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Modelling transpiration and soil water potential in a spruce primeval forest during dry period

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Abstract A three-layer one-dimensional steady-state Soil-Vegetation-Atmosphere Transfer model was developed, tested and designed for simulations of the transpiration with a time step of one hour. Seasonal changes in the soil water potential were simulated with the daily step during the whole growing period balancing changes in the soil water content in the root zone with the interception, precipitations and evapotranspiration. Model input data were obtained in a spruce virgin forest growing in the Biosphere Reserve Poľana (19° 28', 48° 37', 1347 m a. s. l.). Results of model simulations were compared with the stand transpiration scaled up from sap flow measurements and with the soil water content measurements. Compared data sets were closely related and the standard deviation of differences between measured and simulated values was comparable with experimental data error. Consequently, the designed mathematical model can be used as a suitable tool for simulations of stand transpiration and seasonal changes in the soil water content. Results of model simulations indicated the great importance of the root system development for the plant and soil water regime when the rise of the root-shoot ratio had as a result an increase in the transpiration rate and faster drying of the soil.

Key words: *transpiration, soil water content, spruce primeval forest, mathematical modeling*

1. Introduction

Transpiration covers approximately half of annual precipitation total under European conditions (Denmead and Shaw, 1962). The energetic equivalent of this amount of transpirated water represents an important contribution to the energy balance of Earth's surface. In response to water stress, plants regulate their transpiration by decreasing their stomatal conductance *(Sperry, 2000).* This physiological control of transpiration plays an important role in processes of mass and energy exchange between vegetation and the atmosphere. This stomatal feedback is important for atmospheric, hydrological and environmental studies (Calvet, 2000).

The transpiration depends on soil water content in the root zone *(Denmead and Shaw, 1962).* Hence, the soil drought may be a factor significantly affecting the transpiration rate and consequently the partitioning of energy in the energy budget of evaporating surfaces. Since this partitioning of energy determines the properties of the planetary boundary layer *(Wilson and Baldocchi, 2000)*, the transpiration reduced by the water stress may have a significant influence on the climate *(Shukla and Mintz, 1982).* For these reasons, a research on transpiration has become important especially in the last decades when the frequency of extremal weather rises *(Karl, et al., 1995).*

The transpiration has been frequently a subject of the theoretical and experimental research. Many authors of scientific publications analysed the transpiration using results of the sap flow measurements. Based on this methodical approach, the daily and seasonal variability of transpiration was analysed for various forest stands under non limiting soil water conditions and as affected by water stress *(Cienciala et al., 1994; 1997; Čermák et al., 1976, 1982; Kučera et al., 1977; Morikawa et al., 1986; Granier, 1994).* Al Kaisi et al., *(1989)* described and quantitatively expressed the relationship between the leaf area index and transpiration. Jara et al. *(1998)* studied the transpiration as a component of the evapotranspiration.

The estimate of transpiration from results of the sap flow measurements requires a scaling procedure what can be complicated sometimes. Further, the differences between sap flow and transpiration can be neglected over periods longer than one day but they are important over shorter periods or if diurnal courses are studied *(Cienciala et al., 1992).* Therefore, mathematical modelling of transpiration rates has become an alternative approach for determination of transpiration rates. Within the recent years, considerable efforts have been made to improve methods for modelling the transpiration. The recent mathematical models of the water exchange between vegetation and the atmosphere take into account the existence of two sources of water which are the area of leaves and the soil surface *(Choudhury and Monteith, 1988, Iritz et al., 1999, Shuttlewort and Wallace, 1985, Torula and Heikinheimo, 1999, Wallace et al., 1990).*

In spite of many results obtained within the framework of the research on transpiration, the impacts of water stress on the transpiration of field crops have been not examined satisfactorily and the further investigation on this topic is needed. Therefore, the aim of this study is to quantify the response of transpiration from a spruce primeval forest suffering the water stress to changes in soil moisture under high evaporative demands of the atmosphere.

