Effect of soil drought on evapotranspiration of a young spruce forest

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ABSTRACT: Daily courses of the actual transpiration of a forest stand were determined by an experimentally verified mathematical Soil – Vegetation – Atmosphere Transfer model. The results refer to the Norway spruce (*Picea abies* [L.] Karst.) monoculture situated in the highest locations of the Beskids Mts. Drought-free transpiration was estimated as a model simulation run for nonlimiting soil moisture exceeding the level of decreased availability of water. Drought-induced reduction in transpiration was quantified as a difference between actual transpiration and simulated transpiration for moist soil. The results led to conclusions that dry soil causes a significant reduction in actual evapotranspiration and its components in comparison with moist soil. Simultaneously, the effect of soil desiccation was compensated by extremely high evaporative demands of the atmosphere, so that the daily totals of evapotranspiration and its components remained sufficiently high. The high values of global radiation and saturation deficit in the air favourably influenced the water regime of the analysed forest stand in the dry period.

Keywords: evapotranspiration; transpiration; evaporation; soil drought; saturation deficit; Norway spruce

Contemporary research on the energy budget of the Earth surface in the conditions of a possible climate change leads to conclusions that the annual sums of net radiation will slightly increase (WILD et al. 1997; HRVOĽ 1996). Simultaneously, a decrease in annual sums is also expected in climatic scenarios (LAPIN, ŠIPÖCZ 1991; BRÁZDIL, ROŽNOVSKÝ et al. 1996) that can be accompanied by intensive soil desiccation in the summer season (ROŽNOVSKÝ 1998). Though the long term precipitation mean need not change, the occurrence of extremely dry periods may affect the stability of forest ecosystems and cause a loss of their production (CIENCIALA et al. 1998).

Coniferous trees frequently manifest higher values of canopy conductance for the water vapour transfer in comparison with deciduous trees (TAN, BLACK 1976). Consequently, a reduction in transpiration caused by drought in conifers may have a significant influence on their water regime. It could be a reason for a relatively great attention paid in the literature to the problem of transpiration from the coniferous stands. However, many articles published until now refer to the geographic regions whose soil and climatic conditions differ from the situation in the middle of Europe, so that the generalisation of the results is difficult or quite impossible. In coherence with this, the presented paper tries to analyse and quantify the response of a young spruce forest situated in the highest locations of the Beskids Mts. to soil drought as it is manifested by the transpiration of the stand.

MATERIAL AND METHODS

Necessary experimental data were obtained by measurements in and above the Norway spruce young forest from May 15 to June 12, 2000. An experimental site of the investigated spruce forest is situated in the locality Bílý Kříž, Czech Republic (φ = 49°30′17′′, λ = 18°32′28′′) on a mild slope with SW orientation. It is the highest part of the Moravian-Silesian Beskids Mts., 898–908 m a.s.l.

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The above-mentioned experimental site with the coniferous forest vegetation type, tree species *Picea abies* L. Karst., and age of 23 years (at the end of the season 2000) is divided into two parts: Dense Forest with 2,600 trees per ha and Space Forest with 2,100 trees per ha, each with a surface of 2,500 m^2 (JANOUŠ 1995).

According to climatic classification for the Czech Republic (QUITT 1971) Bílý Kříž locality is a cold region (CH 7) where the vegetation season lasts from 120 to 140 days with daily temperature below 10°C, humid and precipitation abundant. The mean annual air temperature is 4.9°C, April average is 4.5°C, May average is 9.5°C. The mean annual precipitation total is 1,100 mm. The mean over the vegetation season is from 600 to 700 mm, April mean is 116 mm, May mean is 125 mm (MAŠKOVÁ, ROŽNOVSKÝ 1999).

