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FOREST SOIL WATER CONTENT ANNUAL COURSES AS INFLUENCED BY CANOPY PROPERTIES

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Abstrakt:

Annual courses of soil water content in upper layer of soil covered by spruce canopy (Picea abies) was analysed, using simulation model with input data measured in the High Tatra mountains in the area influenced by the heavy windthrow at the end of the year 2004. The influence of different spruce tree density followed by the different leaf area index (LAI) – as the result of windthrow – strongly influences interception and evapotranspiration of modified canopy and followingly the upper (rooting) layer of soil water content and should lead to the changes in outflow processes as well. Such a situation can be observed during forest growth and during intentional clearing.

Previously published studies showed the significant influence of canopy properties changes on interception processes, due to LAI changes. Interception of precipitation in forest ecosystems changes in wide range, depending on properties of rain (drops diameter) and tree properties; according to measurements conducted by the Institute of Hydrology, Slovak Academy of Sciences, 30 – 60% of annual precipitation can be intercepted by spruce canopy, depending on meteorological characteristics (mainly wind velocity). To calculate the influence of LAI on water balance structure and on soil water content changes, the simulation model GLOBAL was applied. This proven model was used many times to diagnose soil water regimen under different crops.

This model was applied for summer time interval (April 1, – October 31, 2006), when interception reaches its maximum. The site called FIRE was chosen; this site located nearby Tatranský Smokovec is one of reference sites chosen for intensive measurements. This site was extracted after windthrow and followingly was (probably spontaneously) set in fire. As it was found, changes of canopy structure can lead to serious changes of water balance structure. LAI decrease led to decrease of intercepted water quantity, to decrease of overall evapotranspiration (intercepted water is evaporated at high rate without production efect) and to increase of undercanopy precipitation. This phenomenon led to infiltration increase, followed by soil water content increase. It should be expected runoff increase as well. Results of discharge measurements in catchments located in the area influenced by the windthrow (performed by the Institute of Hydrology at High Tatras) show non – significant, but clearly identified discharge increase, probably due to canopy properties changes. Therefore, it can be stated, that LAI changes in principle can influence interception process and the structure of soil water balance equation. Interception seems to be the most important process changed under such circumstances.

Key words: soil water, rain interception, spruce forest, evapotranspiration

Introduction

Interception of precipitation by forests is significant component of their water balance. In average, 37 % of 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, 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, intercepted amount of water will be less, than the above mentioned values indicates, but not significantly. This amount of intercepted and then evaporated water does not reach soil surface and therefore, cannot be utilized by plants and cannot be evaporated by soil surface.

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

Another consequence of interception is decrease of wet leaves (spruce needless) transpiration, folloved 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 phenomenom 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 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.

Method

The influence of canopy structure on rates of evapotranspiration and its components is extremely difficult to measure. Particular problem arise for forest canopies, because of trees dimension. The only possibility to solve this problem is to apply mathematical simulation models to calculate 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 is 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 canopy surface.

This model, developed at the Institute of Hydrology, Slovak Academy of Sciences in Bratislava, is based on one dimensional Richards governing equation. 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 original method of evapotranspiration and its components (transpiration, evapotranspiration) calculation, as well as animproved methods of interception and root extraction patterns estimation. Evapotranspiration estimation method is in principle Penman – Monteith type, but with different method of ”wind” function estimation based on Obuchov – Monin results, which substantially improves accuracy of evapotranspiration estimation. Verification of the model GLOBAL was made by comparison of measured and calculated soil water content under maize canopy with success (Novák, Majerčák, 1992); it should perform adequately for forest canopy too. The difference is in properties of Soil – Plant – Atmosphere System (SPAC).

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 water and energy movement in such a system. Therefore, special attention is paid to interception process and to this quantification.

