High Tatras forest structure changes and their influence on rain interception and some components of water balance

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A b s t r a c t : This paper contains results of quantitative analysis of the influence of intercepted water by different canopies (grass, coniferous forest) with different *LAI* (leaf area index) characteristics on water balance structure of the soil – plant - atmosphere continuum (SPAC) and especially on soil water movement in soil root zone. Site FIRE near Starý Smokovec in Vysoké Tatry (High Tatras) Slovakia, as a part of the area cleared by windthrow in 2004 was used for the analysis. Simulation model GLOBAL was used as a tool for soil water movement calculation. The summer season (April 1 – October 31, 2006) was used for the simulation. Results of water movement in SPAC demonstrate the importance of canopy changes on the structure of soil water balance and on soil water content of the root zone of soil.

Key words: soil water, interception of rain, pine forest, grass, evapotranspiration

1. Introduction

Interception of precipitation by forests is a significant component of their water balance. In average, 37% of the vegetation period precipitation totals were intercepted by canopies of coniferous forests (Picea abies) at Cingelova site (Central Slovakia); 18% of mean vegetation period precipitation total was intercepted by deciduous forest at the same locality (*Miklánek and Pekárová, 2006*). Those data are averages of 10 year results of measurements (1981–1990). It should be mentioned, that trunk flow was not measured for Picea abies forest, therefore, the intercepted amount of water will be less than the above mentioned values indicate, but not significantly. This amount of intercepted and then evaporated water does not reach the

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soil surface, and therefore cannot be utilized by plants and cannot be evaporated by soil surface.

The next important consequence of the interception is energy consumption due to evaporation of intercepted water. Latent heat of evaporation needed to evaporate the intercepted water changes the structure of the energy balance and has to be subtracted from the energy to be used for evapotranspiration. This phenomenon can lead to a decrease of canopy evapotranspiration and modifies water balance structure of the SPAC system.

Another consequence of interception is a decrease of wet leaves (pine needless) transpiration, followed by the biomass production decrease (*Hanks and Hill, 1980*). The decrease of transpiration of wet leaves was demonstrated by field measurement on agricultural canopies (*Merta et al., 2006*). This phenomenon should occur in forests too. The decrease of transpiration is probably due to flooding of stomata by intercepted water; then stomata conductivity for water vapour and carbon dioxide is strongly limited. Quantitative characteristics of such a process are not available yet.

The aim of this paper is to demonstrate the influence of different canopy properties on water and energy movement in the SPAC system. Another goal is to confirm the hypothesis about dominant influence of precipitation interception and its evaporation on energy and water balance of SPAC under changing canopy properties.

2. Method

The influence of canopy structure on rates of evapotranspiration and its components is extremely difficult to measure. Particular problem arises for forest canopies, because of trees dimension. The only possibility to solve this problem is to apply mathematical simulation models to calculate the necessary information. Among different models known from literature – SWATRE, (*Dam et al., 1997*); HYDRUS – ET, (*Šimůnek et al., 1998*) and GLOBAL (*Majerčák and Novák, 1992*), the last simulation model was chosen. The advantage of the GLOBAL simulation model dwells in the detailed description of the evapotranspiration process. Modified version of the GLOBAL model used in this study is calculating the redistribution of the energy in the canopy, due to energy consumption by evaporation of intercepted water from the canopy surface.

This model, developed at the Institute of Hydrology, Slovak Academy of Sciences in Bratislava, is based on one dimensional Richards governing equation. This model allows to calculate soil water transport during the vegetation period. Daily courses, as well as daily totals of modeled characteristics can be calculated. This model provides an original method of evapotranspiration and its components (transpiration, evapotranspiration) calculation, as well as improved methods of interception and root extraction patterns estimation. Evapotranspiration estimation method is in principle of the Penman – Monteith type, but with different method of "wind" function estimation based on the Obuchov – Monin results, which substantially improves the accuracy of the evapotranspiration estimation.

2.1. Interception of precipitation by a canopy

Forests are known as canopies with high precipitation interception (as it was mentioned above), and it is expected, that this phenomenon can strongly influence the water and energy movement in such a system. Therefore, special attention is paid to the interception process and to its quantification.

Interception of canopy precipitation determination is based on *Benetin et al. (1986)* proposal, based on *Rutter's (1967)* approach:

$$I_c = c_{in} \,.\, LAI \,.\, s_r, \tag{1}$$

$$s_r = A_p/A_s, \tag{2}$$

I_c – interception capacity, the fraction of precipitation intercepted by a unit area of canopy, mm,
LAI – leaf area index (projected), dimensionless,
c_{in} – specific interception capacity per unit of canopy projected LAI, mm,
s_r – relative canopy cover, A_p – is total area of the canopy as projected on the unit area of soil surface A_s.