2. Material and methods

The data used in this study were obtained during the period May - September 2003 at a spruce primeval forest in the Biosphere Reserve Poľana (19° 28', 48° 37', 1347 m a. s. l.). This locality is situated in a humid, cool temperate region with abundant precipitation According to the climatic classification this locality is a temperature cool region, with mean annual air temperature 3.8°C, and the mean annual precipitation total 900-1100 mm.

The forest is 190 years old and its dominant fraction was presented by the Norway spruce (*Picea abies* [L.] Karst). During the analyzed period the experimental forest had the mean height of 25 m and the stand density was changeable due to the primeval forest structure and various age stages.

Measurements of the global radiation, net radiation, air temperature and humidity were made above the spruce primeval forest. All sensors were sampled at intervals of 10 seconds and 10 minute averages were computed and stored on a data logger. The spatial and time variability of soil moisture was measured in three soil layers.

Sap flow of model beech trees was estimated on three representative trees (Tab. 1) by direct non-destructive and continuous measurements by tree-trunk heat balance method (THB) with internal heating of xylem tissues and sensing of temperature.

Tab. 1 Mensuration variables of representative trees *(Picea abies Karst.)*

Representative tree	Stem perimeter [cm]	D.B.H. [cm]	Heigh of the tree [m]
Sm1	190.5	60.8	24
Sm2	193.5	61.8	25
Sm3	202.5	64.6	21

THB method involves heating a xylem segment using 3-5 electrodes inserted in the conducting system. The arrangement of the 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 datalogger 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 opposite sides of the trunk at 2 m height, to take account of possible variation of sap flow within the stem. The measuring points were insulated using 30 mm polyurethane foam covered by 0.5 mm aluminum shield.

The stand transpiration was calculated scaling up the measured sap flows to the whole stand.

3. Model description

The model described here combines and extends the works of Bichele et al. *(1980)*, Choudhury and Monteith *(1988)*, and Wallace *(1995)*. The soil-vegetation-atmosphere continuum is divided in three layers the tops of which are:

- a reference level in the atmosphere,
- the effective sink for momentum within the canopy,
- the soil surface.

The model is conceptually based on the Darcy's law, the continuity equation and idea, that the rate of water uptake by plant from the soil equals to the rate of water loss by transpiration, so the effect of plant water retention on the transpiration can be neglected.

The soil block in the model is represented as a single material profile. Transport of water along the soil profile is not calculated, but due to evapotranspiration an average soil water content *w*, soil water potential Ψ and soil hydraulic conductivity k are changed. Let us assume that matrix potential is the main component of soil water potential. According to Darcy-Buckingham equation, the flux of water in soil q can be expressed as

$$q = -\frac{k}{\rho_w g} grad\,\Psi \tag{1}$$

where ρ_w is the water density, *g* is acceleration of gravity. The values of the soil hydraulic conductivity *k* and the soil water potential Ψ are related according to the empirical equation *(Wind, 1972)*

$$k = a(-\Psi)^{-b} \tag{2}$$

Let's suppose that the mean radius of roots is *r* and the mean distance between roots is *2d*. Let *Ψ(x)* be soil water potential at distance x from the root axis. Then the rate of water uptake *q'* by a segment of the unit root length is

$$q' = -\frac{2\pi x a\,(-\Psi(x))^{-b}}{\rho_w g}\,\frac{d(\Psi(x))}{dx} \tag{3}$$

Assuming that Ψ_R is the soil water potential at $x = r$ and Ψ_S the soil water potential at $x = d$ after integrating (3) taking into account (2) we get

$$q' \int_r^d \frac{dx}{x} = -\frac{2\pi a}{\rho_w g} \int_{\Psi_R}^{\Psi_S} (-\Psi)^{-b} \, d\Psi \qquad (4)$$

