measured and simulated sap flow rates of co-dominant and sub-dominant sample trees, the data recorded under nonlimiting soil water conditions in June and July when the assimilating organs were fully grown, were used in this paper. The response of daily sap flow rate to average daily air temperature is high for sample trees and similar for co-dominant trees and sub-dominant ones (Fig. 5).

The maximum measured daily tree sap flow for co-dominant sample trees No. 228 (d.b.h. = 49.8 cm) and No. 306 (d.b.h. = 44.1 cm) amounted to 370.7 litres and 236.2 litres, respectively. The daily maximum for sub-dominant sample tree No. 301 (d.b.h. = 25.5 cm) was 83.2 litres. The average daily value for the period from May to October

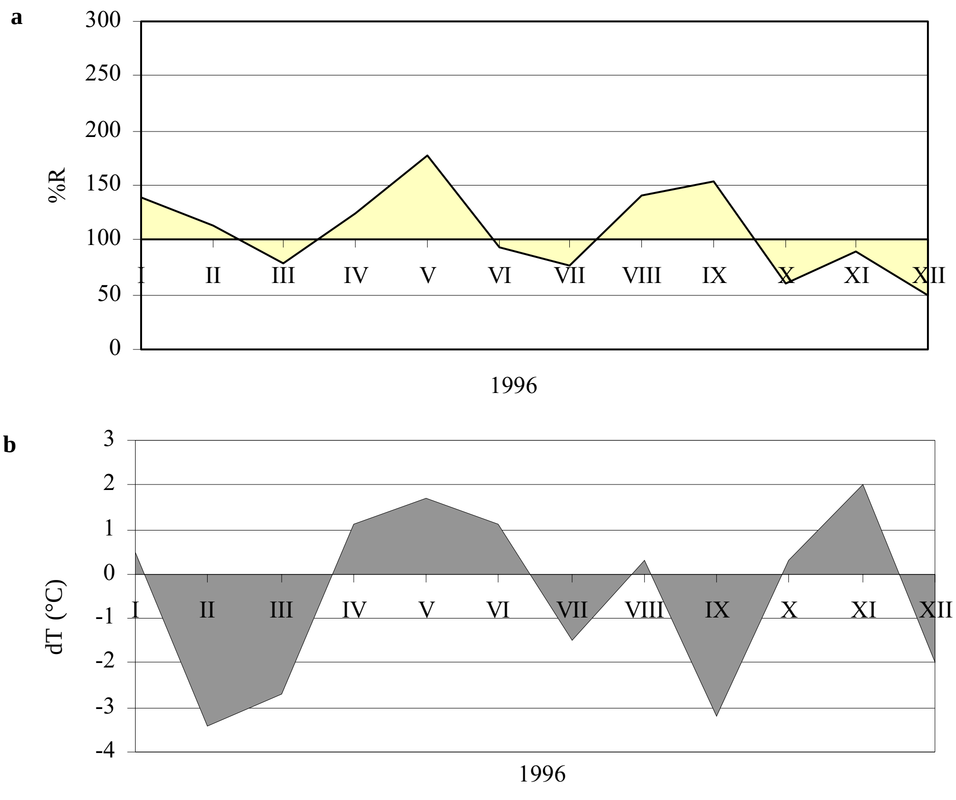


Fig. 3. Deviations of monthly precipitation totals (a) and monthly average temperature (b) in 1996 from the long-term average (1951 to 1980)

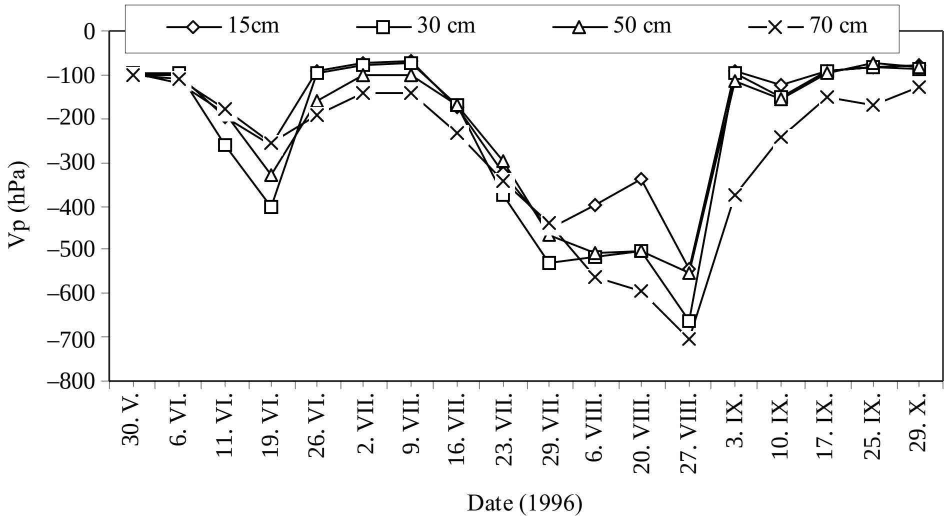


Fig. 4. Soil water potential in various soil depth in 1996 at Poľana – Hukavský grúň

($n = 184$) was 79 litres for tree No. 228, 64 litres for tree No. 306 and 18 litres for sub-dominant tree No. 301. The sap flow rate of the sub-dominant tree ranged from 10% to 30% of the respective values of co-dominant trees. In spite of large differences in the amounts of water transpired by trees with various social position, the seasonal course of the sap flow rate of these trees was similar (Fig. 5); it was also confirmed by coefficients of correlation (from 0.93 to 0.97) between daily sap flow rates of sample trees.