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

$$I_c = c_{in}.LAI.s_r \qquad (1)$$

$$s_r = A_p / A_s \qquad (2)$$

I_c – 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 pojected 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 LAI values, relative canopy cover can be calculated approximately

$$s_r = s_{r,\max} \frac{LAI}{LAI_{\max}} \qquad (3)$$

Specific interception capacity c_{in} can be calculated as

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

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, 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 runoff or it is stored in the soil.

$$Z_s = Z - I_c + I_t \qquad (5)$$

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

Site and soil

Research site, characteristics of which were used to model potential evapotranspiration and its components was chosen as one of four official sites at Vysoké Tatry (High Tatra Mountains), which undergo intensive monitoring through couple of participating research groups. Chosen site acronym is FIRE and is located west of Starý Smokovec, north of the main road Starý Smokovec – Štrbské Pleso. This cleared area was later set on fire, so from there is its acronym FIRE. 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 fired, thus minimally changing soil properties of the studied area, shown in Tab.1.

Canopy characteristics

Important canopy characteristics needed to evaluate evapotranspiration and components of its structure (transpiration, evaporation) is albedo of evaporating surface. Green gass canopy and/or broadleave forest albedo is usually taken as a = 0.22, but albedo of coniferous forest, particularly of spruce (Picea abies) is significantly lower. Its value is generally changing during the day, with its maximum at about noon and minimum during morning and evening hours, and with forest density albedo decrese. An average values af spruce albedo is in the range 0.1 – 0.11 (Perttu, 1970). For our calculation, albedo a = 0.11 was used. This means, net radiation od spruce forest is nearly twice as big as net radiation of grass and broadleaved forest. Roughness length z_o of spruce forest published by (Hurtalová et al., 2004) were used. Rooting depth was estimated from measurements at this site, according to the appearance of roots in the test pit; the depth of the roots was found 0.5 m. The distribution of root mass density below soil surface was taken as exponential, in accordance with the results published by Jackson et al., (1996).

Canopy characteristics needed to calculate precipitation interception by canopy are: (projected) leaf area index (LAI), relative canopy cover s_r , specific interception capacity c_{max}, corresponding to $u = 0$, and to LAI =1; it is maximum specific interception capacity of the canopy, c_{min} - specific interception capacity (minimum) corresponding to u_{max}, mm. To calculate interception of the canopy grown at site FIRE, results of spruce 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., spruce trunks were of average diameter 18 cm, relative cover was 0,537 (Majerčáková, 1983). Specific interception capacity was calculated according to the equation (6):

$$c_{in} = I_c / LAI \, . \, s_r \qquad (6)$$

Daily totals of intercepted rain were estimated as the difference between daily precipitation total at meteorological station (glade), and daily precipitation total measured in the forest below trees, 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. Spruce 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.

Next important characteristic, needed to calculate specific interception capacity is LAI. In previously cited work performed at Jasna pod Chopkom (Majerčáková, 1983) it was not measured, therefore data from literature earned under similar conditions should be used. In numerous papers devoted to this topic it is not easy to find data for Spruce forest grown at height 1200 m a.s.l. with appropriate age and density. Interesting is, that LAI of spruce 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 spruce forest 20 years old, Bolstad and Gower, (1990) estimated LAI = 10 for spruce forest at Wisconsin, for 30 years old spruce 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 spruce forest their data are in the range $2.4 \leq LAI \leq 12$, majority of LAI are below 3.8, Bičanová and Fleischer (2006) present for spruce forest close to forests in Vysoké Tatry LAI = 7.0 estimated by Guenther et al.(1993). For calculation, LAI = 7.0 was chosen. All the above mentioned values are so called “projected LAI” , it means they are projected to the horizontal surface. Measured values of interception capacity (Majerčáková, 1983) were estimated for unit area of “projected” surface, $s_r = 1$.

Then, using equation (6) , maximum specific interception capacity of spruce forest was evaluated as c_{max} = 0.7.

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 FIRE site. The time interval of 220 consecutive days without snow interception was modeled (April 1 - October 31, 2006).