The value of q' multiplied by the total root length of one plant l_r evidently gives the total amount of water taken up by one plant in the unit time interval. Root system, however, is often characterized by its total area $\mathbf{S_R}$, rather than by its length. Using $S_R = 2\pi rlR$, transpiration of N plants growing on one square meter, ET can be expressed as

$$E_T = \frac{aNS_R}{\rho_w g r \ln(d/r)} (\Psi_S{}^b - \Psi_R{}^b) \qquad (5)$$

The root potential Ψ_R cannot be measured directly therefore it is not a suitable model input. However, it can be eliminated using van Honert's relationship expressing transpiration rate as proportional to the difference between root and leaf water potentials $\Psi_R - \Psi_L$ (Honert, 1948)

$$E_T = \frac{1}{g} \frac{\Psi_R - \Psi_L}{r_p} \qquad (6)$$

Expressing leaf water potential Ψ_R according to van den Honert's relationship and substituting it in (5) we get

$$\frac{1}{-\Psi_S} = \frac{1}{-g\,{}_pE_T - \Psi_L} + \beta E_T \qquad (7)$$

with the parameter β expressed as

$$\beta = \frac{g \ \ln(d/r)}{aNS_R} \qquad (8)$$

The transpiration rate E_T depends on the canopy resistance and on external factors according to the Penman-Monteith equation (Monteith, 1965) expressed in terms used in Fig. 1 as

$$LE_T = \frac{\Delta r_1 R_v + \rho c_p D_b}{\Delta r_1 + \gamma (r_1 + r_c)} \qquad (9)$$

where Δ is the temperature derivative of the saturated water vapour pressure, r_l is the boundary resistance and r_c means the canopy resistance. The net radiation at the canopy R_v is determined as the difference of the net radiation above the canopy R_n and the net radiation at the soil surface R_s provided that the net radiation at the soil surface is calculated according to Choudhury and Monteith *(1988)* by means of the relationship $R_s = R_n \exp(-\alpha'' LAI)$. The value of α'' = 0.7 is used in later calculations.

The leaf resistance r_L depends mainly on the radiation intercepted by leaves Q_L and on the leaf water potential Ψ_L *(Choudhury and Idso, 1985)*. This relationship was empirically determined during the four growing seasons as follows *(Matejka and Huzulák, 1995)*

$$r_L = r_0 \left(1 + \frac{n}{Q_L}\right) \exp(m\Psi_L) \qquad (10)$$

where r_0 is the minimum leaf resistance and *m, n* are empirical constants. The total conductivity g_c of the canopy with the leaf area index *L* is related to the leaf conductivity g_L in individual canopy layers according to following equation *(Choudhury and Monteith, 1988)*

$$g_c = \int_0^L g_L \, dL \qquad (11)$$

The global radiation *Q(L')* in a homogeneous canopy below a leaf area index *L'* measured from the top of the canopy can be expressed using the extinction coefficient τ as follows

$$Q(L') = Q \exp(-\tau L') \qquad (12)$$

Then the average amount of the global radiation Q_L absorbed by the leaf unit area in a given layer is

$$Q_L = -\frac{\partial Q(L')}{\partial L'} = \tau\, Q \exp(-\tau\, L') \qquad (13)$$

After the integration in (11) using the equations (10) and (13) we can finally obtain

$$r_c = r_0 \exp(-m\Psi_L) \left(LAI + \frac{1}{\tau} \ln \frac{1 + \frac{n}{Q\tau}}{1 + \frac{n}{Q\tau} \exp(-\tau LAI)} \right) \qquad (14)$$

Equations (7), (8) and (9) constitute a system of three equations which can to be solved for the three unknowns Ψ_L, r_c and E_T. In the next step of the model, the soil evaporation Es is calculated by means of the Penman-Monteith equation using appropriate parameters of the soil surface as inputs to the Eq (9). These involve net radiation at the soil surface, the vapour pressure deficit, and the aerodynamic resistance below the canopy. Values of the soil surface resistance r_s, which is now used instead of the canopy resistance in denominator of the Eq (9), were calculated as a function of the soil moisture *(Katerji and Perrier, 1985).* Finaly, the evapotranspiration rate E is determined as the sum of the transpiration E_T and soil evaporation E_s rates.