Having known the LAI values, relative canopy cover can be calculated approximately

$$s_r = s_{r,\max} \frac{LAI}{LAI_{\max}}. \tag{3}$$

Specific interception capacity c_{in} can be calculated as

$$c_{in} = c_{\min} + (c_{\max} - c_{\min}) \exp[-p(u-1)] \tag{4}$$

$c_{\min}$ – specific interception capacity (minimum) corresponding to $u_{\max}$, mm,
$c_{\max}$ – specific interception capacity (maximum) corresponding to $u = 0$, mm,
u – wind velocity, $\mathrm{m\,s^{-1}}$,
p – empirical parameter (usually $p = 0,5$ is used)

Resulting precipitation reaching the soil surface Z_s is the amount of water which is infiltrating the soil and undergoing evapotranspiration, to run off or to be stored in the soil.

$$Z_s = Z - I_c + I_t, \tag{5}$$

Z – precipitation measured at meteorological station, mm,
I_t – trunk flow, mm.

2.2. Site and soil

The research site, the characteristics of which were used to model the potential evapotranspiration and its components, was chosen as one of four official sites at Vysoké Tatry (High Tatra Mountains), which undergo intensive monitoring by a couple of participating research groups. The chosen site acronym is FIRE and is located west of Starý Smokovec, north of the main road Starý Smokovec – Štrbské Pleso. This cleared area later caught

Table 1. Characteristics of the soil profile at site FIRE, used as input data of the model GLOBAL.

SOIL CHARACTERISTICS			
	0 - 5 cm	5 -15 cm	15 - 100 cm
$_{v}$	0.18	0.14	0.27
$_{fc}$	0.396	0.464	0.391
$_{s}$	0.704	0.658	0.622
K_s [cm d^{-1}]	1000	320	670
	0.26749	0.20454	0.10592
n	1.17952	1.13446	1.23345

on fire, thus its acronym. But measurements of soil characteristics showed minimum decline of the fire affected parts from non-affected parts of this site. Only a top few millimeters of organic matter was burned, thus minimally changing soil properties of studied area, shown in Table 1.

θ_v – volumetric soil water content corresponding to the wilting point, $cm^3\,cm^{-3}$,

θ_{fc} – soil water content corresponding to the “field capacity”, $cm^3\,cm^{-3}$,

θ_s – water content of the saturated soil, $cm^3\,cm^{-3}$,

K_s – hydraulic conductivity of the soil saturated with water (saturated hydraulic conductivity), $m.s^{-1}$, α, cm^{-1}

α and n – van Genuchten’s equation coefficients

2.3. Canopy characteristics

Canopy characteristics needed to calculate precipitation interception by canopy are: (projected) leaf area index (LAI), relative canopy cover s_r, $c_{\max}$ it is maximum specific interception capacity of the canopy corresponding to $u = 0$, and to $LAI = 1$;, $c_{\min}$ – specific interception capacity (minimum) corresponding to $u_{\max}$, mm. To calculate interception of the canopy grown at site FIRE, results of pine canopy interception measurement at site Jasná pod Chopkom (Central Slovakia) were used. This site was similar to site FIRE; it was located at 1170 m a.s.l., pine trunks were of average diameter 18 cm, relative cover was 0,537 (*Majerčáková, 1983*). Specific interception capacity was calculated according to the following equation:

$$i_c = I_c/LAI \,.\, s_r \tag{6}$$

Daily totals of intercepted rain were estimated as the difference between daily precipitation total at meteorological station (glade), and daily precipitation total in the forest, plus trunk flow. Specific interception capacity $c_{\max}$ was estimated using an average value of the highest daily interception capacities I_c during vegetation periods of years 1981 and 1982. Pine forest highest values of interception capacity were in the range $4.8 \leq I_c \leq 5.5$ mm; they are assumed to represent interception capacity under optimum conditions (minimum wind velocity, dry leaves surface, low rain intensity). The average value was $I_c = 5.0$ mm.