The micrometeorological measurements of the vertical profiles of wind speed, air temperature and air humidity were conducted on a 12 m high tower in and above the spruce stand at the experimental site Dense Forest. The mean height of trees in May was 7.92 ± 0.06 m and the measurement levels were: 6, 7, 8, 9 and 12 m for wind speed, 2, 6, 7, 9 and 12 m for air temperature and air humidity. The measurement levels were measured from the ground surface. The investigated parameters were recorded by automatic measuring equipment (data logger – DL3000, sensors of air temperature and air humidity of model RHA1, and anemometers of model AN1) completed by the DELTA-T Devices LTD. The measurements were carried out continuously during 24 hours with 10-minute records of data averages.

With the aim to quantify and analyze the mass and energy transfer between the leaf canopy and the surrounding air, a three-layer one-dimensional steady-state Soil – Vegetation – Atmosphere Transfer model was developed, tested and designed for simulations of daily courses of perceivable and latent heat fluxes in the surface layer of the atmosphere above plant canopies (MATEJKA 1997). The verification of the model was carried out by help of experimental data referring to forest stand (MATEJKA et al. 1999) and field crops (MATEJKA 1995, 1997).

The model to be described here combines and extends the work of BICHELE et al. (1980), CHOUDHURY and MONTEITH (1988), and WALLACE (1995). The soil – vegetation – atmosphere continuum is divided into three layers, the tops of which are:

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

The idea of the model is based on Darcy's law, continuity equation and the assumption that the effect of plant water reserves on transpiration can be neglected. This leads to a system of three equations as follows:

– Penman-Monteith equation (CHOUDHURY, MONTEITH 1988),
– relationship existing between the soil water potential, leaf water potential and transpiration (BICHELE et al. 1980; MATEJKA, HUZULÁK 1995),
– energy budget of the stand (SEEMAN et al. 1979; ROŽNOVSKÝ, MAŠKOVÁ 1996).

The inputs of this model involve hydrophysical parameters of the soil including soil moisture in the root zone, biometric characteristics of the stand and meteorological elements such as global radiation, wind speed, air temperature and humidity. The outputs of the model provide parameters of the water regime of the stand and turbulent and latent heat flux that can be expressed in terms of the amount of evaporated water as evapotranspiration and its components.

The model gives an opportunity to quantify also the role of changes in the leaf area index, parameters of the root system, stomatal resistances, and soil moisture in the processes of mass and energy exchange between plant canopies and the atmosphere.

RESULTS AND DISCUSSION

As to the weather conditions, the analysed period of 30 days can be divided into two different parts. At the beginning and at the end of the period sunny and warm weather with dry soil and extremely high evaporative demands of the atmosphere prevailed: it was manifested by

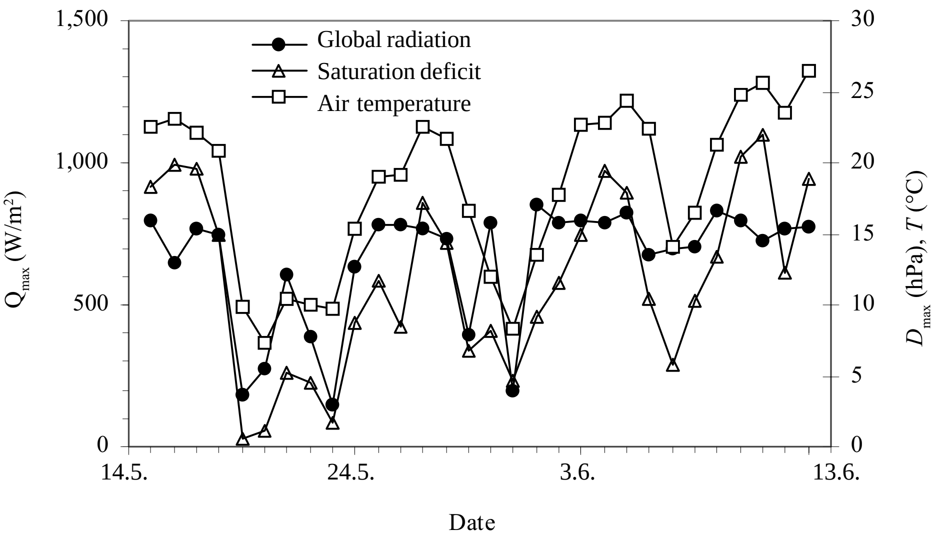

Fig. 1. Daily maxima of global radiation (Q_{max}), water saturation deficit (D_{max}) and air temperature (T)