The beginning of extremely warm weather in the first decade of June caused a sudden increase in daily totals of transpired water in all three investigated individuals.

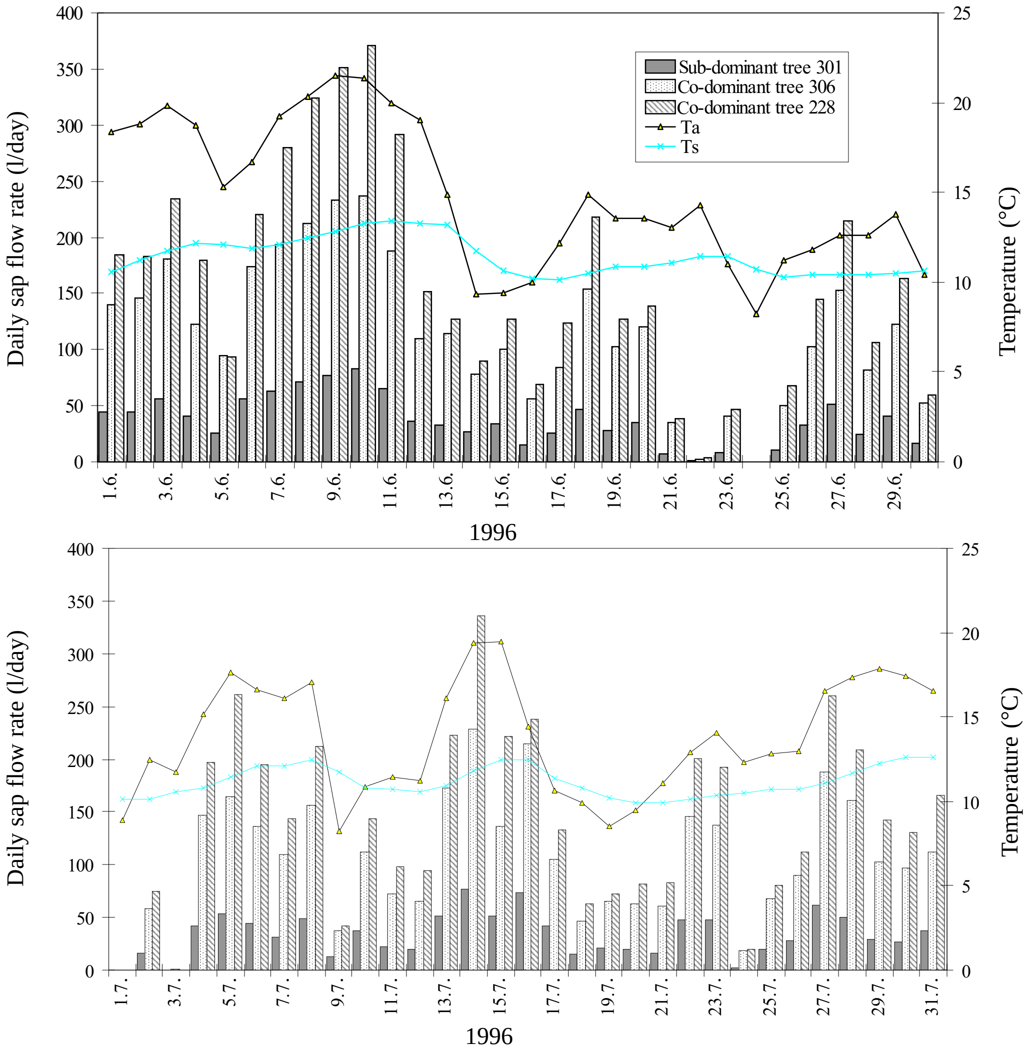


Fig. 5. Daily sap flow rates of sample trees and average air and soil temperature

Table 2. Daily sap flow rates and average daily air temperatures (Ta), global radiation (GR), vapour pressure deficit (dE), wind velocity (V), potential evapotranspiration (PET) and precipitation (R) during warm summer anticyclonic weather in the first decade of June and subsequent change to west zonal advection with precipitation in the second decade of June 1996

Date 1996	Daily sap flow rate (l)			Ta	GR	dE	V	PET/R
	tree 228	tree 306	tree 301	(°C)	(kW/m^2)	(hPa)	(m/s)	(mm)
6. VI.	220.3	174.3	56.0	16.7	8.9	8.9	1.4	3.4/0
7. VI.	279.3	193.2	62.8	19.2	8.8	8.8	2.3	3.7/0
8. VI.	324.5	212.5	71.6	20.3	8.8	8.8	1.2	3.8/0
9. VI.	351.5	233.2	77.0	21.4	8.7	8.7	1.1	3.8/0
10. VI.	370.7	236.2	83.2	21.4	7.6	7.6	1.5	3.8/0
11. VI.	291.6	187.2	65.0	19.9	6.4	6.4	1.5	3.7/8.4
12. VI.	151.8	109.9	36.1	19.0	5.5	5.4	1.1	3.6/9.8

Daily totals of transpired water as well as meteorological characteristics observed on extremely warm days are presented in Table 2.

