Influence of snow damage on aerodynamic characteristics of spruce stand

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Abstract Influence of snow damage on the aerodynamic characteristics of the forest stand was investigated during the growing seasons of the 2005 and 2006 before and after the winter 2005/2006 which caused the forest damage. With this aim the wind speed profiles measured in and above investigated spruce forest stand were analyzed. This forest is situated in the experimental site at Bílý Kříž (49^{0}30'17" N, 18^{0}32'28" E, 898–908 m a.s.l.) in Moravian-Silesian Beskydy, the Czech Republic. The experimental site consisting of two plots (Fd and Fs) with different stand density is created by the monoculture of a Norway spruce stand. In the growing season 2005 the mean tree height in Fd plot with density 2044 trees/ha was 11.9 m and 11.0 m in Fs plot with density 1652 trees/ha. The microclimatic profile measurements of the wind speed were realized in 6 levels on 26 m high tower in the both plots.

The winter of the years 2005/2006 in the investigated locality was characterized by continuous snow blanket from November 2005 to April 2006 with high water value. Forest damage by this snow was noticeable, mainly in denser plot. About 30% from investigated trees were broken in Fd plot and 13% in Fs plot. It evokes occurring of new conditions for airflow within and above this forest stand and then changes of the aerodynamic characteristics: the dynamic roughness length (z_0) and the zero plane displacement height (d).

Key words: *snow damage, spruce stand, wind speed, roughness length, zero plane displacement*

Introduction

Forest damage caused by wind, snow, and frost is a serious economical problem concerning forestry in Europe. On the other site the damaged forest influences the airflow and meteorological characteristics in the atmosphere layer affected by this stand. It was found that recently thinned forest is more likely to be damaged than unmanaged dense forest stand. Openness seems to increase the possibilities for damage especially in windstorm. Snow damages forest also in the middle of the stand (Pellikka, Järvenpää, 2003). The severity of snow damage is related to tree characteristics. Stem taper and crown characteristics are the most important factors controlling the mechanical trees stability (Nykänen et al., 1997).

The majority of forest ecosystems in the Czech Republic are composed of Norway spruce stands which have more than 80% share. The extensive research of the climate of the Norway spruce monoculture is carried out at the Experimental Ecological Study Site at Bílý Kříž in the Moravian-Silesian Beskydy Mts, the Czech Republic (Kratochvílová et al., 1989). In the framework of this research the radiation measurements, the soil temperature measurements, the profile measurements of the wind speed, the air temperature and humidity in and above this forest stand have been carried out. So, the microclimate of this spruce stand can be studied on the basis of these measurements from the growing season of 1997 (Rožnovský, J., 1998; Matejka et al., 2000). The winter 2005/2006, which was characterized by long time continuous snow blanket with high water value, caused the forest damage in this locality. It caused, that the microclimatic characteristics of this forest were changed.

The aim of this contribution is the analysis of the influence of snow damage on the airflow and the aerodynamic characteristics of the spruce stand: the dynamic roughness length and the zero plane displacement. Mainly two growing seasons of this stand were compared, the growing season (May – October) of 2005, before damage and of 2006 one, when the spruce stand was damaged by snow.

Experimental site and data

The experimental data needed for this study were obtained by measurements in the Experimental Ecological Study Site of the Institute of Systems Biology and Ecology, Academy of Sciences of the Czech Republic. This experimental site is situated on a mild slope with SW orientation in the locality

Bílý Kříž ($49^0 30'17''$ N, $18^0 32'28''$ E, 898–908 m a.s.l.) in the highest part of the Moravian-Silesian Beskydy Mts (Janouš, Schulzová, 1995). The investigated forest is formed by the Norway spruce monoculture (*Picea abies* [L.] Karst) with age of 16 years in 1997 (age of the trees was 20 years), when the automatic wind speed profile measurements in and above this forest stand in Fd plot started. The automatic profile measurements in Fs plot started in 1998.

Within the spruce stand two plots with different stand densities were established after thinning at autumn 1996 and 1997 for further continuous research. In this way two experimental plots with dense forest (Fd) and sparse forest (Fs) have arisen. Each of these plots had the area of 0.25 ha. Later, in early May 2001, an additional thinning was carried out in Fs plot. In the growing season 2005 in Fd plot the density was 2044 trees/ha and their mean tree height (*h*) was 11.9 m. In Fs plot the density was 1652 trees/ha and the mean tree height 11.0 m.