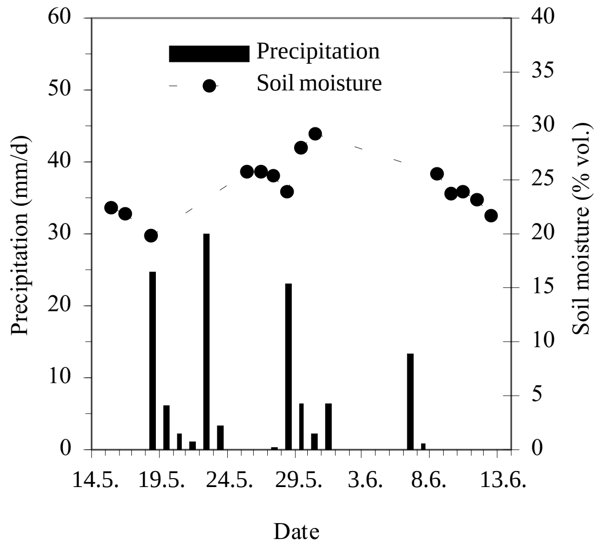

Fig. 2. The soil moisture in the layer 0–43 cm and daily totals of precipitation

daily maxima of the water saturation deficit in the air exceeding 20 hPa (Fig. 1). In spite of this, in the middle of the analysed period there occurred a few cooler cloudy days with relatively high soil moisture approaching 30% by volume at the turn of May and June (Fig. 2). The highest amount of precipitation in the analysed time interval was registered in late May and early June while the sum of precipitation for the whole period amounted to 121.4 mm. But from April 8 to May 17 the sum of precipitation was only 33.6 mm. The April sum of precipitation was 83 mm, May sum was 116 mm.

Despite of the relatively high precipitation, soil moisture decreased below 22% by volume, which points to intensive evapotranspiration.

Using the mathematical model described above, the actual transpiration, evaporation from the soil, and consequently evapotranspiration were calculated with a time step of one hour. The values of wind speed, air temperature and humidity measured at the level of 12 m above the soil surface served as meteorological inputs to the model. The daily totals of evapotranspiration and its components reached relatively high values, except at the beginning and at the end of the analysed period when the soil was evidently dry (Fig. 3). The mean daily sum of transpiration was 1.28 mm/day while the maximum amounted to 2.69 mm/day. A little lower values were obtained for evaporation from the soil, namely 0.29 mm/day as the mean for the period and 1.15 mm/day for the maximum. Consequently, the evapotranspiration determined as the sum of transpiration and evaporation from the soil had the mean value of 1.57 mm/day and its maximum was 3.84 mm/day. The mean ratio of soil evaporation to transpiration was 0.32. This value was affected by the maximum 4.31 that occurred on May 31. It was an overcast day with precipitation, having exceptionally low global radiation that reduced the opening of stomata. The high stomatal resistance accompanied by low evaporative demands of the wet air caused a strong decrease in transpiration. However, the surface resistance of the moist soil remained low, which created suitable conditions for evaporation from the soil. In this situation, evaporation from the soil exceeded transpiration. Excluding this extreme, the ratio of evaporation from the soil to transpiration fell to 0.18.

It should be said that the mere data presented in Fig. 1 do not enable to asses the reduction of transpiration caused by soil draught. The relationship between transpiration and soil moisture is not a suitable tool for this purpose either because this formal statistical dependence reflects the fact that the soil is moist usually during rainy days when transpiration is low as a result of low solar radiation which determines the energy available for evaporation from the forest stand. Therefore transpiration seems to be illusorily independent of the soil moisture (Fig. 3).