In consequence of the extremely warm weather at the beginning of June the highest values of daily totals of transpired water for the whole growing season were recorded just in that period. Temperatures measured in July fell down below average values with a frequent occurrence of cold fronts. This variable character of weather also prevailed in August negatively influencing the transpiration rate. The highest daily totals were recorded during warm sunny days (June 8, 9 and 10) with high average daily air temperature and low wind speed. Under the influence of the west zonal air circulation the weather on the 11th and the 12th of June changed, it turned cold and precipitation amounts increased. This caused a decrease in the values of air saturation deficit as well as in daily totals of transpired water in all investigated individuals (Table 2).

The transpiration in June was higher than in July, which corresponds with the higher average of air temperatures recorded in the former month (Figs. 5 and 6). In spite of the highest monthly average temperature recorded in August the transpiration of all three sample trees was lower than in June and July (Fig. 6). It was probably due to a gradual decrease in the water potential of soil to the value close to –800 hPa at the end of the month, which also reflected a decrease in the available amount of soil water (Fig. 4). Although the soil moisture content decreased, there was not observed any decrease in the transpiration rate during noon hours. The amounts of water transpired by sample trees during a month and during the growing season 1996 are presented in Figs. 6 and 7.

As the transpiration intensity of individual trees is influenced to a large extent by the amount of solar radiation incident upon the assimilating organs, the amount of water transpired by trees also depends on their social status in the forest stand. This fact was confirmed by LADEFOGED (1963) in a beech stand in Denmark and by measurements carried out by ČERMÁK and KUČERA (1987), who investigated a mature spruce stand in Bohemia. According to the quoted authors, the transpiration of subdominant beech trees was less intensive (their

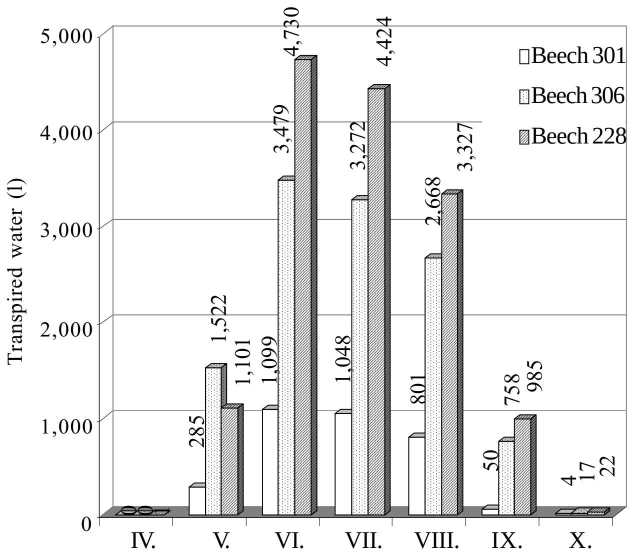


Fig. 6. Monthly totals of water transpired by sample trees in 1996

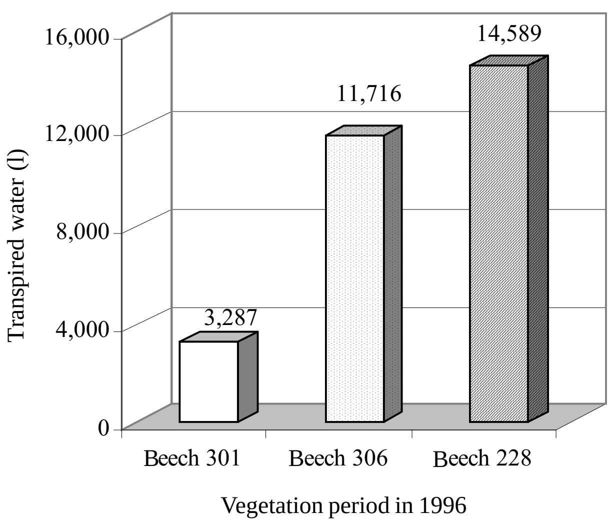


Fig. 7. Amounts of water transpired by sample trees during the growing season 1996

Table 3. Statistical characteristics of model verification for a co-dominant sample tree

Sample tree No. 228	Mean (l/h)	Maximum (l/h)	Minimum (l/h)	Standard deviation (l/h)	Coefficient of variation (%)
Sap flow	6.57	51.74	0.00	10.13	1.54
Modelling	8.45	35.40	0.00	9.71	1.15

transpiration intensity represented on average 10–30% of the transpiration intensity of co-dominant individuals). LADEFOGED (1963) explained this fact by the tree social status in the forest. According to his research dominant trees had higher transpiration per 1 m^2 of their leaf area than sub-dominant and co-dominant ones. He determined a dependence of transpiration intensity on the tree crown position for several tree species. Transpiration intensity was highest for dominant trees with wide crowns growing in the main layer of the stand. Whereas trees of the same height but with narrow and pyramidal crowns, whose main leaf biomass grew at lower layers, had considerably lower transpiration intensity. According to BAUMGARTNER (1956) the tree height has a decisive influence on transpiration intensity because potential evaporation, due to unlimited radiation and fastest air current, is highest nearly above the forest stand. Transpiration in the middle parts of the crown is lower considering that the air current is slower (MONTEITH, UNSWORTH 1990). KRAMER and KOZLOWSKI (1979) use the term “oasis” effect that influences trees that overgrow the stand level. The transpiration intensity of exposed trees is increased because the advection, that means horizontal air current, supplies trees with energy from their surroundings that conditions the evaporation. The research carried out by KÖSTNER et al. (1992) in the forest stand of *Nothofagus* showed that three trees overgrowing the main stand level transpired 50% of totally transpired water from the research plot consisting of 14 trees. Similarly, HAIMANN (1995) found out in the spruce forest stand in Harz, Germany, that the spruce trees with smaller and overshadowed crowns had lower values of transpiration flow.