By the climatic classification the locality Bílý Kříž is a cool and humid region with abundance of precipitation. The mean annual air temperature is 5 – 6 ^{0}C, the mean annual precipitation total is 1000 – 1200 mm, and the mean air humidity is 80 – 85%. The mean number of days with continuous snow blanket is 120 – 140 (Tolasz et. al., 2007).

The prevailing wind direction above the investigated spruce forest stand is south, in spite of this, generally in this part of the Beskydy Mts north and west airflow predominates. It is a result of the orographic broken terrain (Havránková et al., 2001).

The wind speed and direction was measured continuously by the measured system InSituFlux (Sweden). It is a system to measure the fluxes of energy and substances between a surface and boundary layer of the atmosphere using the eddy-covariance method. Simultaneously the microclimatic profile measurements of the wind speed, air temperature and humidity in and above investigated forest stand were realized in 6 levels on 26 m high tower in both experimental plots. The wind speed values were continuously measured by automatic measuring equipment with data logger (DL3000, Delta-T, U.K.) and anemometers (AN1, Delta-T, U.K.) in the 10-minute intervals and recorded each 30-min.

Aerodynamic characteristics of an air layer affected by vegetation can be described using parameters: the roughness length z_0 and the zero plane displacement height *d*. The *d* values were determined by processing the vertical wind speed profiles measured at the neutral thermal stratification of the atmosphere (Brutsaert, 1982). The values of z_0 can be obtained from the analysis of the vertical wind speed profiles measured above an active vegetation surface under different atmosphere thermal stratification (Monin, Obukhov, 1954; Matejka et al., 2000). Following from the Monin-Obukhov similarity theory each vertical wind speed profile $\bar{u}_k(z_i)$ can be approximated by the relation

$$u_k(z_i) = A_k(\gamma + \log z_i) + C_k z_i, \quad (1)$$

where *k* is the profile number. The values of A_k, γ, and C_k parameters are calculated by the least squares method for every profile. Then the values of z_0 are obtained from following relationship (Monin,Obukhov, 1954)

$$z_0 = 10^{-\gamma}. \quad (2)$$

For the analysis of the vertical wind speed profiles a selected set was used. The analysed mean hourly values of measured wind speed fulfilled the condition: $u(h-1) > 1.0$ m s^{-1}. This selection provided that the wind speed profiles were measured in the conditions of turbulence development.

Results and discussion

The winter of the years 2005/2006 in the investigated locality was characterized by continuous snow blanket from the half of November, 2005 to end of April, 2006 with high water value.

Experiment site at Bílý Kříž in April 20, 2006

The mean monthly value of height total of snow blanket and the mean monthly value of its water value is in the Table 1 (data base CHMI).

Table 1 The mean monthly value of height total of snow blanket (h_s) and of snow water value (SWV) in the locality Bílý Kříž during winter 2005/2006.

year	**month**	h_s **[cm]**	**SWV [mm]**
2005	November	31	75
	December	81	163
2006	January	140	313
	February	154	424
	March	140	468
	April	54	300

Forest damage by this snow was noticeable, mainly in denser plot. A lot of trees were damaged and more trees were removed. In the end of growing season 2005 in Fd plot the density was 2044 trees/ha and 1652 trees/ha in Fs plot. The tree density in 2006 was 1652 trees/ha in Fd and 1428 trees/ha in Fs plot. It means that 19% of all trees in Fd and only about 1% in Fs plot were removed. And further about 30% from investigated trees were broken in Fd and about 13% in Fs plot. The tree heights were measured on 514 individuals in Fd and on 414 ones in Fs plot. In Fd plot the mean tree height in 2006 year was 13.1 m and h value of broken trees was 5.5 m. The mean tree height including broken trees $h^* = 10.8$ m. In Fs plot $h = 11.9$ m, h value of broken trees 4.0 m, and $h^* = 10.9$ m. It evokes occurring of new conditions for airflow within and above this forest stand and then changes of its aerodynamic characteristics.