Taking into account this limitation of statistical methods in the research of interrelations between the vegetation and the atmosphere, another approach should be used. The effect of drought on transpiration can be quantified by

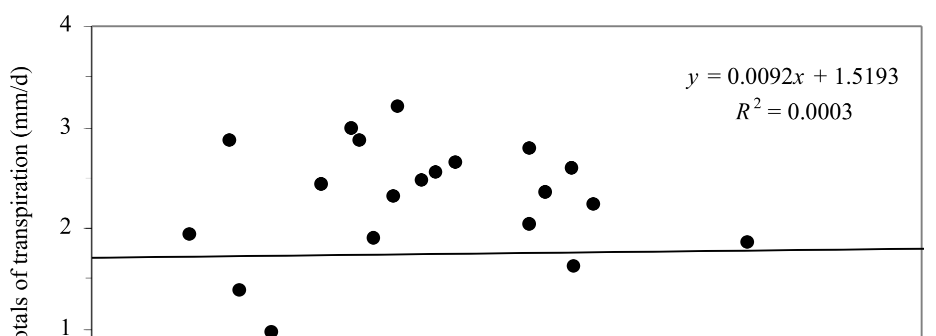

Fig. 3. The statistical relationship between soil moisture and transpiration

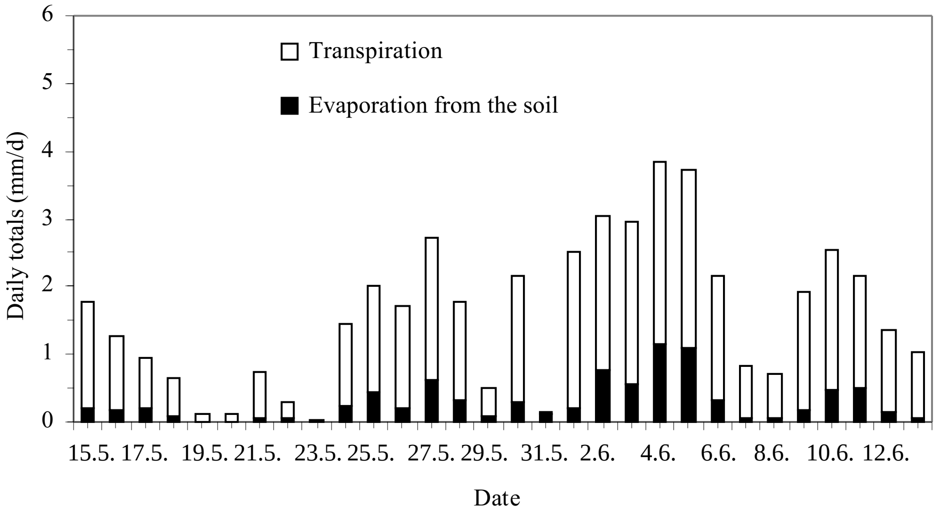

Fig. 4. Evapotranspiration of the young spruce forest and its components

means of the difference between drought-free transpiration and actual transpiration as it was presented in Fig. 4. This difference is called a transpiration deficit in the literature (CIENCIALA et al. 1998). For the estimation of drought-free transpiration the mathematical model described above was used again. However, this model simulation was carried out with sufficiently high and constant value of soil moisture at the model input. All other inputs of the model remained unchanged. The constant value of soil moisture characterising a sufficiently moist soil was taken as 35% by volume, which is the value that doubtless does not limit transpiration in the given soil conditions.

The results of these model simulations providing the estimation of drought-free transpiration together with the daily totals of actual transpiration and its components are graphically represented in Fig. 5. It is obvious now that the actual transpiration of the investigated young spruce forest was significantly reduced by soil drought at the beginning and at the end of the analysed period. The mean ratio of actual to drought-free transpiration calculated for the whole analysed period was 77.2%, but for the days with low soil moisture it falls below 50%. It means that the soil drought was able to reduce transpiration to one half of the drought-free level in a few days. Taking into account that drought-free transpiration is very close to potential transpiration, it can be concluded that the analysed young spruce forest suffered from an intensive water stress in the first and last four days of the analysed time interval.