Inputs to this model involve the hydrophysical parameters of soil including the soil moisture in the root zone, biometric characteristics of the stand and meteorological elements as global radiation, net radiation, wind speed, air temperature and humidity. The outputs of the model provided the parameters of the water regime of the stand. Running the model with a step of one hour, the daily course of the stand transpiration was calculated. Summarizing the hourly sums of transpiration over the whole day, the daily totals of the transpiration was determined. Finally, the changes in the soil water content in the root zone was estimated by the procedure which balanced precipitation, interception, water uptake by roots and soil evaporation from the soil layer with depth 0 – 60 cm.

4. Model verification

To verify the model described above, the results of stand transpiration determined scaling up the sap flow measurements performed in the investigated spruce primeval forest during the period June – September 2003 were used. Meteorological conditions during the period May - October 2003 were generally characterized by higher than normal values of global radiation and air temperature through the main part of this period. As a result of low albedo, a large part of incident solar radiation was absorbed in the canopy so daily sums of the net radiation reached high values as well. During the whole growing season, the prevailing part of the available energy exceeding beyond 56% was used for the evapotranspiration. Besides, the extremely high evaporative demands of the atmosphere brought on intensive evapotranspiration what results in following rapid decrease of the soil water content. Consequently, the extremely dry period occurred during the second half of June and in the middle of July. Later, soil water content increased slowly so that soil moisture in the root zone did not exceed 32% of volume until the end of the vegetation period. Thus, the model was verified in the conditions of intensive soil and atmospheric drought.

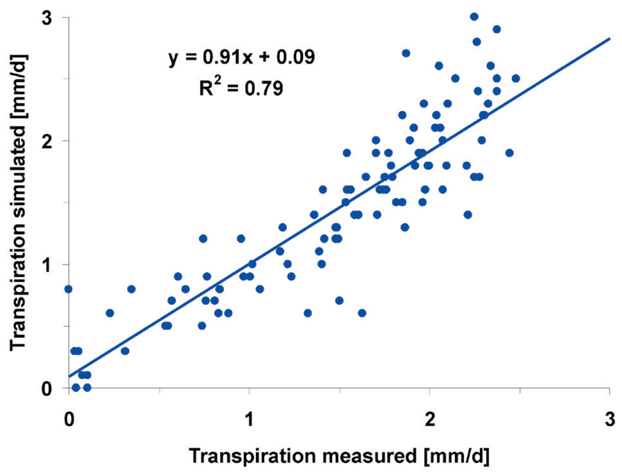

Fig. 1 Daily totals of the stand transpiration of the spruce primeval forest determined from the sap flow measurements (transpiration measured) compared with results of the model simulations (transpiration simulated).

The daily totals of the stand transpiration simulated by means of the model were compared with corresponding measured data. All days were taken into account in the comparison including the days with precipitation. The daily totals of the stand transpiration concurrently determined from the sap flow measurements by scaling up the measured values to the stand transpiration and simulated using the model are comparable in size (Fig. 1), with a reasonably close correlation coefficient (r = 0.89) statistically significant at the level α =0.05 and negligible systematic differences between the two data sets. The existing differences between compared data are normally distributed with a standard deviation of 0.49 mm/d, corresponding to the probably error of the model equaling to 0.32 mm/d.

It is obvious that the model is able to simulate daily totals of the stand transpiration quite satisfactorily. Consequently, the seasonal courses of daily totals of the stand transpiration determined by the two methods are also quite similar (Fig. 2).