Results and discussion

Results of water movement simulation of the SPAC system are in Fig. 1- 4 and in Table 3. 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 this, which occurred in Vysoké Tatry in 2004 or during the intentional trees density changing. Potential evapotranspiration in Fig. 1 does not involve evaporation of intercepted water. Evaporation of intercepted water is shown separately in Tab. 3 (as E_i). Results presented (curves 1 – 3) were calculated with energy balance of the SPAC system, accounting for energy used for evaporation of intercepted water. The energy used for evaporation of intercepted water was subtracted from total amount of energy used for evapotranspiration; and it led to significant decrease of available energy for latent heat of evaporation and folowingly 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 mean vegetation period precipitation total, with maximum more than 41% ; the range of seasonal interception totals expressed as its the ratio to seasonal precipitation was 0.30 – 0.41 (Miklánek and Pekárová, 2006). So, the calculated difference between forest seasonal potential evapotranspiration total with LAI =6 and this without interception involvement was found 122 mm water layer, which is really significant ammount modifying the water balance structure of the SPAC system (Fig.1).

For comparison, seasonal course of potential evapotranspiration total of grass and components of its structure for conditions of FIRE site is 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 as influenced by different LAI values; it is result of different undercanopy precipitation totals and by decreased amount of energy for evapotranspiration due to its consumption by evaporation of intercepted water.

Table 3. contains seasonal totals of potential evapotranspiration and its components, intercepted rain water (it is evaporating) and the ratio of seasonally intercepted water and seasonal precipitation total. Potential evapotranspiration is presented, because they clearly illustrate the role of canopy, not influenced by the water state of the SPAC system. Results of 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 spruce forests with LAI = 6 and LAI = 1.5 was estimated 180

mm of water layer (Tab.2.). Vose and Swank (1994) demonstrated decrease of runoff with decreasing of undercanopy precipitation.

Increase of SWC (see Figs.3 and 4) due to forest canopy clearing can lead to increase of runoff. As it was shown by Hlavatá et al. (2008), results of measurements in some small cotchments in the area partially influenced by windthrow and clearing shown the increase of outflow during the period of minimum daily flow (March, April), but this increase was not significant. This findings are in accordance with the results of soil water balance modeling. This change during the canopy properties changes cannot influence high flow significantly.

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

Conclusions

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

Important consequence of spruce 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 followingly soil water content increase. This can lead to evapotranspiration as well as to runoff 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 significant difference.

It can be expected (and it was confirmed), that canopy structure changes and LAI decrease can lead to overal evapotranspiration decrease, folloved by SWC increase and to runoff increase. As it was shown by direct measurements, the effect of LAI decrease on runoff increase was not significant (Hlavatá et al., 2008).

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

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Tab. 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
θ_v	0.18	0.14	0.27
θ_{fc}	0.396	0.464	0.391
θ_s	0.704	0.658	0.622
K_s [cm d^{-1}]	1000	320	670
α	0.26749	0.20454	0.10592
n	1.17952	1.13446	1.23345

θ_v – volumetric soil water content corresponding to the wilting point, cm^3cm^{-3}, θ_{fc} – soil water content corresponding to the „field capacity“, cm^3cm^{-3}, θ_s – water content of the saturated soil, cm^3cm^{-3}, K_s – hydraulic conductivity of the soil saturated with water (saturated hydraulic conductivity), $m.s^{-1}$, α, cm^{-1} and n – van Genuchten's equation coefficients

Tab. 2. Canopy characteristics, used as input data of the model GLOBAL.

SURFACE		LAI	z_0 (m)	α
SPRUCE FOREST	01.04. - 31.10.2007	1.5 3.0 6.0	0.3	0.11
BARE SOIL	01.04. - 31.10.2007	0.0	0.03	0.15
GRASS	01.04. - 31.05.2007	0.5	0.02	0.25
	01.06. - 30.06.2007	1.5	0.03	
	01.07. - 31.08.2007	5.0	0.05	
	01.09. - 30.09.2007	4.0		
	01.10. - 31.10.2007	0.5	0.02	