The next important characteristic, needed to calculate specific interception capacity is LAI. In previously cited work performed at Jasná pod Chopkom (*Majerčáková, 1983*) it was not measured, therefore data from literature obtained under similar conditions should be used. In numerous papers devoted to this topic it is not easy to find data for Pine forest grown at height 1200 m a.s.l. with appropriate age and density. It is interesting, that LAI of pine forests are concentrated in wide range of values; it is nearly impossible to find out relationship between LAI and age of the trees. Detailed data about forests are usually lacking. *Pokorný and Marek, (2000)* estimated $LAI = 8.6$ for pine forest 20 years old, *Bolstad and Gower (1990)* estimated $LAI = 10$ for pine forest at Wisconsin, for 30 years old pine forest of density 2600 trees per hectar *Hurtalová et al. (2000)* presented $5.6 \leq LAI \leq 7.9$, *Scurlock et al. (2001)* demonstrated LAI of canopies from all over the world taken from literature published in years 1932–2000; for pine forest their data are in the range $2.4 \leq LAI \leq 12$, majority of LAI are below 3.8, *Bičárová and Fleischer (2006)* present for pine forest close to forests in Vysoké Tatry $LAI = 7.0$ estimated by *Guenther et al. (1993).* For our calculation, $LAI = 7.0$ was chosen. All the above mentioned values are the so called "projected LAI", it means they are projected to the horizontal surface. Measured values of interception capacity (*Majerčáková, 1983*) were estimated for a unit area of "projected" surface, $s_r = 1$.

Then, using Eq. (6), maximum specific interception capacity of pine forest was evaluated as $c_{\max} = 0.7$.

2.4. Meteorological characteristics

Meteorological characteristics needed as inputs to the simulation model GLOBAL are results of measurements at meteorological station Tatranská Lomnica, run by the Institute of Geophysics, Slovak Academy of Sciences. For the season 2006 daily precipitation total, average daily air temperature, average daily air humidity, average daily wind velocity and daily sunshine duration were used. The distance of this MS from the site FIRE is about 10 kilometers, so it was used as characteristic for the FIRE site. The time interval of 220 consecutive days without snow interception was modeled (April 1 – October 31, 2006).

3. Results and discussion

Results of water movement simulation of the SPAC system are presented in Figs. 1–4 and in Table 2. To illustrate the influence of different canopy properties on seasonal courses of soil water content of the upper layer of soil, water and energy movement was simulated at site FIRE during summer season of 2006 (April 1 – October 31).

Fig. 1 presents cumulative values of daily potential evapotranspiration of coniferous forest (Picea abies) with different (but hypothetical) LAI values. Such changes can appear due to windthrows, similar to that, which occurred in Vysoké Tatry in 2004. Potential evapotranspiration in Fig. 1 does not involve evaporation of intercepted water. Results presented (curves 2–4) were calculated with modified energy balance of the SPAC system. The energy used for evaporation of intercepted water was subtracted from the total amount of energy used for evapotranspiration; and it led to significant decrease of available energy for latent heat of evaporation and subsequently

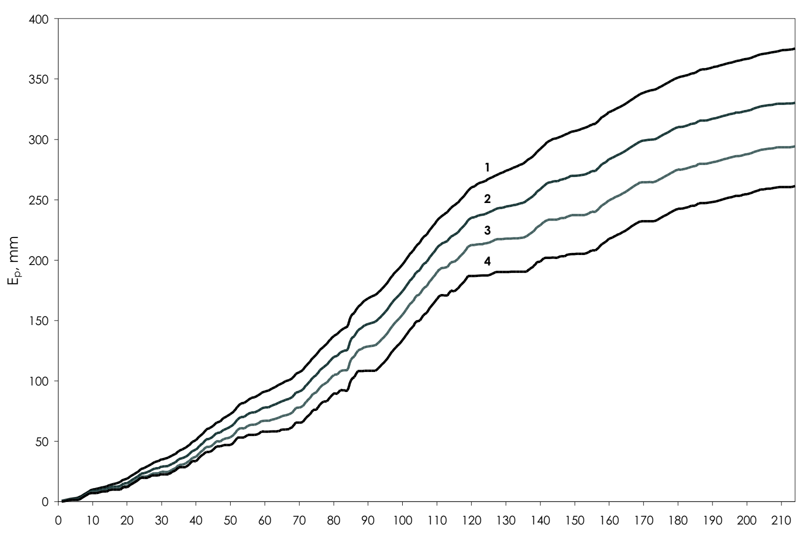

Fig. 1. Cumulative potential evapotranspiration of coniferous forest (Picea abies) for different (hypothetical) $LAI = 1.5$; 3 a 6 (curves 2,3,4) and forest potential evapotranspiration without interception, i.e. precipitation below trees is the same as it is on free surface (curve 1). Vysoké Tatry (Slovakia), site FIRE, April 1 – October 31, 2006.

