Development of Vaporization Process from Young Stands of Norway Spruce and European Beech after Snow Breakage

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Abstract: The extreme disturbance of the forest environment in the young experimental spruce stand in the Orlické hory Mts after the snow breakage disaster in the winter of 2005/2006 became the impulse for the present study. 98% spruce trees were affected, the stand density decreased from 1550 to 950 trees per ha, the needle foliage of the stand was reduced to about 40%, and the stand canopy was markedly disturbed. The investigation consisted of two methodical procedures: the assessment of evapotranspiration of the forest stands (ET) based on continuous measuring of the water content in the root zone of the soil profile, and intermittent measuring of evaporation from the soil surface including the ground vegetation (Es). Comparative investigation was simultaneously done in a young experimental beech stand with minimum disturbance. ET totals (evaporation from the soil surface and ground vegetation Es + transpiration of trees T) were comparable in both stands (200 to 235 mm during the growing season). Until 2006, ET was ± 10% higher in the spruce stand, whereas in 2007, ET was 10% higher in the beech stand. An extremely high increase of the soil surface evaporation (Es) was observed in a gappy spruce stand. Immediately after the disaster, maximum daily totals of evaporation ranged from 1.5 to 2.0 mm in the spring and summer 2006, while in the beechstand they reached half these values. In the following year 2007, with gradual weeds infestation of the stand gaps, whose cover extended to 80% in the summer and autumn, the values of Es in the spruce stand reached up to 3 mm per day, on warm summer days being on the level of the weed-infested clear felled area. In the same days, evaporation in a fully closed beech stand was usually 3 to 4 times lower. The evaporation from the soil surface and ground vegetation evidently substituted the reduced transpiration of the spruce broken canopy, if ET total did not change significantly.

Keywords: evapotranspiration; soil evaporation; young forest stand; Norway spruce; snowbreakage; European beech; Orlické hory Mts

A long-term observation of the water balance elements during the forest regeneration of a Norway spruce stand and that of European beech on the Deštenská hillside in the Orlické hory Mts serves also for comparing evapotranspiration (ET) of both stands. ET represents the transpiration of trees, evaporation from the forest soil, and transpiration of the ground vegetation. The first observations were made in mature spruce- and mature beach stands (1976–1981); a clearcut harvest with hole planting of spruce and beech transplants followed in 1982. Then, the research

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continued during the growth, development, and thinning of both stands from the stage of young plantation up to the small pole stage (1983–2006). The transpiration of the tree species was calculated as the only unknown of the water balance equation (Kantor 1989). In 1998, we started a continual measuring of soil moisture volume in layers of the soil segments with the aim to come up with a new procedure of direct determination of ET. In 2005, a method of ET determination in the spruce and beech stands was devised on the basis of volumetric moisture changes in the soil profile (ET by Soil Water Content Variation, in abbreviation ET-SWCV) and the results obtained in the growing season of 2005 were published (Šach *et al.* 2006). In the winter of 2005/06, the young spruce stand (25 years old) was completely damaged by crown and stem snowbreaks (Figure 1).

The extreme disturbance of the forest environment in the young experimental spruce stand after the snow breakage disaster in the winter of 2005/2006 became an impulse to carry out the study. The investigation was based on two methodical procedures:

– assessing the evapotranspiration of the forest stands based on continuous measuring of the water content in the root zone of the soil profile,

– intermittent measuring of the evaporation from the soil surface including the ground vegetation.

A comparative investigation was simultaneously done in the young experimental beech stand.

The aim of this paper is to present the results obtained in two subsequent growing seasons, 2006 and 2007, which followed immediately after the snowbreakage, and to perform the related comparison and assessment.