It should be added that evaporation from the soil was reduced by drought even more. It is proven by the ratio of actual to drought-free soil evaporation with the mean of 39.5% and minimum only 16.4%. Such a strong reduction of soil evaporation can be explained by the fact that the roots of the tree are able to extract water from the whole root zone but the resistance of a thin surface layer of dry soil can be extremely high.

The drought-induced reduction in evapotranspiration also varies in the wide range where the mean ratio of actual to drought-free evapotranspiration reached the value of 66.6%, so that the evapotranspiration was reduced to two thirds.

Similar results referring to Norway spruce were also presented by CIENCIALA et al. (1998). They found a reduction in sap flow approaching 10% of drought-free transpiration in a few individual days. However, it has to be stressed that these results were obtained in Central Sweden where the daily maxima of saturation deficit do not exceed 8 hPa on the days with the most intensive reduction in sap flow. The mean daily totals of actual transpiration are higher in the Scandinavian climatic conditions, where a higher soil water content is available, reaching the value of 1.8 mm/day (CIENCIALA et al. 1992). Hence, the reason for the lower reduction in transpiration in the Beskids Mts. can be higher evaporative demands of the atmosphere as are manifested by daily maxima of the saturation deficit exceeding 20 hPa.

CONCLUSIONS

The transpiration of the investigated young spruce forest responses sensitively to changes in the soil moisture. In coherence with this statement, evapotranspiration and its components were strongly reduced by a decrease in soil moisture. The mean reduced actual transpiration in the analysed period of 30 days was 77% of the drought-free transpiration. The evaporation from the soil was reduced even more.

Despite this significant reduction in transpiration, its daily sums remained relatively high. It was caused by the extremely high values of saturation deficit. Hence, the drought-induced reduction in transpiration in the Beskids Mts. was partly compensated by the high evaporative demands of the air which had a positive influence on the water regime of the young spruce forest.