Mathematical modelling of transpiration rate for one sample tree

To verify the described model, the results of model simulations were compared with the respective measurements of sap flow carried out in June and July 1996 at the locality Poľana – Hukavský grúň. The relationships between the measured sap flows and calculated transpiration rates for co-dominant sample tree No. 228 and subdominant sample tree No. 301 are presented in Figs. 8 and 9.

Sap flow and transpiration rate are in a close statistical correlation. It is proved by the correlation coefficients $r_{228} = 0.91$ and $r_{301} = 0.92$ for sample trees No. 228 and No. 301, respectively. The absolute coefficients in the regression lines are low and the slope of the regression lines approaches unity. Hence, the systematic errors of the model can be considered as negligible. The differences between measured and modelled values can be represented by the standard deviation 4.2 l/h in the case of the co-dominant tree and 0.93 l/h for the subdominant sample tree, which corresponds to probable errors 2.8 l/h and 0.6 l/h, respectively. As can be seen from Table 3 containing other statistical characteristics of compared entities, the characteristics of variability are also similar in both series of measured and calculated values with the exception of

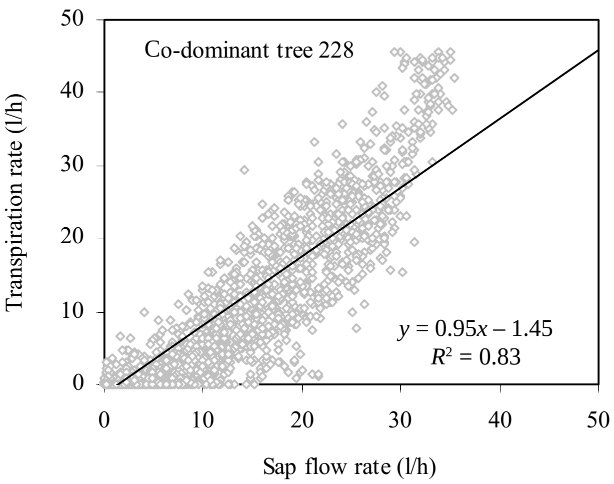


Fig. 8. The relationship between the measured sap flows and simulated transpiration rates for a co-dominant sample tree

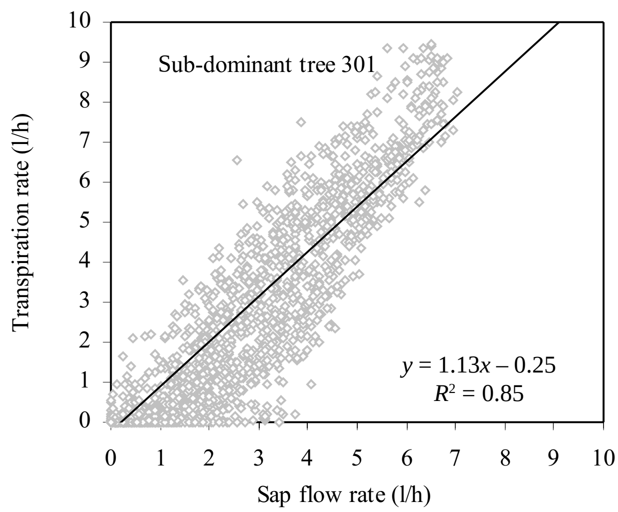


Fig. 9. The relationship between the measured sap flows and simulated transpiration rates for a sub-dominant sample tree

Table 4. Statistical characteristics of model verification for a subdominant sample tree

Sample tree No. 301	Mean (l/h)	Maximum (l/h)	Minimum (l/h)	Standard deviation (l/h)	Coefficient of variation (%)
Sap flow	1.51	19.56	0.00	2.32	1.54
Modelling	1.56	7.04	0.00	1.91	1.22

maximum values where the model tends to smooth the time variability of transpiration rates.

The results of sap flow measurements carried out on co-dominant sample tree No. 228 and subdominant sample tree No. 301 were used in the process of model verification. Sap flow measurements on second co-dominant sample tree No. 306 are also available. However, this beech tree was partially overshadowed by a higher fir tree situated beside the beech (STŘELCOVÁ, MINĎÁŠ 1998). It is practically impossible to quantify exactly such a complicated radiation regime and for this reason the sap flow measurements carried out on sample tree No. 306 cannot be used for model verification.

Errors of the model are caused first of all by simplifying assumptions used in the construction of the model. The model does not account for the dynamics of water storage in trees and for internal processes in plants that influence the behaviour of stomata and it can also be a factor of model errors. Nevertheless, the results of the statistical analysis of relationships between the measured values of sap flow and results of model simulations allow to conclude that the designed mathematical model can be applied to simulate the transpiration rates for individual sample trees with different social position in the stand.