MATERIAL AND METHODS

Experimental area

The Deštenská stráň experimental area in the Orlické hory Mts (50°19'20''N; 16°21'45''E) was established for studying the water balance of the Norway spruce and European beech ecosystems as the representatives of two most important tree species of the middle-altitude mountain locations in the Czech Republic. It consists of a pair of balance plots. Both of these balance plots (each sized 40 × 30 m) are cca 50 m apart from each other, being situated on a slope with WSW aspect and a mean gradient of 16 degrees at the altitude of 890 m. The mean annual daily air temperature is 4.9°C and the mean annual sum of precipitations is 1200 mm. The soils in both stands can be considered typical acid Cambisols of higher altitudes, sandy loam to loamy sand with 50% mean volume admixture of skeleton, the proportion of which reaches 90%–98% at a depth of 0.7–1.0 m (weathered parent rock being mica schist). The spruce and beech stands belong to the most widespread forest type of the spruce/beech forest vegetation zone, to the forest type of a spruce/beech stand on acid sites with *Deschampsia* (6K1).

Figure 1. Disturbed 25 years old Norway spruce stand and minimally disturbed 25 years old European beech stand

Description of forest stand development and present feature of the spruce and beech stands on experimental balance plots

1976–1981: observation of the water balance components run in the mature spruce and beech large-diameter stands (interception and transpiration of trees, soil surface evaporation, soil moisture changes, surface runoff, seepage of water, snow cover parameters, air temperature and humidity) (Kantor 1984).

1982: forest regeneration by the clear felling method and hole planting of spruce and beech.

1983–2005: following the observation of the water balance components during the growth and progress, and tending both stands from plantation to small pole stage and pole stage stands (Kantor 1992, 1995) including foliage biomass (Kantor *et al*. 2009).

2005–2006: 25-year-old spruce stand was severely damaged in winter by crown and stem snow breaks, the young beech stand was afflicted with snow breaks only minimally; 98% spruce trees were affected by snow breakage, the stand density decreased from 1550 to 950 trees per ha, the needle foliage of the stand was reduced to about 40%, and the stand canopy was markedly disturbed

2006: following the observation of the water balance components in the recovering spruce and beech stands after the snow disaster

2007: stand gaps began to get infested by forest weeds whose cover reached up to 80% in the summer and autumn.

Total evapotranspiration of the young spruce and beech stands – ET

During the growing season from May 1 to October 31 in 2005, 2006 and 2007, ET was determined by the calculation obtained through the continuous measurement of the volumetric moisture changes in the soil profile (Šach *et al*. 2006, 2007). An analogous procedure, e.g. Tesař *et al*. (1992) and Vilhar *et al.* (2005), was also used but with discrete data from discontinuous observations. By rooting through depth, we induced the thickness of the root zone equal to 500 mm for calculating ET (similarly Tužinský 2004). The volumetric soil moisture was measured with the VIRRIB transducers by Doležal and Vlčková (2006) belonging to sufficiently precise ones in the estimation of the changes in the volumetric soil moisture. The transducers were placed into the deductive root zone in depths of 50 mm, 200 mm, and 500 mm with 3 repetitions. The repeating followed the forest stand variability. In 3 depths with 3 repetitions the total of 9 transducers were placed into each forest stand.

Procedure of calculating evapotranspiration of a forest stand

The calculation of evapotranspiration in mm for a particular soil layer per month was done by using the formula:

$$ET_{LM} = \Sigma W_V \times D_{SL} \times (1 - S_{VP})$$

ET_{LM} – evapotranspiration for a soil layer (mm/month)
ΣW_V – sum of volumetric soil moisture decrements as decimal number
D_{SL} – soil layer thickness (mm)
S_{VP} – skeleton volumetric proportion as decimal number (an especially important entry e.g. by Childs & Flint 1990 or by Boyles & Tajchman 1984)

The sum of ET_{LM} for three observed soil layers of the root zone represents the evapotranspiration of the forest stand in the respective month. Using the newly devised metod, we can also calculate the daily values of ET (Šach *et al.* 2006).

Criteria for calculating evapotranspiration of a forest stand

– We included the changes of the volumetric soil moisture into the calculation (the mean of 3 repetitions in the same depth) if the volumetric soil moisture in the subsequent record was lower than that in the preceding one.

– We did not usually include into the calculation small decreases in the volumetric soil moisture at night considering six-hour intervals (0, 6, 12, 18, 0, 6, ... hours of Central European Time – CET = UTC + 1).