Tab. 3. 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		SPRUCE FOREST			GRASS	BARE S.
LAI		1.5	3	6	VARIABLE	0
E_p	(mm)	346.92	309.33	273.03	342.96	475.24
E_{tp}		173.69	232.21	256.06	189.07	0
E_{ep}		173.22	77.12	16.97	153.89	475.24
E_i		83.27	166.54	333.08	136.32	0
E_p+E_i		430.19	475.87	606.11	479.28	475.24
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	0.34	0.68	0.28	0.00

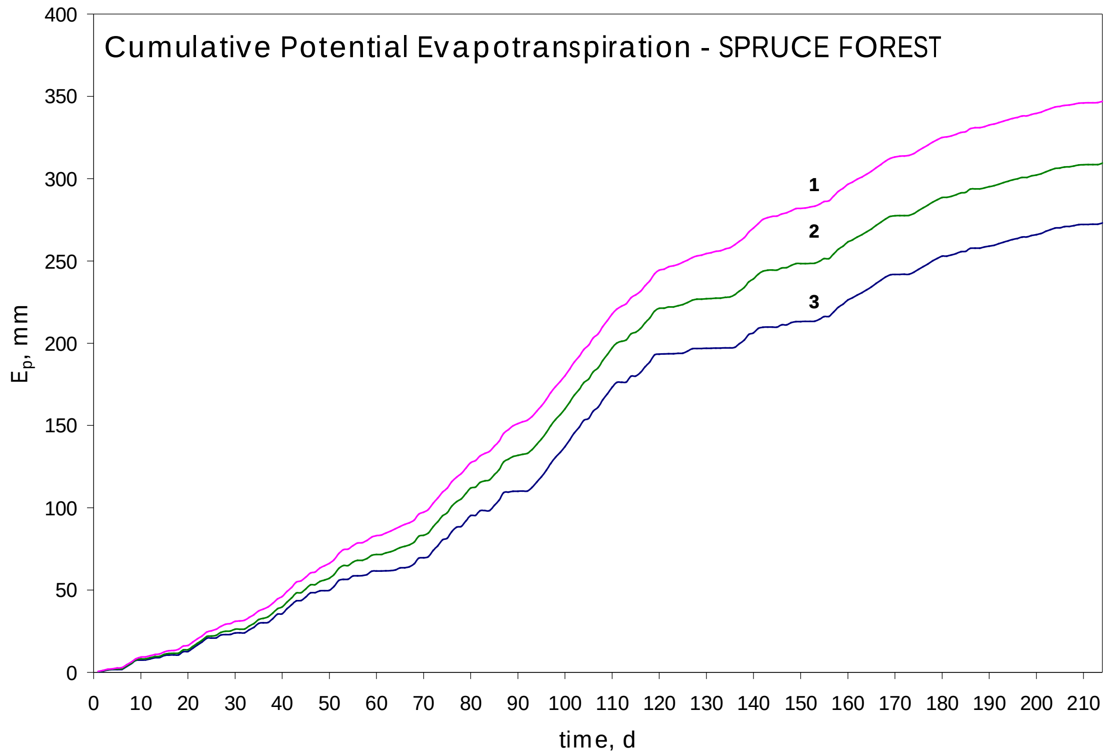

Fig. 1. Cumulative potential evapotranspiration of coniferous forest (Picea abies) for different (hypothetical) LAI = 1,5; 3 a 6 (curves 1,2,3). Vysoké Tatry (Slovaka), site FIRE, April 1– October 31, 2006.