Table 2. Seasonal totals of potential evapotranspiration E_p and its components, potential transpiration E_{tp}, potential evaporation E_{ep}, evaporation of intercepted water E_i, and seasonal total of precipitation P, calculated for different canopies at site FIRE (Vysoké Tatry) for season of 220 days (April 1 - October 31, 2006).

SURFACE		PINE FOREST			GRASS	BARE S.
LAI		1.5	3	6	VARIABLE	0
E_p	(mm)	325	289	256	342	475
E_{tp}		162	217	240	189	0
E_{ep}		162	72	15		475
E_i		83	166	333	136	0
E_p+E_i		408	455	589	479	475
E_{tp} / E_p		0.50	0.75	0.94	0.55	0.00
E_{ep} / E_p		0.50	0.25	0.06	0.45	1.00
E_i / P		0.17	0.24	0.67	0.28	

to the decrease of canopy evapotranspiration. This decrease is significant.

As it was mentioned before, under similar conditions (coniferous forest) the average vegetation period interception was about 37% of the mean vegetation period precipitation total, with maximum higher than 41%; the range of seasonal interception totals expressed as its ratio to seasonal precipitation was 0.30–0.41 (*Miklánek and Pekárová, 2006*). So, the calculated difference between the forest seasonal potential evapotranspiration total with $LAI = 6$ and that without interception involvement was found as a 122 mm water layer, which is really a significant amount modifying the water balance structure of the SPAC system (Fig. 1).

For comparison, seasonal course of potential evapotranspiration total of grass and the components of its structure for conditions of FIRE site are shown in Fig. 2.

Results of canopy properties change on soil water content are in Fig. 3 and 4. It can be seen different seasonal courses of soil water content are influenced by different LAI values; it is a result of different undercanopy precipitation totals and of decreased amount of energy for evapotranspiration due to its consumption by evaporation of intercepted water.

Table 2 contains seasonal totals of potential evapotranspiration and its components, intercepted rain water (evaporating) and the ratio of seasonally intercepted water and seasonal precipitation total. Potential evapotranspiration is presented, because it clearly illustrates the role of canopy, not

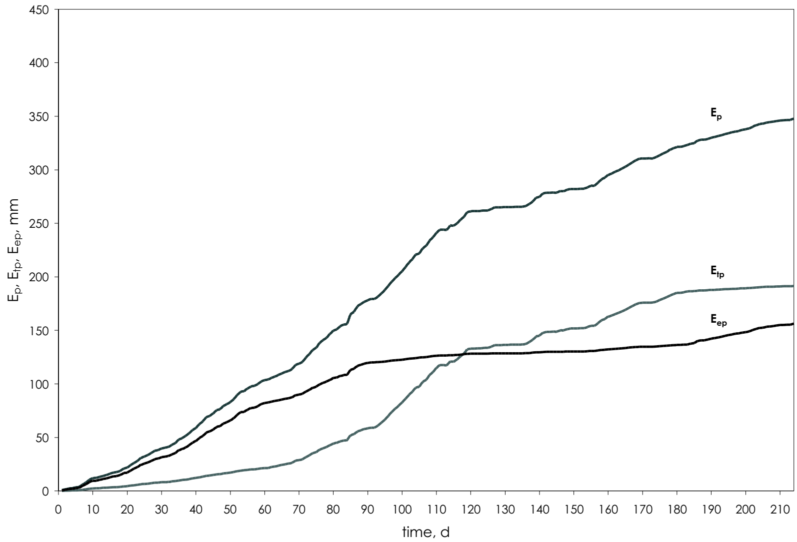

Fig. 2. Cumulative potential evapotranspiration of grass (E_p) and componets of its structure-potential evaporation from soil surface (E_{ep}) and potential transpiration (E_{tp}). Vysoké Tatry (Slovakia), site FIRE, April 1 – October 31, 2006.