Such model simulations were performed with the aim to analyse the influence of changes in the height of the tree and its horizontal crown projection on the daily dynamics of tree transpiration. It was a warm sunny day with relatively high evaporative demands of the air. The soil with moisture content in the root zone 30.9 percent by volume was sufficiently wet, so that the soil moisture was not a factor reducing transpiration. The daily courses of basic meteorological elements are presented in Fig. 10. This set of meteorological data remained unchanged in all model simulations. However, the height of the tree changed gradually from 31 m to 37 m. Simultaneously the horizontal crown projection was adjusted in the range between 10 m^2 and 70 m^2 approximately proportionally to the height of the tree. Hence, the transpiration rates on the model output correspond to the chosen combinations of tree height and horizontal crown projection (Fig. 11). As can be seen from the results of model simulations, the transpiration of beech tree is very sensitive to the differences in tree height. For example, the daily sum of transpiration in a model tree 34 m in height and with horizontal crown projection 40 m^2 does not exceed 50% of the daily sum of water transpired by a co-dominant tree 37 m in height. In a model tree 32 m in height and with horizontal crown projection 20 m^2 this ratio decreased to 22%.

The course of transpiration curves in Fig. 11 is significantly smoother for lower trees, consequently, the influence of meteorological factors on transpiration is more intensive in co-dominant trees.

CONCLUSIONS

Taking into account the tree social status in the forest stand we can state that the transpiration of subdominant individuals represents 10–30% of the transpiration values of dominant trees. In spite of the diametrically differ-

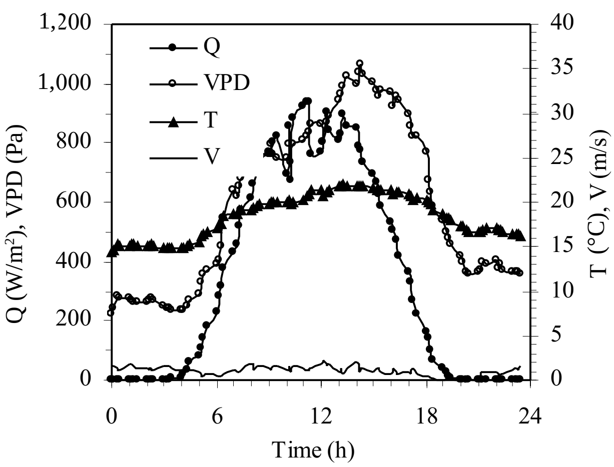


Fig. 10. Daily courses of main meteorological variables on the day 6. 1. 1996

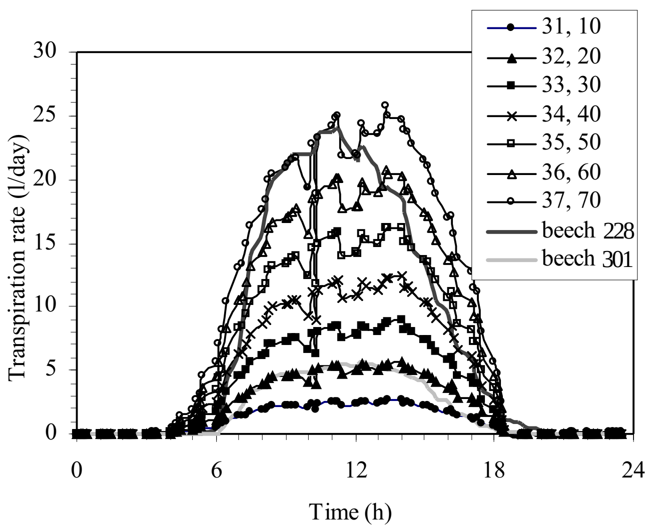


Fig. 11. Transpiration rates for the chosen values of tree height and crown projection (the figure see the legend – m, m^2)

ent daily transpiration totals of beech trees with different social status in the forest stand we can state that the curves representing the seasonal course of transpiration intensity in these trees have an almost identical shape, except for the spring foliation. This is also confirmed by the values of correlation coefficients of daily transpiration totals of individual trees (r_{xy} = 0.93–0.99, at the level of significance $\alpha = 0.01$, number of measurements 184). The value of daily transpiration totals of individual trees is proportional to their leaf area and their irradiation intensity. As the leaves of subdominant individuals get direct radiation only exceptionally, or none, the water consumption for cooling, especially on clear sunny days, is several times lower than that of co-dominant and dominant trees whose crowns are exposed to direct radiation during the day.

The mathematical model of transpiration designed for one tree seems to be a suitable tool for the quantitative analysis of transpiration rates of trees with different social position in the stand. The results of model simulations allowed to better understand the decisive role of tree height and horizontal crown projection in the process of water transfer from the tree to the atmosphere. The results also showed that the transpiration rates of co-dominant trees responded more sensitively to changes in meteorological factors in comparison with sub-dominant trees. In spite of some limitations of model applications, this approach offers a good opportunity to quantify the relationships between the water regime of one tree in the stand and environmental factors.