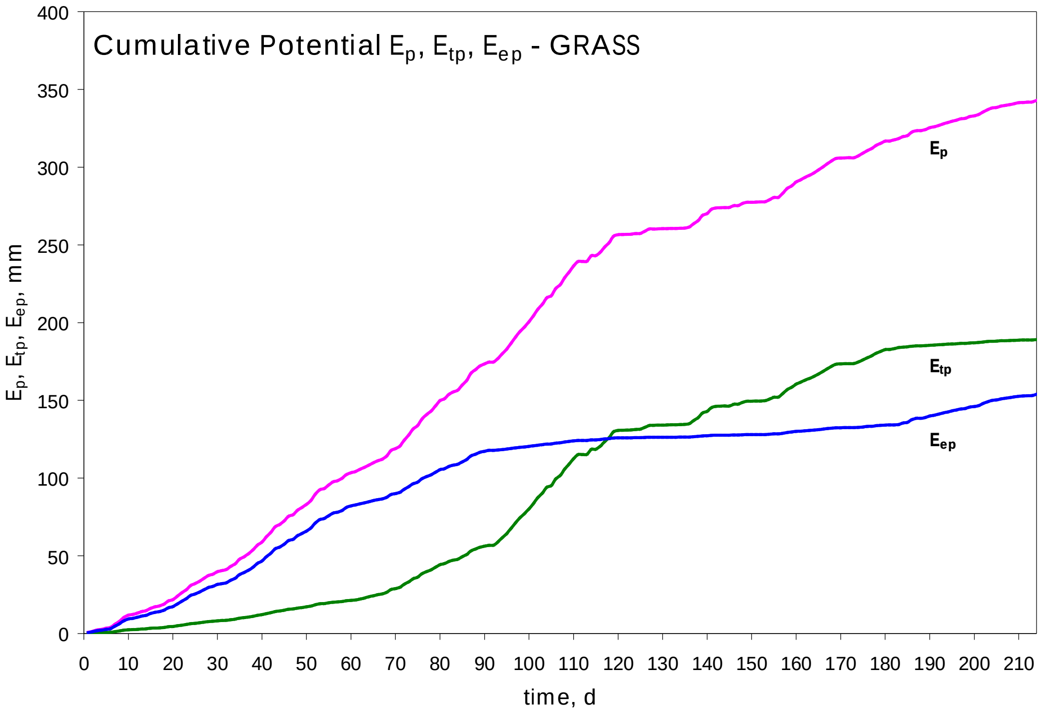

Fig. 2. Cumulative potential evapotranspiration of grass (E_p) and componets of its structure– potential evaporation from soil surface (E_{ep}) and potential transpiration (E_{tp}). Vysoké Tatry (Slovakia), site FIRE, April 1– October 31, 2006.