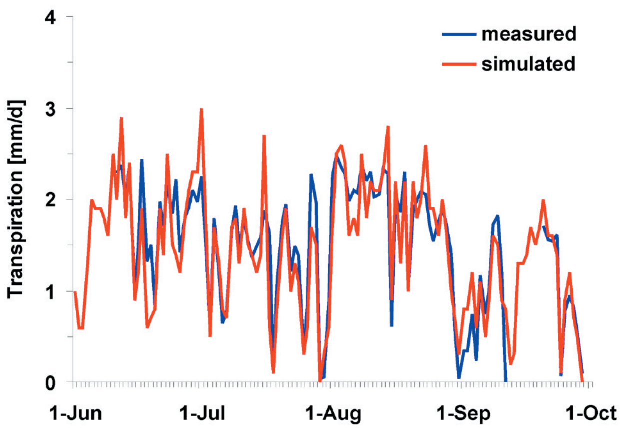

Fig. 2 Seasonal courses of the stand transpiration daily totals determined concurrently from the sap flow measurements and simulated by the model.

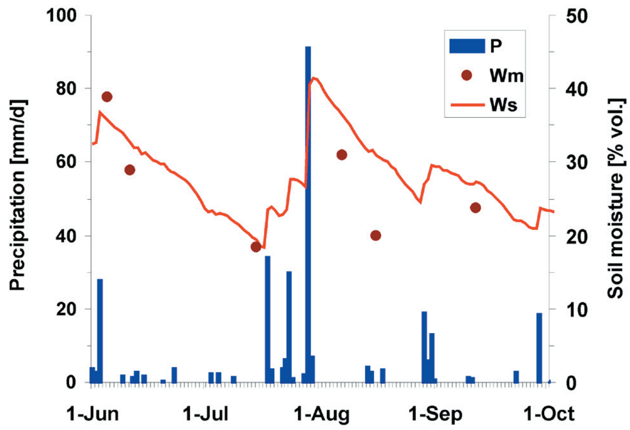

Fig. 3 Seasonal courses of the soil moisture in the soil layer 0 – 60 cm measured (Wm) and simulated (Ws) and daily totals of the precipitation (P).

Seasonal changes in the soil water content in the root zone of the investigated spruce primeval forest were simulated during the vegetation period 2003 by the soil block of the model which balanced precipitation, water uptake by roots and soil evaporation from the soil layer with depth 0 – 60 cm. Results of model simulations were compared with measurements of soil water content carried out by drying and weighing of soil samples (Fig. 3). Compared data sets are closely related and the standard deviation of differences between measured and simulated values is comparable with experimental data error.

Errors in the model simulations are caused first of all by errors in input data and by simplifying assumptions used in the construction of the model. The model also does not account for internal plant processes that influence the behavior of stomata. Despite all this, results of the model verification graphically presented in Fig. 1 and Fig. 2 allow to conclude that the designed mathematical model can be applied to simulate the daily and seasonal variability in the stand transpiration quite realistic and with acceptable accuracy. Simultaneously, the simulations of changes in the soil water content in the root zone can be performed balancing precipitation, interception, water uptake by roots and soil evaporation from the soil layer with depth 0 – 60 cm.

5. Sensitivity of the model to changes in environmental factors

The values of the stand transpiration calculated according to the model formed by equations (7), (8), (9) depend on various soil, canopy and atmospheric characteristics. From theoretical and practical points of view, it is important to know how the transpiration rates respond to changes in input data. Such sensitivity analysis allows to quantify the partial effects of environmental parameters on the transpiration rates and daily totals and to assess their relative importance.

Partial relationships of surface fluxes to different parameters of the soil-plant-atmosphere system, which at the same time are inputs of the model, will be simulated in meteorological conditions, corresponding to midday values on a bright summer day. In addition, it is assumed that LAI = 8 and the averaged soil moisture content in the root zone is 40% of the volume, what means that the soil moisture is not limiting the evapotranspiration.

As to the atmospheric factors, transpiration of the stand well supplied with soil water respond most markedly to changes in global radiation, followed by the vapour pressure deficit and air temperature. Simulation results showed that wind speed has a special effect on the transpiration, so that the transpiration can either increase or decrease with increasing the wind speed. A detailed explanation of this fact is beyond the scope of this contribution and readers with special interests in these aspects are referred to other sources [8].