– Decreases in the volumetric soil moisture during 12 hours after rain were considered to be a vertical flow and, especially at a low air temperature and a high air humidity (usually 100%), we did not take them into calculation (similarly Cheng 1987 under comparable conditions).

– During rain, when the volumetric soil moisture usually increases, we did not take ET into consideration.

Evaporation from soil surface including ground vegetation in the young spruce and beech stands – Es

Es was determined by intermittent accurate weighing sets of Popov's evaporimeters (Uhlíř 1961) in the summer hydrologic half year of 2005, 2006, and 2007. The evaporimeter with evaporative circle cross-section equal to 160 square centimetres indicated the evaporation from the soil layer 0–20 cm. The evaporimeter set (more than 10, usually 16) represented the proportional soil cover in the spruce and beech stands, and newly for comparison also on the clearcut. The observations were realised during characteristic rainless periods on the beginning, in the middle, and at the end of the growing season. They provided the results about the morning, afternoon, and night evaporation (in detail Kantor & Karl 2006; Kantor *et al.* 2007, 2008). The determination of evaporation is based on an accurate weighing of evaporative vessels at regular time intervals 3 to 4 times per day by a digital balance of KERN KB 6000-1 company (weighing rate 6100 g) with accuracy of ± 0.1 g. In the presented paper, three comparable 5-day cycles were evaluated from the 14th to the 19th June in the respektive years.

Related comparisons and assessments of the data samples were done using paired *t*-test. Statistically significant differences were expressed by *P*-value (probability of acceptance of H_0 hypothesis related to equality of means) and at the significance level of 0.05 are considered to be important. The test is highly convenient in view of normal distribution of the time series in question and correlated data (Brooks *et al.* 2003).

RESULTS AND DISCUSSION

Evapotranspiration of the spruce and beech stands

The results of the determination of evapotranspiration of the spruce and beech stands in particular

Table 1. Evapotranspiration (ET) of young spruce and beech stands in particular months of the summer hydrological half-year 2005 (calculation based on the continuous measurement of soil moisture) (in mm)

Month	Open area precipitation	Spruce ET	Beech ET
May	196.0	51.3	36.5
June	84.4	51.1	38.3
July	169.6	43.6	54.9
August	97.6	46.0	52.0
September	69.8	23.3	22.8
October	17.4	18.8	15.7
Total	634.8	234.1	220.2

Table 2. Evapotranspiration (ET) of young spruce and beech stands in particular months of the summer hydrological half-year 2006 (calculation based on the continuous measurement of soil moisture) (in mm)

Month	Open area precipitation	Spruce ET	Beech ET
May	174.6	49.0	47.1
June	87.5	48.0	40.5
July	77.9	36.9	33.3
August	332.0	26.7	27.5
September	133.8	46.8	42.9
October	69.3	13.4	10.0
Total	875.1	220.8	201.3

Table 3. Evapotranspiration (ET) of a young spruce and beech stand in particular months of the summer hydrological half-year 2007 (calculation based on the continuous measurement of soil moisture) (in mm)

Month	Open area precipitation	Spruce ET	Beech ET
May	66.5	38.7	33.6
June	122.2	33.8	39.5
July	173.0	53.1	61.5
August	78.2	35.7	37.1
September	141.2	27.4	33.5
October	125.0	18.2	18.6
Total	706.1	206.9	223.8

months of the summer hydrological half-year 2005 are presented in Table 1. These data indicate a gradual increase of evapotranspiration of the beech stand from May to July associated with foliage. In September and October, the spruce and beech stands did not show any practical differences at low values of evapotranspiration. In total, evapotranspiration amounted to 234.1 mm with the spruce stand and 220.2 mm with the beech stand. The difference was negligible (non significant at P-value of paired t-test = 0.603).