The analysed set, which fulfilled the condition mentioned before, contained 474 wind speed profiles in growing season (May – October) 2005 and 856 ones in 2006 in Fd plot. From these same growing seasons in Fs plot 1899 profiles and 1747 ones were analysed. So, the selection of analysed profiles differs between Fd and Fs plot in the same growing season. More wind speed profiles with the fulfilled condition were analysed in Fs than in Fd plot in all investigated growing seasons. It can be explained by the influence of local broken terrain on the airflow in these experimental plots (Havránková et al., 2001).

In Fd plot the wind speed were measured in six levels: 9, 11, 12, 14, 18, and 26 m during growing season 2005 when the mean tree height $h = 11.9$ m and 10, 12, 13, 14, 18, and 26 m during season 2006 with $h = 13.1$ m. In Fs plot the measured levels were 8, 10, 11, 13, 18, and 26 m in 2005, $h = 11.0$ m and 9, 10, 12, 13, 18, and 26 m in 2006 with mean tree height $h = 11.9$ m. These profiles were divided into following ranges:

$$\begin{array}{ll} \text{I} & 1.0 < u(z) < 2.0 \text{ m s}^{-1}, \\ \text{II} & 2.0 \le u(z) < 3.0 \text{ m s}^{-1}, \\ \text{III} & 3.0 \le u(z) < 4.0 \text{ m s}^{-1}, \\ \text{VIII} & 8.0 \le u(z) < 9.0 \text{ m s}^{-1}, \end{array} \qquad (1)$$

where $u(z)$ is the wind speed value measured in the level $z \approx h$, it means $z = 12.0$ m (2005), 13.0 m (2006) in Fd plot, and 11.0 m (2005) and 12.0 m (2006) in Fs. Per cent representation of analysed wind speed profiles in these ranges is in Table 2.

Table 2 Per cent representation of analysed wind speed profiles in ranges by Eqs (1) measured in both plots during growing seasons 2005 and 2006.

Ranges	**Fd**		**Fs**	
	2005 [%]	**2006 [%]**	**2005 [%]**	**2006 [%]**
I	7.4	3.9	44.6	39.8
II	44.3	18.7	29.4	32.7
III	39.9	34.0	18.0	16.6
IV	8.4	24.2	7.4	8.4
V	- - -	13.4	0.7	2.3
VI	- - -	4.6	- - -	0.2
VII	- - -	1.1	- - -	- - -
VIII	- - -	0.2	- - -	- - -

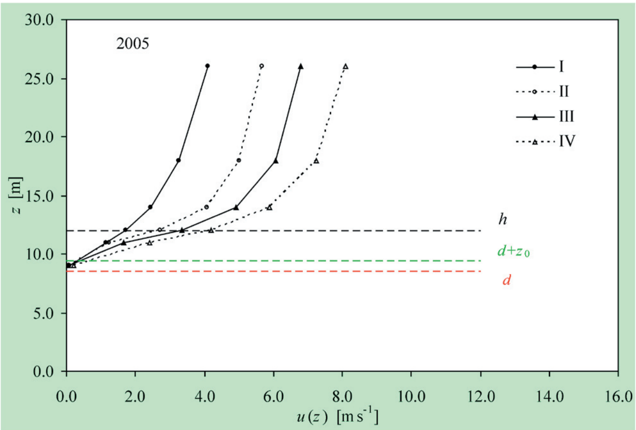
From this analysis, Table 2, it follows, that airflow in growing season 2006 was stronger in both plots, mainly in denser plot, when more than 50% analysed profiles were in range III and IV. In Fs plot more than 70% ones were in range with lower wind speed I and II. It was caused by different conditions for airflow in forest damage in these plots.

The mean vertical wind speed profiles in ranges by Eqs (1) are graphically presented in Figs 1 and 2. Stronger airflow in both plots during growing season 2006 is evident also from mean wind speed profile courses. The zero plane displacement (d) and dynamic roughness length (z_0) are important characteristics of vegetation aerodynamic properties. The zero plane displacement increased with stand density and with the height of the centre of gravity of the vegetation. It can be expected that the penetration of airflow into forest was reduced as a result of a gain of the biomass at this development stage of the forest (Jeager, 1984). Simultaneously, the ratio d/h varied during investigated growing seasons in dependence on spruce stand characteristics, Table 3. Since 1997, the specific architecture of this spruce forest, being sparse in the upper part and denser near the ground, started to show more expressive. The value of d as well as of ratio d/h in both plots during investigated growing seasons is relatively high, besides in 2006, Table 3.