With aim to evaluate the influence of changes in soil moisture on the stand transpiration of the spruce primeval forest, the relationship between transpiration and soil water content in the root zone was simulated for meteorological conditions typical for a bright summer day. To separate the influence of atmospheric factors on transpiration rates, the dependence of the ratio between actual and potential transpiration on the soil moisture was analyzed. The relationship between the ratio of the actual/potential evapotranspiration and soil moisture in the root zone is presented in Fig. 4. The effect of soil moisture on changes in transpiration rates manifests itself if its values fall below 35% of volume.

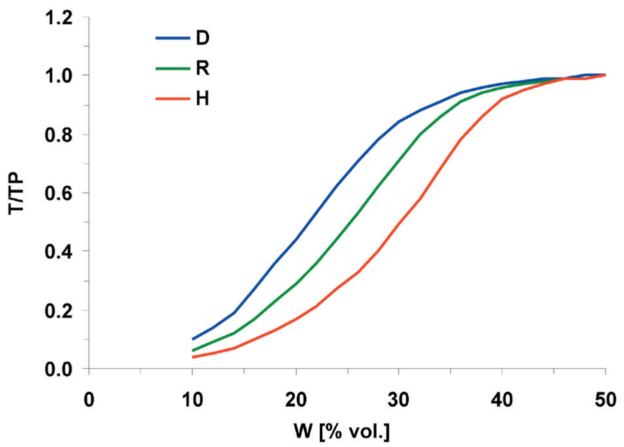

Fig. 4 The response of the relative transpiration T/TP to changes in soil moisture as simulated alternatively for the real situation (R), halved (H) and doubled (D) values of the root shot ratio.

In addition to atmospheric factors, the transpiration rates are influenced by plant characteristics, leaf area index, root system development and the response of stomata to changes in environmental factors. It followed from analysis of the governing model equations that transpiration rates are strongly affected by the root-shoot ratio S_R/S_L. With aim to quantify the influence of this parameter on the transpiration, the model simulations of transpiration rates were performed for the real situation (Fig. 4 - green line) and then repeated with root-shoot ratio reduced to one half (Fig. 4 - blue line) or increased two times (red line) in comparison with real situation (Fig. 4 - red line). Results of model simulations indicated that the transpiration rates in the hypothetical forest stand with doubled root-shoot ratio was more intensive and consequently, drying of the soil was significantly faster in comparison with the real situation. On the contrary, the forest stand with reduced root-shoot ratio economized the soil water.

6. Conclusions

The designed SVAT model describes and quantifies the homogeneous plant canopies. In this contribution, the approach used by Bichele et al. *(1980)* resulting in modeling the water regime, photosynthesis, and surface fluxes for an individual plant has been extended to the whole canopy. In comparison with the four-layer SVAT model presented by Choudhury and Monteith *(1988)*, the model developed here simplifies the basic scheme of the soil-vegetation-atmosphere system incorporating the soil resistance into considerations. This step provides a possibility to avoid complications connected with the definition and quantification of the "soil horizon above which evaporation from the soil is assumed negligible and below which the soil atmosphere is saturated with water vapour" [2]. Hence, the model described, combines and extends the previous works creating a SVAT model being quite realistic in outputs and simple enough to be used in various conditions.

The designed model can be used to simulate the surface fluxes above homogeneous forest stands in the given real situation or to predict impacts of the expected climatic change on heat and water vapour fluxes above extended surfaces covered with vegetation. Besides, the influence of changes in parameters of soil, vegetation and atmosphere on the evapotranspiration and its structure can be determined.

The described mathematical model can be used as a tool for simulations of seasonal changes in the soil water content in the root zone. Results of model simulations indicated the great importance of the root system development. It was shown that seasonal changes in the root-shoot ratio can significantly influence the soil water dynamics in the root zone during the growing period. It appeared that the seasonal reduction of the soil water content in the root zone beneath the stand with high root-shoot ratio was greater in comparison with situation below stands with lower root-shoot ratio growing under the same environmental conditions. The root system characteristics, together with the leaf area index and hydrophysical parameters of soils, affect substantially the transpiration and consequently the soil water dynamics in the root zone.

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