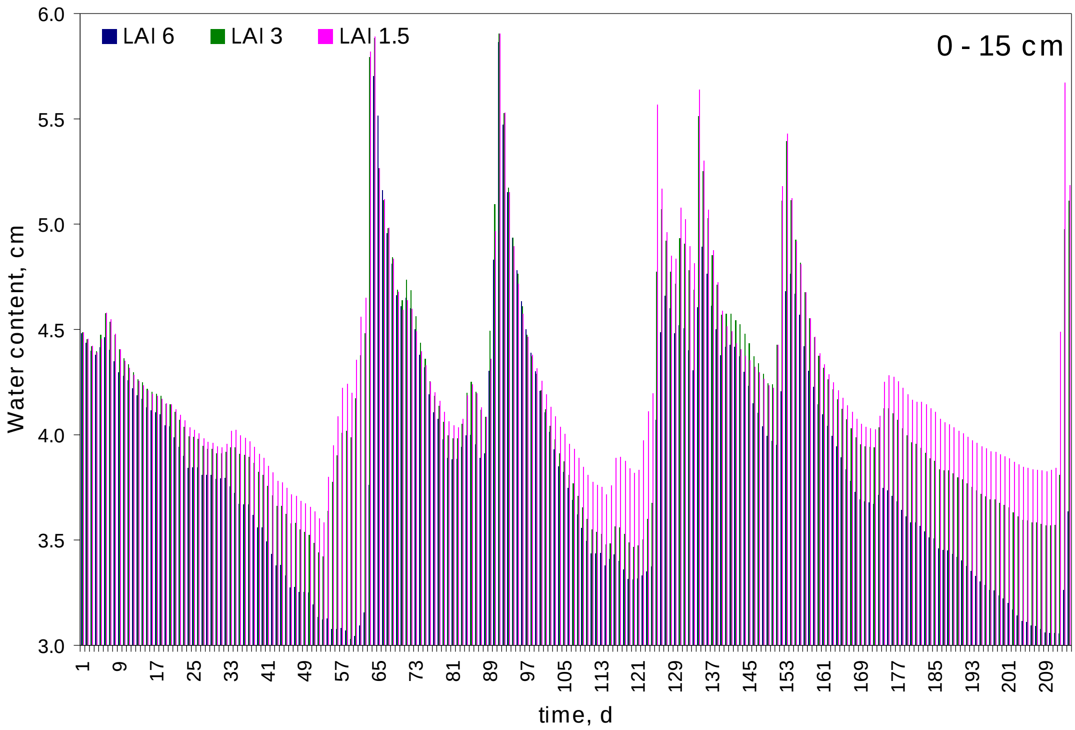

Fig. 3. Seasonal curses of daily values of soil water content of the upper 0,15 m soil layer under canopy of deciduous forest (Picea abies) with different (hypothetical) LAI = 1,5; 3 and 6. Vysoké Tatry (Slovakia), site FIRE, April .– October 31, 2006.

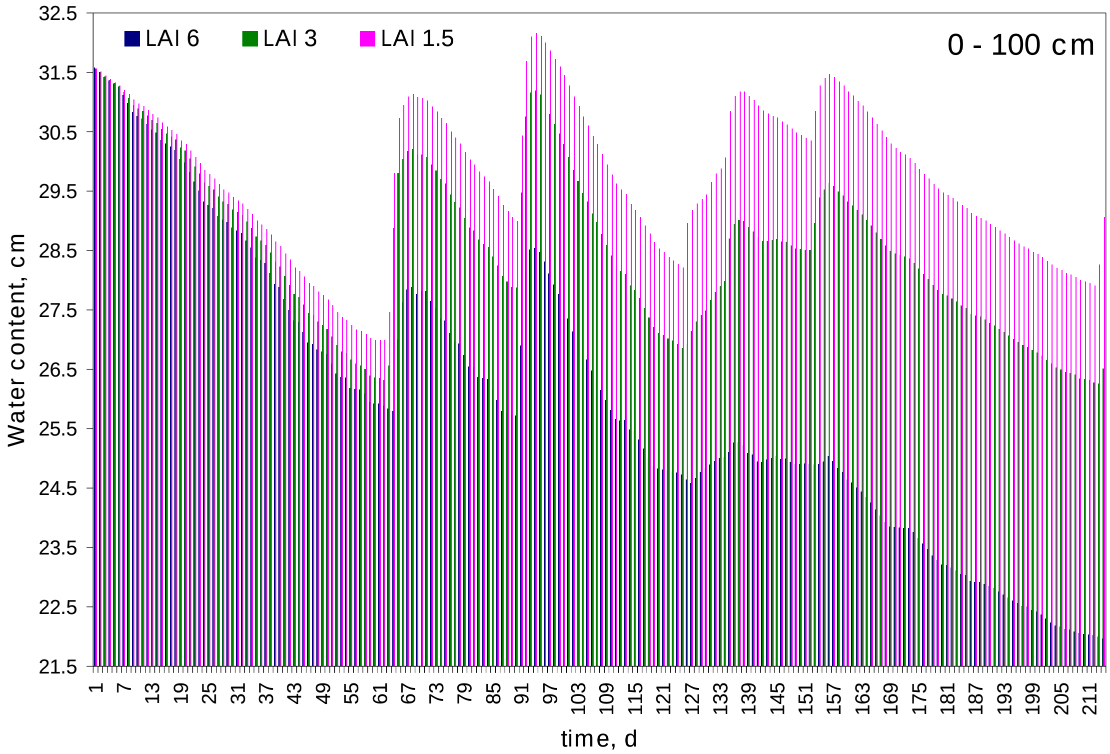

Fig. 4. Seasonal curses of daily values of soil water content of the upper, one meter soil layer under canopy of deciduous forest (Picea abies) with different (hypothetical) LAI = 1,5; 3 and 6. Vysoké Tatry (Slovakia), site FIRE, April 1– October 31, 2006.