Table 3 Values of ratio d/h averaged over nine grooving seasons in both experimental plots.

	1998	1999	2000	2001	2002	2003	2004	2005	2006
Fd	0.75	0.76	0.76	0.76	0.74	0.76	0.77	0.72	**0.59**
Fs	0.69	0.70	0.76	**0.60**	0.70	0.70	0.68	0.64	**0.62**

The significant decrease of d value in Fs during growing season 2001, d/h = 0.60, was obviously caused by the trees thinning performed in this plot in May 2001, which reduced the stand density from 2400 trees/ha to 1880 trees/ha. The other situation was in growing season 2006. The strong forest damage in Fd plot caused significant fall in the d value, d = 8.5 m in 2005 and d = 7.5 m in 2006. The forest damage in Fs plot was not to strong and d value was 7.0 m in both seasons 2005 and 2006.



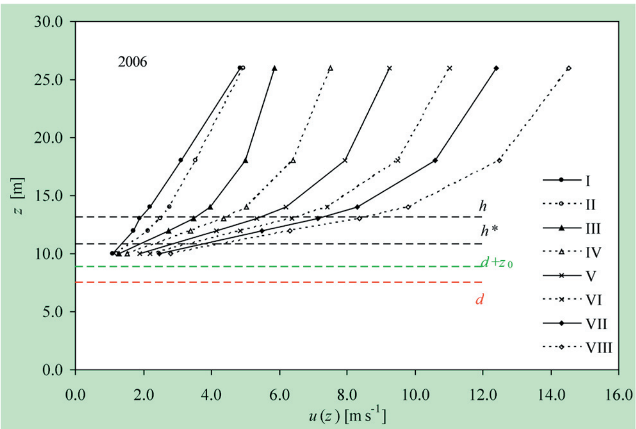
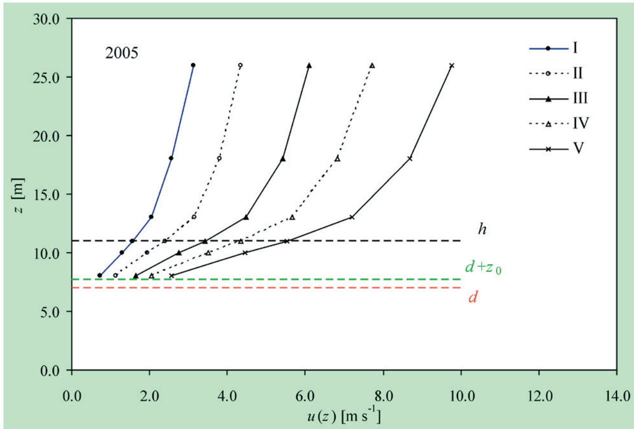


Fig. 1 Mean vertical wind speed profiles in ranges Eqs (1) in Fd plot during growing season 2005 and 2006.
h – mean tree height, h^* - mean tree height including broken trees, d – zero plane displacenemt, z_0 – dynamic roughness length



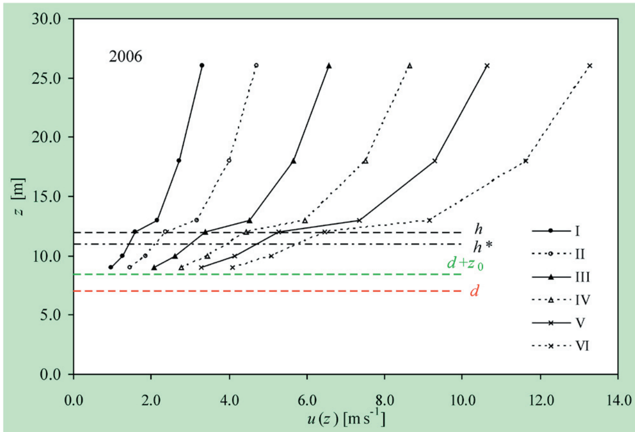


Fig. 2 Mean vertical wind speed profiles in ranges Eqs (1) in Fs plot during growing season 2005 and 2006.
The symbols h, h^*, d, and z_0 as in Fig. 1.