Seasonal dynamics of tree transpiration is influenced to a great extent by climatic characteristics of the locality and by the weather course during the growing season. At the beginning and at the end of the growing season it has a dominant influence upon the beech foliage.

The above-mentioned facts and factors influencing the amount of water transpired by individual trees should be respected by practical silvicultural measures taken in forest stands as it is possible to influence the amount of solar radiation incident upon the crowns by thinning and thus the microclimatic conditions in the crown layer.

Acknowledgements

We thank JIŘÍ KUČERA for methodical assistance in using THB method for measuring sap flow and VILIAM PICHLER for assistance during measurements of soil water potential. The study was supported by grants from the Scientific Grant Agency VEGA, Research projects No. 1/9265/02, No. 1/9207/02 and No. 2/7064/20.

References

BAUMGARTNER A., 1956. Untersuchungen über den Wärme- und Wasserhaushalt eines jungen Waldes. Ber. Dtsch. Wetterdienstes, *5*: 28.

BICHELE Z., MOLDAU H., ROSS J., 1980. Matematičeskoje modelirovanije transpiracii i fotosinteza rastenij pri nedostatke počvennoj vlagi. Leningrad, Gidrometeoizdat: 222.

CIENCIALA E., ECKERSTEN H., LINDROTH A., HÄLLGREN J.E., 1994. Simulated and measured water uptake by *Picea abies* under non-limiting soil water conditions. Agric. For. Meteorol., *71*: 147–164.

CHOUDHURY B.J., MONTEITH J.L., 1988. A four-layer model for the heat budget of homogeneous land surfaces. J. R. Meteorol. Soc., *114*: 373–398.

ČERMÁK J., PALÁT M., PENKA M., 1976. Transpiration flow rate in a full-grown tree of *Prunus avium* L. Estimated by the method of heat balance in connection with some meteorological factors. Biol. Plant., *18*: 111–118.

ČERMÁK J., KUČERA J., 1981. The compensation of natural temperature gradient in the measuring point during the sap flow rate determination in trees. Biol. Plant., *23*: 469–471.

ČERMÁK J., ULEHLA J., KUČERA J., PENKA M., 1982. Sap flow rate and transpiration determination in full-grown oak (*Quercus robur* L.) in floodplain forest exposed to seasonal floods, as related to potential evapotranspiration and tree dimensions. Biol. Plant., *24*: 446–460.

ČERMÁK J., KUČERA J., 1987. Transpiration of Mature Stands of Spruce (*Picea abies* (L.) Karst.) as Estimated by the Tree – Trunk Heat – Balance Method. In: Forest Hydrology and Watershed Management. Proc. of the Vancouver Symposium, August 1987. IAHS, Publ. No. 167: 311–317.

ČERMÁK J., MATYSSEK R., KUČERA J., 1993. Příčiny odumírání vyspělých buků na těžkých půdách po náhlém proředění porostu. Lesnictví-Forestry, *39*: 175–183.

HEIMANN J., 1995. Xylemsaftfluss 40-jähriger Fichten (*Picea abies* [L.] Karst.) im Wassereinzugsgebiet der Langen Bramke, Harz. [Dissertation.] Göttingen, Georg-August Universität: 148.

IRITZ Z., LINDROTH A., HEIKINHEIMO M, GRELLE A., KELLNER E., 1999. Test of a modified Shuttlerworth – Wallce estimate of boreal forest evaporation. Agric. For. Meteorol., *98–99*: 605–619.

KRAMER P., KOZLOWSKI T.T., 1979. The Importance of Water and the Process of Transpiration. In: Physiology of Woody Plants. New York, San Francisco, London, Academic Press: 402–444.

KÖSTNER B.M.M., SCHULZE E.D., KELLIHER F.M., HOLLINGER D.Y., BYERS J.N., HUNT J.E., MCSEVENY T.M., MESERTH R., WEIR P.L., 1992. Transpiration and canopy conductance in a pristine broad-leaved forest of Nothofagus: An analysis of xylem sap flow and eddy correlation measurements. Oecologia, *91*: 350–359.

KUČERA J., ČERMÁK J., PENKA M., 1977. Improved thermal method of continual recording the transpiration flow rate dynamics. Biol. Plant., *19*: 413–420.

MATEJKA F., HUZULÁK J., 1995. Analysis of the relationships between winterwheat leaf water potential and atmospheric factors. Biologia, *50*: 105–114.

LADEFOGED K., 1963. Transpiration of forest trees in closed stands. Physiol. Plant., *16*: 378–414.

MC GEE C.E., 1986. Budbreak for twenty-three upland hardwoods compared under forest canopies and in recent clearcuts. Forest Sci., *32*: 924–935.

MONTEITH J.L., 1973. Principles of Environmental Physics. London, Edward Arnold: 241.

MONTEITH J.L., UNSWORTH M.H., 1990. Principles of Environmental Physics. London, New York, Melbourne, Auckland, Arnold: 291.

SHUTTLERWORTH W.J., WALLACE J.S., 1985. Evaporation from sparse crops – an energy combination theory. Q. J. R. Meteorol. Soc., *111*: 839–855.

STŘELCOVÁ K., MINĎÁŠ J., 1998. Sezónna dynamika transpiračného prúdu buka lesného (*Fagus sylvatica* L.) v stredohorskej oblasti Poľany. Lesnícky časopis – Forestry Journal, *44*: 245–260.