The total evapotranspiration in the spruce pole-stage stand slightly decreased (220.8 mm) in 2006 as compared to the previous year, however, it was lower even in the beech small pole-stage stand, viz. 201.3 mm (Table 2). Thus, the anticipated reduction of the spruce layer transpiration was compensated by the soil surface evaporation and the ground vegetation transpiration. However, ET lower by 20 mm in the beech stand was statistically significant in comparison with that in the spruce stand (P-value = 0.032).

Table 4. Evaporation from the soil surface and ground vegetation (Es) in June 2005

Date	Time of measurement	Temperature (°C)	Humidity (%)	Precipitation (mm)	Spruce Es (mm/h)	Spruce Es (mm/day)	Beech Es (mm/h)	Beech Es (mm/day)
14/6	8:00	13.1	91.3	0.0	0.00	0.67	0.00	0.64
	12:00	20.4	65.6		0.06		0.05	
	16:00	21.6	55.7		0.10		0.10	
15/6	8:00	17.0	75.6	3.4	0.04	0.70	0.05	0.89
	12:00	16.4	88.8		0.01		0.02	
	16:00	15.6	100.0		0.01		0.01	
16/6	8:00	15.0	92.3	0.2	0.00	0.41	0.00	0.49
	12:00	17.9	77.7		0.05		0.04	
	16:00	18.6	70.8		0.06		0.08	
17/6	8:00	16.6	76.2	0.0	0.03	0.81	0.04	1.07
	12:00	16.0	79.4		0.03		0.04	
	16:00	16.5	79.4		0.05		0.06	
18/6	8:00	11.4	94.2	2.0	0.00	0.77	0.00	0.93
	12:00	15.9	55.6		0.09		0.11	
	16:00	17.2	59.6		0.10		0.12	
19/6	8:00	13.2	72.3	0.0	0.03	0.81	0.04	0.96
	12:00	16.6	61.0		0.02		0.02	
	16:00	20.4	58.3		0.03		0.03	
Total				5.6		4.17		4.98

Table 5. Evaporation from the soil surface and ground vegetation (Es) in June 2006

Date	Time of measurement	Temperature (°C)	Humidity (%)	Precipitation (mm)	Spruce Es		Beech Es	
					(mm/h)	(mm/day)	(mm/h)	(mm/day)
14/6	8:00	15.2	57.7	0.0	0.02	1.83	0.01	0.92
	12:00	22.7	42.5		0.15		0.08	
	16:00	23.4	36.2		0.21		0.05	
	20:00	15.4	54.4		0.10		0.10	
15/6	8:00	15.4	63.3	0.0	0.03	1.92	0.02	0.81
	12:00	23.8	44.4		0.11		0.03	
	16:00	25.3	35.6		0.19		0.05	
	20:00	16.6	60.4		0.09		0.06	
16/6	8:00	20.0	57.9	0.0	0.03	1.96	0.02	0.72
	12:00	26.5	64.0		0.11		0.02	
	16:00	27.1	39.9		0.18		0.03	
	20:00	19.4	63.5		0.10		0.06	
17/6	8:00	13.9	100.0	1.2	0.01	0.73	0.01	0.31
	12:00	22.6	66.1		0.02		0.01	
	16:00	21.2	65.8		0.11		0.05	
	20:00	16.5	81.4		0.07		0.03	
18/6	8:00	13.0	76.1	0.0	0.02	1.42	0.01	0.54
	12:00	19.2	57.8		0.08		0.02	
	16:00	21.2	53.5		0.15		0.03	
	20:00	15.2	75.1		0.07		0.04	
19/6	8:00	17.0	74.6	0.0	0.02	1.32	0.02	0.77
	12:00	27.8	49.2		0.07		0.02	
	16:00	26.9	54.2		0.13		0.03	
	20:00	19.6	85.6		0.04		0.04	
Total				1.2		9.18		4.07

The values of evapotranspiration of the spruce and beech stands in particular months of the summer hydrological half-year 2007 are presented in Table 3. Monthly totals are primarily dependent on the climatic factors. Thus, they were markedly the highest in the warmest and precipitation-favourable July (spruce 53.1 mm, beech even 61.5 mm). In the following spring and summer months, the evapotranspiration of both stands was balanced ranging from 27.4 (September) to 38.7 mm (May) in the spruce- and from 33.5 (September) to 39.5 mm (June) in the beech stands. In the last month of the vegetation half-year (in October), the evapotranspiration of both stands decreased to 18.2 or 18.6 mm. Thus, throughout the whole growing season of 2007, the spruce stand consumed 206.9 mm water for evapotranspiration in total and the beech stand by 10% more, i.e. 223.8 mm. The difference was nevertheless small and non significant at P-value of paired t-test = 0.219.