Average seasonal values of the mean tree height and the zero plane displacement in both plots, and the dynamic roughness length in Fd one during ten growing seasons are graphically presented in Fig. 3. The z_0 values of the sparse forest in Fs plot are lower than in Fd plot (Hurtalová et al., 2004, 2006).

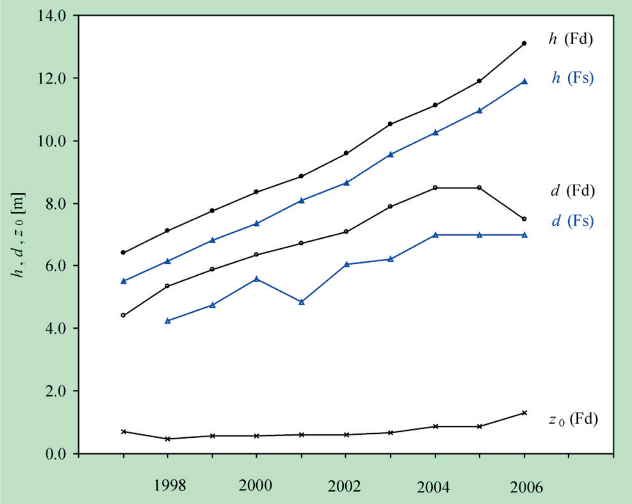


Fig. 3 Average seasonal values of the mean tree height (h), the zero plane displacement (d), and the roughness length (z_0) of investigated spruce stand during ten growing seasons.

It takes into consideration, that in the case of flexible vegetation cover d and z_0 values vary with the wind speed (Hayashi, 1983). In Fd plot mean monthly values of z_0 during investigated ten seasons fluctuated between 0.2 and 1.9 m (Hurtalová et al., 2004, 2006). The mean annual value of z_0 of damage forest increased from 0.9 m in 2005 on 1.3 m in 2006.

Conclusions

It is known, that airflow in and above forest stand is dependent on aerodynamic properties of this stand. It means that damage forest with broken trees creates new conditions for airflow. The analysis of influence of snow damage on aerodynamic characteristics of spruce stand confirmed it.

Forest damage caused by wind and snow depends on several factors: meteorological factors (wind speed and precipitation), topographical factors, forest stand characteristics, tree species and factors related to landscape, especially openness (Nykänen et al., 1997). Summary of these factors and continuous snow blanket from November 2005 to April 2006 with high water value in the locality Bílý Kříž caused considerable damage of investigated spruce stand. This damage was different in dense (Fd) and sparse (Fs) plots. In Fd plot 19% of all trees were removed and above 30% from investigated trees were broken. In Fs plot about 1% was removed and about 13% trees were broken. It evokes occurring of new conditions for airflow within and above this forest stand and then changes of its aerodynamic characteristics.

It was shown, that airflow in growing season 2006 was stronger in both plots, mainly in denser one, when more then 50% analysed wind speed profiles were in ranges $3.0 \leq u(z) < 4.0$ m s^{-1} (34.0 %) and $4.0 \leq u(z) < 5.0$ m s^{-1} (24.2%). Further the strong forest damage in Fd plot caused significant fall in the zero plane displacement value, $d = 8.5$ m in 2005 and $d = 7.5$ m in 2006. The forest damage in Fs plot was not to strong and d value was 7.0 m in both seasons 2005 and 2006. The annual mean value of z_0 of damage forest in Fd increased from 0.9 m in 2005 on 1.3 m in 2006.

Numerous authors cited by Nykänen et al. (1997) have proved that trees are especially susceptibility to damage after 5 to 10 years after thinning. Within the investigated spruce stand two plots with different stand densities were established after thinning at autumn 1996 and 1997 for further continuous research. Further the trees thinning performed in Fs plot in May 2001, which reduced the stand density from 2400 trees/ha to 1880 trees/ha. In spite of this forest damage was more intense in Fd than in Fs plot. It can be explained by the orographic broken terrain. Snow accumulation is the highest during light winds (Pellikka, Järvenpää, 2003). And as it follows from our analysis more wind speed profiles with the fulfilled condition $u(h-1) > 1.0$ m s^{-1} were analysed in Fs than in Fd plot during all investigated growing seasons.

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