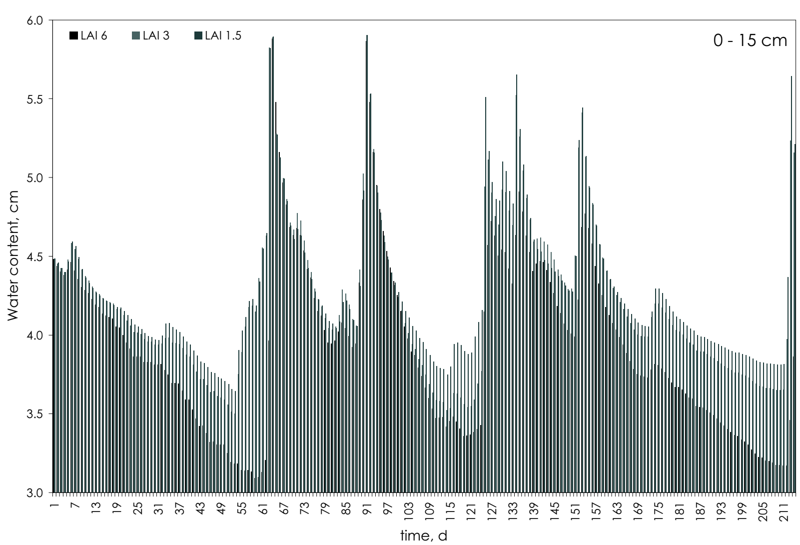

Fig. 3. Seasonal curses of daily values of soil water content of the upper 0,15 m soil layer under canopy of deciduous forest (Picea abies) with different (hypothetical) $LAI = 1.5$; 3 and 6. Vysoké Tatry (Slovakia), site FIRE, April 1 – October 31, 2006.

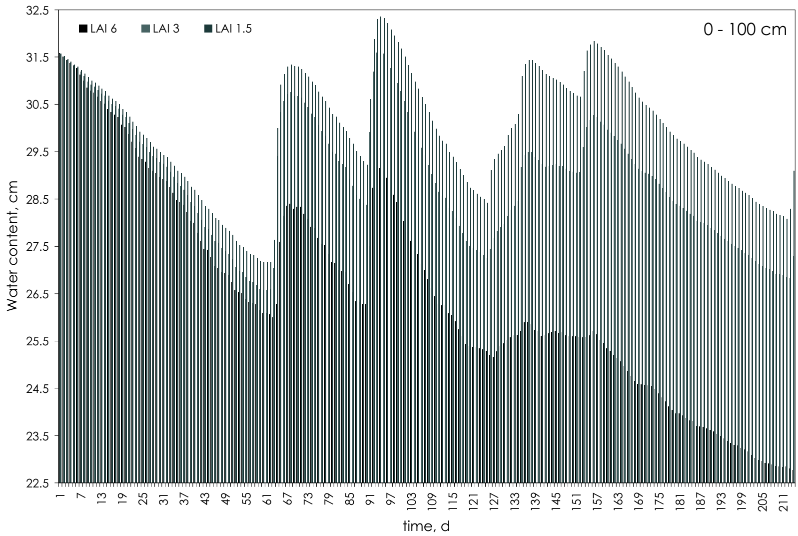

Fig. 4. Seasonal curses of daily values of soil water content of the upper, one meter soil layer under canopy of deciduous forest (Picea abies) with different (hypothetical) $LAI = 1.5$; 3 and 6. Vysoké Tatry (Slovakia), site FIRE, April 1 – October 31, 2006.

influenced by the water state of the SPAC system. Results of our simulation clearly demonstrate the role of canopies (characterized by LAI) in the water balance structure formation. Soil under sparse canopy, with low LAI and low interception, can infiltrate more water in comparison to soil under dense canopy, and thus create higher soil water content and runoff. The difference in SWC can be really important; in our illustrative example the difference in potential evapotranspiration (including evaporation of intercepted water) between pine forests with $LAI = 6$ and $LAI = 1.5$ was estimated 180 mm of water layer (Table 2). *Vose and Swank (1994)* demonstrated a decrease of run – off with decreasing undercanopy precipitation.

Results presented here are results of a simulation. This was the only possibility to acquire such data at that time. The results are approximate, but they are in accordance with theoretical assumptions. The next step will be to increase the accuracy of the input data (soil, LAI and interception capacity) at the sites of interest.

4. Conclusions

The results of water and energy movement calculations by the simulation model GLOBAL applied to the SPAC system at site FIRE (Vysoké Tatry, Slovakia) have shown a significant influence of canopy structure changes (Pine forest – grass) or changes of pine forest density (different LAI) on the structure of their water balance.

Important consequence of pine forest density decrease (decrease of LAI) – due to eventual windthrow – is significant decrease of rain interception, decreased consumption of energy as latent heat of intercepted water evaporation and subseqeqently soil water content increase. This can lead to evapotranspiration increase, as well as to run-off increase.

Seasonal course of soil water content below canopies differs for different LAI; the difference in soil water content of the upper 1 m soil layer with different $LAI = 1.5$ and $LAI = 6$ (which is close to the LAI of 70 years old forest) can reach 53 mm of water layer, during the time interval April 1 – October 31, 2006; it is a significant difference.

Simulations were conducted for homogeneous soil. In reality soil at FIRE site contains boulders, which can affect results of the simulation quantitatively, but not qualitatively.

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