Evaporation from the soil surface

The results of the evaporation measurements from the soil surface and ground vegetation carried out in 2005, 2006, and 2007 (always from 14/6 to 19/6) are compiled in Tables 4, 5, and 6, and the development of cumulative values in

Table 6. Evaporation from the soil surface and ground vegetation (Es) in June 2007

Date	Time of measurement	Temperature (°C)	Humidity (%)	Precipitation (mm)	Spruce Es (mm/h)	Spruce Es (mm/day)	Beech Es (mm/h)	Beech Es (mm/day)
14/6	8:00	19.3	75.0	0.0	0.03	3.15	0.02	0.73
	12:00	23.6	52.3		0.22		0.02	
	16:00	24.4	45.1		0.36		0.06	
	20:00	18.9	70.7		0.11		0.05	
15/6	8:00	20.2	80.3	0.0	0.03	3.05	0.01	0.58
	12:00	29.1	52.3		0.24		0.01	
	16:00	28.3	49.7		0.34		0.04	
	20:00	19.2	77.3		0.10		0.05	
16/6	8:00	10.4	100.0	5.4	0.00	0.75	0.00	0.48
	12:00	14.9	100.0		0.01		0.00	
	16:00	17.7	82.3		0.07		0.03	
	20:00	14.8	75.1		0.11		0.09	
17/6	8:00	14.3	74.4	0.0	0.03	2.60	0.03	1.01
	12:00	19.6	51.8		0.18		0.04	
	16:00	22.0	48.3		0.28		0.06	
	20:00	17.9	61.0		0.12		0.06	
18/6	8:00	14.6	100.0	1.6	0.02	0.62	0.02	0.44
	12:00	13.3	100.0		0.00		0.00	
	16:00	18.6	94.9		0.01		0.00	
	20:00	16.1	80.7		0.09		0.04	
19/6	8:00	17.6	74.7	0.0	0.02	2.65	0.02	0.81
	12:00	22.8	58.7		0.19		0.03	
	16:00	26.1	44.9		0.30		0.04	
	20:00	17.2	74.4		0.11		0.06	
Total				7.0		12.82		4.05

Figure 2. As already noted in methodology, the evaporation vessels were installed in the fully closed beech stand were are permanently covered with litter. The same surface occurred also in evaporimeters placed in the spruce stand in 2005. After the disastrous snow breakage in the winter of 2005/2006, however, a marked disturbance of the crown canopy occurred. The stand gaps (including evaporimeters placed there) began to be gradually colonised with forest weeds, the cover of which reached 50 to 60% in the summer and autumn of 2006 and up to 80% in 2007. On the basis of this starting situation, it is also necessary to evaluate the results obtained.

Table 4 shows that on the turn of the spring and summer of 2005, the soil surface evaporation was quite comparable in both fully closed stands. The difference was small and without any practical importance, although it was significant at P-value of paired t-test = 0.021. In the course of 5 days, the evaporation in the spruce stand amounted to 4.17 mm, and in the beech stand a little more, viz. 4.98 mm. The daily values ranged from 0.41 to 1.07 mm depending on the course of weather. Thus, a markedly lower evaporation was observed at night than during the day in both stands.