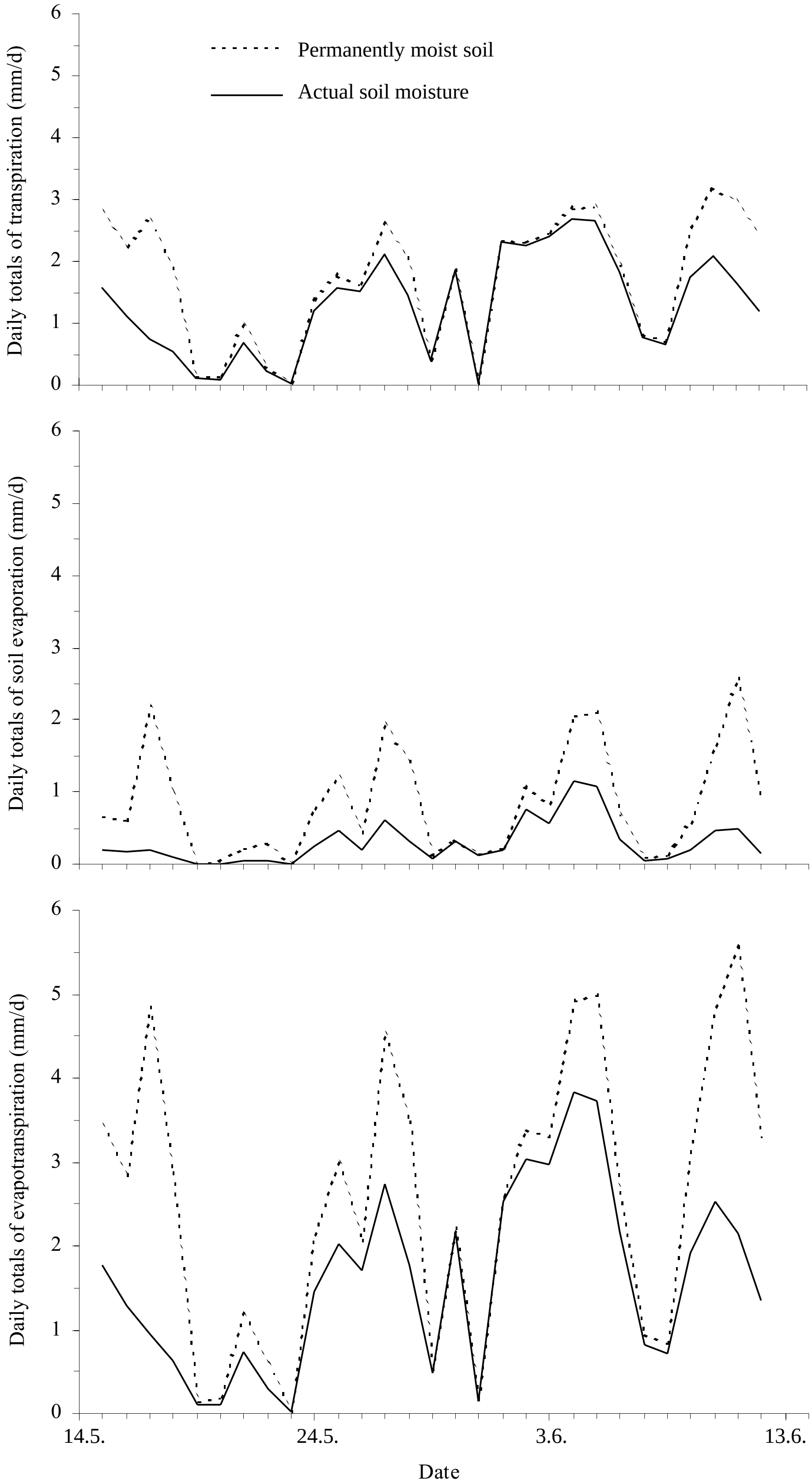

Fig. 5. The drought-induced reduction in evapotranspiration and its components

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Vliv půdního sucha na evapotranspiraci mladé horské smrčiny

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ABSTRAKT: Denní chody aktuální transpirace smrkového porostu byly stanoveny pomocí matematického modelu přenosu hmoty a energie v systému půda – rostlinný porost – atmosféra. Získané výsledky vycházejí z měření ve smrkové monokultuře (*Picea abies* [L.] Karst.) nacházející se ve vrcholových polohách Moravskoslezských Beskyd. Dále byla stanovena transpirace porostu pro vlhkou půdu jako modelová simulace pro vysokou půdní vlhkost, která měla hodnoty nad hranicí snížené dostupnosti vody pro porost. Redukce transpirace vlivem sucha byla kvantifikována jako rozdíl mezi aktuální transpirací a transpirací simulovanou pro vlhkou půdu. Získané výsledky vedly k závěrům, že suchá půda způsobila významné snížení aktuální transpirace a jejích složek v porovnání s případem vlhké půdy. Vliv suché půdy byl však současně kompenzovaný extrémně vysokými evaporačními požadavky vzduchu, takže denní úhrny evapotranspirace a jejích složek zůstávaly dosti vysoké. To znamená, že vysoké hodnoty globálního záření a sytostního doplňku příznivě ovlivňovaly vodní režim sledovaného porostu v průběhu suchého období.

Klíčová slova: evapotranspirace; transpirace; evaporace; půdní sucho; sytostní doplněk; smrk ztepilý

Průběh počasí v jarních měsících roku 2000 byl typický výskytem nižších srážkových úhrnů a naopak větším počtem dnů bez srážek. Toto počasí ovlivnilo růstové podmínky i smrkových porostů ve vyšších nadmořských výškách. Předkládané výsledky vycházejí z gradientových měření ve smrkové monokultuře (*Picea abies* [L.] Karst.), nacházející se ve vrcholových polohách Moravskoslezských Beskyd v nadmořské výšce 908 m n. m., se souřadnicemi 49°30´10´´ severní z. š. a 18°32´20´´ východní z. d. Průměrná roční teplota vzduchu je 4,9 °C, roční úhrn srážek je 1 100 mm. V průběhu období od 8. 4. do 17. 5. 2000 byly zaznamenány srážky ve výši pouze 33,6 mm. Srážkový úhrn za duben činil 83 mm, za květen 116 mm.