ŠTEFANČÍK I., 1995. Fenológia v lesníctve. 1. Začiatok vegetačnej činnosti. Lesnícky časopis – Forestry Journal, *41*: 193–198.

TORULA T., HEIKINHEIMO M., 1999. Modelling evapotranspiration from a barley field in the growing season. Agric. For. Meteorol., *91*: 2237–2500.

TÜRC L., 1961. Évaluation des besoins en eau d'irrigation evapotranspiration potentielle. Ann. Agron., *12*: 13–49.

WALLACE J.S., ROBERTS J.M., SIVAKUMAR S.V.K., 1990. The estimation of transpiration from sparse dryland millet using conductance and vegetation area indices. Agric. For. Meteorol., *51*: 35–49.

Received 23 May 2001

Stanovenie transpirácie jedincov buka s rôznym výškovým postavením v lesnom poraste

K. STŘELCOVÁ [1], F. MATEJKA [2], J. MINĎÁŠ [3]

[1]*Technická univerzita, Lesnícka fakulta, Zvolen, Slovenská republika*

[2]*Geofyzikálny ústav SAV, Bratislava, Slovenská republika*

[3]*Lesnícky výskumný ústav, Zvolen, Slovenská republika*

ABSTRAKT: V práci sú analyzované výsledky kontinuálnych meraní transpiračného prúdu metódou tepelnej bilancie na dvoch úrovňových a jednom podúrovňovom vzorníku buka v dospelom zmiešanom jedľovo-smrekovo-bukovom poraste v lokalite Poľana – Hukavský grúň (φ= 48°39′, λ = 19°29′, H = 850 m n. m.) v Biosférickej rezervácii UNESCO. Pre kvantitatívnu analýzu denných priebehov transpiračného prúdu bol navrhnutý matematický model dennej dynamiky transpirácie fungujúci na úrovni jedného stromu, ktorý umožnil zohľadniť vplyv výškového postavenia stromu v poraste na intenzitu transpiračného prúdu jednotlivých vzorníkov a vyjadriť závislosť intenzity transpiračného prúdu od výšky stromu a plochy jeho korunovej projekcie.

Kľúčové slová: *Fagus sylvatica* (L.); metóda tepelnej bilancie; matematický model SVAT; mikrometeorologické podmienky; dendrometrické charakteristiky stromov

Kľúčom k pochopeniu funkčných vzťahov medzi meniacim sa prostredím, najmä vplyvom nárastu koncentrácie CO_2 v ovzduší a fyziologickými procesmi v drevinách, je kvantifikácia jednotlivých zložiek týchto procesov pomocou vhodných metód. Ďalším krokom je parametrizácia a modelovanie procesov v zmenených podmienkach.

Meranie a modelovanie spotreby vody drevinami v zmiešaných vertikálne diferencovaných porastoch je komplikovanejšie než v homogénnych lesných porastoch. Množstvo transpirovanej vody jednotlivými stromami je ovplyvnené najmä plochou asimilačných orgánov a ich ožiarením. Pre meranie intenzity transpirácie na úrovni celých stromov je vhodné použiť metódu tepelnej bilancie (THB), ktorá umožňuje objemové meranie prietoku vody v kmeňoch drevín (ČERMÁK et al. 1976, 1982; KUČERA et al. 1977; CIENCIALA et al. 1994). V posledných rokoch bolo venované mnoho úsilia vývoju metód stanovenia transpirácie. Väčšina súčasných matematických modelov vychádza z úrovne celého lesného porastu. Pokusy simulovať transpiráciu jednotlivých stromov sú veľmi zriedkavé (BICHELE et al. 1980). V tejto súvislosti sa dostáva do popredia potreba lepšieho pochopenia vzájomných vzťahov medzi vodným režimom jednotlivých drevín a podmienkami prostredia.

Cieľom práce je kvantifikovať množstvo transpirovanej vody bukmi s rôznym výškovým postavením v zmiešanom vertikálne diferencovanom lesnom poraste a navrhnúť matematický model dennej dynamiky transpirácie na úrovni jedného stromu, umožňujúci zohľadniť vplyv výškového postavenia stromu v poraste na intenzitu transpirácie.

Výskum transpirácie sme uskutočnili v roku 1996 na lokalite Poľana – Hukavský grúň, ktorá sa nachádza asi

10 km severne od mesta Hriňová (48°39´ SZŠ, 19°29´ VZD) v nadmorskej výške okolo 850 m na pravidelnom severovýchodne orientovanom svahu so sklonom 5–10°. Porast patrí do 5. lesného vegetačného stupňa, živného radu B, skupiny lesných typov *Abieto-Fagetum*, lesný typ nitrofilná jedľová bučina. Zastúpenie drevín na výskumnej ploche je nasledovné: buk lesný 70 %, smrek obyčajný 20 %, jedľa biela 3,5 %, ojedinele jaseň štíhly, javor horský a topoľ osikový. Transpiračný prúd bol meraný na troch modelových vzorníkoch buka, ktorých charakteristika je uvedená v tab. 1.