Diametrically different results were, however, noted in the following year 2006 (Table 5). As a

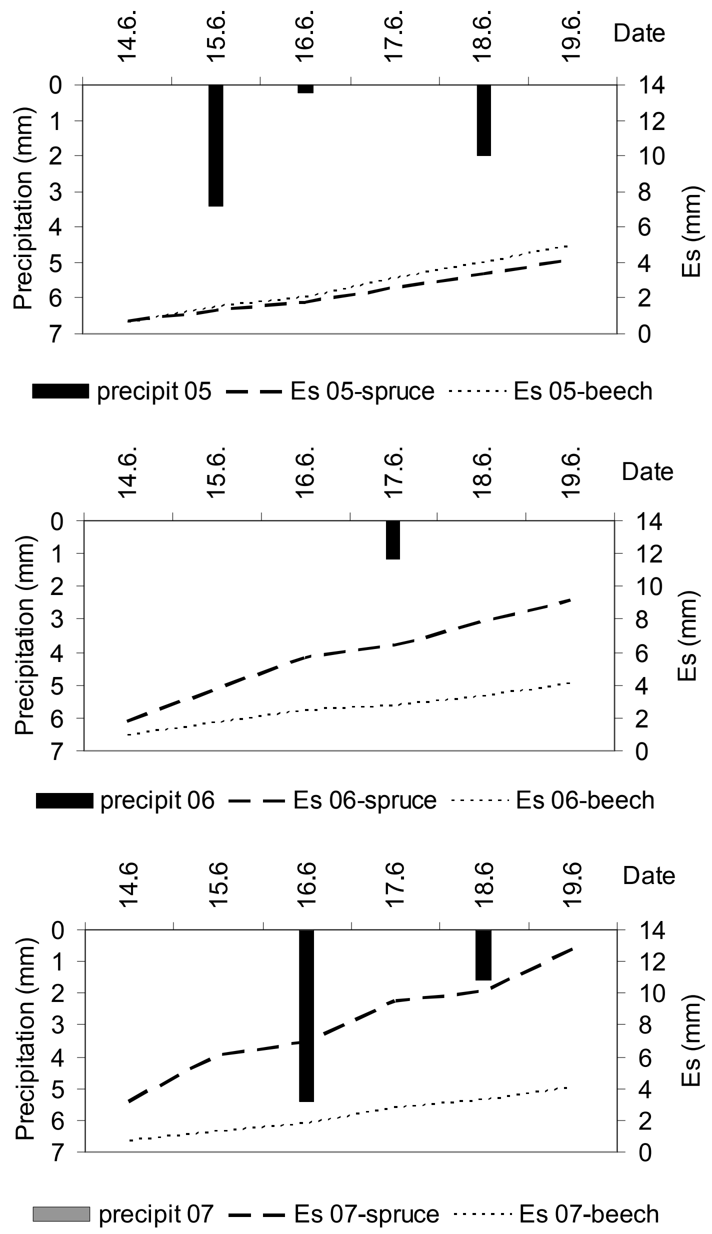

Figure 2. Differing evaporation Es between young Norway spruce and European beech stands due to snowbreakage (upper – 2005, middle – 2006, lower – 2007)

rule, a markedly higher evaporation was generally noted in the gappy spruce stand (significant at *P*-value of paired *t*-test = 0.001). The mean differences between the spruce and beech stands were more than double in the morning evaporation and even fourfold in the afternoon evaporation. Only the evening and night evaporations were virtually balanced in both stands with differences being negligible. During 5 days of measurements in June, by 5.11 mm more water evaporated in the spruce stand than in that of beech.

Table 6 shows again an extremely high evaporation in the spruce stand as compared to the beech stand in 2007. This difference was even markedly higher than in the previous year (significant at *P*-value of paired *t*-test = 0.017). In the spruce stand, the morning evaporation ranged depending on the course of weather up to 0.24 mm per hour, in that of beech only to 0.04 mm per hour. The afternoon evaporation was again markedly higher in the spruce stand (up to 0.36 mm per hour) than in that of beech (at the most 0.06 mm per hour).

The evening evaporation amounted to 0.11 mm on average per hour in the spruce stand, in that of beech to 0.06 mm per hour.