Vyhodnoceno bylo následné období od 15. 5. do 12. 6. 2000. Pro posouzení vlivu půdního sucha na evapotranspiraci smrkových porostů byly vzaty denní chody aktuální transpirace smrkového porostu, stanovené pomocí matematického modelu přenosu hmoty a energie v systému půda – rostlinný porost – atmosféra. Dále byla stanovena transpirace porostu pro vlhkou půdu jako modelová simulace pro vysokou půdní vlhkost, která měla hodnoty nad hranicí snížené dostupnosti vody pro porost. Redukce transpirace vlivem sucha byla kvantifikována jako rozdíl mezi aktuální transpirací a transpirací simulovanou pro vlhkou půdu.

Je nutné zdůraznit, že evaporace z půdy byla omezena suchem, tj. hlavně suchým povrchem. To můžeme doložit poměrem mezi aktuální evaporací a evaporací z vlhké půdy, který měl průměrnou hodnotu 39 % a minimum 16,4 %. Silné snížení půdní evaporace lze vysvětlit tak, že kořeny stromů jsou schopny čerpat vodu z kořenové zóny, ale odpor tenké vrstvy povrchu suché půdy může být extrémně vysoký. Snížení evapotranspirace způsobené suchem se liší v širokém rozsahu, kdy průměrný poměr mezi aktuální a simulovanou evapotranspirací dosáhl hodnoty 66,6 %. Evapotranspirace byla takto redukována na dvě třetiny. K podobným výsledkům došli u smrkových porostů také CIENCIALA et al. (1998). Tito autoři zjistili v několika jednotlivých dnech snížení vodního provozu dosahující 10 % transpirace z vlhké půdy. Pro využití tohoto poznatku v našich podmínkách je však třeba připomenout, že výsledky s největší redukcí vodního provozu byly získány v centrálním Švédsku, kde denní maxima sytostního doplňku nepřekročila 8 hPa. Ve skandinávských klimatických podmínkách se nejvyšší denní celkové sumy transpirace, a to 1,8 mm, vyskytují za vysoké půdní vlhkosti. Důvodem pro menší snížení transpirace v Beskydech může být větší výsušná schopnost vzduchu. V denních maximech dosahují hodnoty sytostního doplňku v hodnocených porostech přes 20 hPa.

Z našich výsledků vyplývá, že transpirace hodnoceného mladého smrkového porostu velmi citlivě reaguje na změny půdní vlhkosti. V souvislosti s tímto poznatkem můžeme konstatovat, že evapotranspirace a její součásti byly silně omezeny sníženou půdní vlhkostí. Průměrné snížení aktuální transpirace v 30denním analyzovaném období činí 77 % transpirace z vlhké půdy. Evaporace z půdy byla suchem redukována ještě více. Získané výsledky vedly k závěrům, že suchá půda způsobila významné snížení aktuální transpirace a jejích složek v porovnání s případem vlhké půdy.

Zajímavostí je, že přes výrazné snížení transpirace její denní sumy zůstávají relativně vysoké. Předpokládáme, že je to způsobeno extrémně vysokými hodnotami sytostního doplňku. Dochází tak k tomu, že redukce transpirace způsobená suchem je částečně kompenzována vysokými vysoušecími vlastnostmi vzduchu (vysokým sytostním doplňkem), takže denní úhrny evapotranspirace a jejích složek zůstávaly dosti vysoké. To znamená, že vysoké hodnoty globálního záření a sytostního doplňku příznivě ovlivňovaly vodní režim sledovaného porostu v průběhu suchého období.

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