Na meranie transpiračného prúdu sme použili metódu tepelnej bilancie (THB) s vnútorným (priamym) elektrickým ohrevom vodivých pletív pomocou piatich elektród, zarazených do vodivej časti xylému (ČERMÁK et al. 1973, 1982; KUČERA et al. 1977). Teplotu, vlhkosť vzduchu a slnečnú radiáciu sme merali na meteorologickej veži umiestnenej v sledovanom poraste. Meranie prebiehalo kontinuálne, v 30-sekundovom intervale s automatizovaným režimom ukladania dát spriemerovaných za 10 minút na meraciu ústredňu DELTA-T. V práci sme použili nasledovné meracie hladiny nad povrchom pôdy: teplota a vlhkosť vzduchu 34 m, globálna radiácia 37 m, teplota pôdy v hĺbke 10 cm, úhrn zrážok 37 m. Potenciál pôdnej vody sme merali v hĺbkach 15, 30, 50 a 70 cm v týždenných intervaloch za pomoci tenziometrov s keramickými hlavami vo vzdialenosti 0,5 m a 1 m nadol a nahor od kmeňa skúmaných stromov.

Z hľadiska postavenia stromov v poraste môžeme konštatovať, že transpirácia podúrovňových jedincov je v porovnaní s úrovňovými stromami 10–30%. Napriek diametrálne odlišným denným transpiračným úhrnom bukov s rôznym výškovým postavením v poraste môžeme konštatovať, že tvar krivky sezónneho priebehu intenzity transpirácie týchto stromov je takmer identický s výnimkou jarného obdobia olisťovania. Potvrdzujú to aj hodnoty korelačných koeficientov medzi hodnotami denných úhrnov pre jednotlivé stromy (r_{xy} = 0,93–0,99, na hladine významnosti α = 0,01, pri počte meraní 184). Hodnota denných úhrnov jednotlivých stromov je úmerná ploche ich asimilačných orgánov a stupňu ich ožiarenia. Keďže na asimilačné orgány podúrovňových jedincov dopadá priame žiarenie len výnimočne alebo vôbec, spotreba vody na chladenie je najmä počas jasných slnečných dní pri týchto jedincoch niekoľkonásobne nižšia, než je tomu pri úrovňových a nadúrovňových stromoch s korunou vystavenou priamemu žiareniu počas dňa. Maximálne denné úhrny transpirovanej vody sme zaznamenali počas teplých dní s jasným a slnečným počasím v období mesiacov jún, júl a august. Úrovňové buky transpirovali maximálne 370,7 l ($d_{1,3}$ = 49,8 cm) a 236,2 l ($d_{1,3}$ = 44,1 cm) a podúrovňový strom 83,2 l ($d_{1,3}$ = 25,5 cm) vody za deň. Priemerná denná intenzita transpirácie za celé vegetačné obdobie roku 1996 máj až október (184 dní) bola pre podúrovňový buk 18 l a pre dva úrovňové buky 64 l a 79 l. Sezónna dynamika transpirácie drevín je vo veľkej miere ovplyvnená klimatickými charakteristikami lokality a konkrétnym priebehom počasia vo vegetačnom období.

Matematický model dennej dynamiky transpirácie fungujúci na úrovni jedného stromu, navrhnutý pre kvantitatívnu analýzu denných priebehov intenzity transpiračného prúdu, umožnil zohľadniť vplyv sociálneho postavenia stromu v poraste na intenzitu transpiračného prúdu jednotlivých vzorníkov a vyjadriť závislosť intenzity transpiračného prúdu od výšky stromu a plochy jeho korunovej projekcie. Z výsledkov experimentálnej verifikácie navrhnutého modelu vyplynulo, že tento model realisticky popisuje denné chody transpiračného prúdu pre každý z troch modelových vzorníkov a možno ho teda využiť na podrobnejšiu kvantitatívnu analýzu dennej dynamiky transpiračného prúdu jednotlivých stromov s rôznym sociálnym postavením v poraste. Vykonané simulačné výpočty ukázali, že za jasných dní reagujú úrovňové stromy zmenami transpiračného prúdu oveľa citlivejšie na zmeny hodnôt globálneho žiarenia, rýchlosti vetra, teploty a vlhkosti vzduchu nad porastom než podúrovňové jedince. Naproti tomu sa v prípade zamračených dní stáva limitujúcim faktorom pre transpiračný prúd podúrovňových stromov globálne žiarenie a ich reakcia na zmeny tohto meteorologického prvku je oveľa výraznejšia v porovnaní s nadúrovňovými stromami. Získané výsledky teda svedčia o tom, že sociálne postavenie stromov v poraste môže určovať aj ich reakciu na zmeny parametrov okolitého prostredia.

Uvedené skutočnosti a faktory ovplyvňujúce množstvo transpirovanej vody jednotlivými stromami by sa mali rešpektovať pri praktických pestovných zásahoch v porastoch, kedy je možné prebierkami ovplyvňovať množstvo slnečného žiarenia dopadajúceho na koruny jednotlivých stromov a tým aj mikroklimatické podmienky v korunovom priestore.

Corresponding author:

Ing. KATARÍNA STŘELCOVÁ, PhD., Technická univerzita, Lesnícka fakulta, Katedra prírodného prostredia, T. G. Masaryka 24, 960 53 Zvolen, Slovenská republika
tel.: + 421 45 520 62 18, fax: + 421 45 533 26 54, e-mail: strelcov@vsld.tuzvo.sk