The night evaporation was then already markedly lower in both the spruce and the beech stands, viz. 0.03 mm per hour at the most. The extremely high evaporation in the spruce stand (in the course of the day 7–10 times higher than in the beech stand) is explainable by the ground vegetation evapotranspiration, whose cover reached about 65% after disturbing the stand canopy in the spring of 2007.

DISCUSSION

The method of ET computation in the young spruce- and the young beech stands based on the volumetric moisture changes in the soil profile (soil water content variation) as applied on the Deštenská hillside in the Orlické hory Mts, comes from similar principals as the method based on tensiometric measuring of the suction pressure in the soil profile in mature spruce and beech stands on a NE slope in the experimental object Zdíkov-Liz in the Šumava Mts (Mráz *et al.* 1990). Also the observed soil profile depths (100, 200 and 500 mm) corresponded practically to those on the Deštenská hillside including the features and course of drawing water for ET. In the observed growing seasons of 1986–1989, the calculated ET in the mature spruce stand were equal to 274 mm on average. ET in the mature beech stand was calculated only in the growing season of 1989 and its value exceeded 300 mm (Mráz *et al.* 1990). There exists a methodically related procedure by Tesař *et al.* (2001), who introduced the term of "actual retention capacity of soil" as the difference between the "field capacity" and "wilting point". In that range, similarly described by Švihla *et al.* (2007), a forest stand realises the water uptake for ET. The values of ET from the Deštenská hillside correspond with those given by other authors doing research in comparable mountain conditions (e.g. Střelcová & Minďáš 2000; Střelcová *et al.* 2004; Tesař *et al.* 2001; Tužinský 2000, 2004). These results were also discussed in the papers by Šach *et al.* (2006) and Černohous and Šach (2008).

Before the snowbreak (2005) the evaporation from the soil surface and ground vegetation (Es) did not greatly differ between the spruce and beech stands in the snowbreak year (2006) and after (2007), it differed in an important way. It is possible to estimate easily that per 1 mm Es in the beech stand in the second decade of June (from 14^{th} to 19^{th}) in the year before the snowbreakage (2005) there came 0.8 mm, in the year of the snowbreakage (2006) 2.3 mm, and in the year after snowbreakage (2007) 3.2 mm Es in the spruce stand. By intermittent measuring, the evaporation from the soil surface and ground vegetation evidently substituted the reduced transpiration of the spruce broken canopy, if total ET did not change significantly (similar values for grassy vegetation were estimated by Duffková 2003 or by Tesař *et al.* 2001). At the same time, per l mm ET in the beech stand there came respectively 1.0 mm, 1.6 mm, and 0.8 mm ET in the spruce stand calculated by the method of ET-SWCV by daily database of ET (an example see Šach *et al.* 2006).

CONCLUSION

Primarily, an extremely high increase of the soil surface evaporation was found in a gappy spruce stand disturbed by snow breakage. Immediately after the disaster, maximum daily totals of evaporation ranged from 1.5 to 2.0 mm in the spring and summer of 2006, while in the beech stand they reached half these values. In the following year 2007, with gradual weed infestation of the stand gaps, the values of evaporation in the spruce stand reached up to 3 mm per day (exceptionally even more), being on the level of weed-infested clear felled area on warm summer days. On the same days, the evaporation in the fully closed beech stand was usually 3 to 4 times lower.

Total evapotranspiration ET (evaporation from the soil surface and ground vegetation + transpiration of trees) was comparable in both stands (200 to 235 mm for the growing season). Until 2006, ET was 10% higher in the spruce stand, whereas in 2007, ET was 10% higher in the beech stand.

It follows that the actual transpiration of the spruce itself markedly decreased after the snow disaster. The main reason resides in the marked reduction of the tree needle foliation (qualified estimate – about 40% of the original values remained in 2006).

As concerns the following years, it is possible to anticipate gradual stabilisation of the spruce stand (of course, with a worse quality of individual trees – bayonet-shaped trees), canopy closing, increasing transpiration and, on the other hand, decreasing evaporation from the soil surface. In the course of further years, it will be possible to assess if this scenario has taken the expected course or, vice versa, if other destruction of the spruce stand can occur.

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