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Influence of snow damage on aerodynamic characteristics of a spruce stand

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Abstract

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Influence of snow damage on aerodynamic characteristics of a spruce stand was investigated during the growing seasons 2005 and 2006 before and after the winter 2005/2006 that caused damage to the forest. With this aim, the wind speed profiles measured in and above the investigated forest stand were analyzed. This forest is situated in the Experimental Ecological Study Site Bílý Kříž in the Moravian-Silesian Beskydy Mountains, the Czech Republic. The experimental site consists of two plots with Norway spruce monocultures with different stand densities. In the growing season 2005, the mean tree height was 11.9 m on the "dense" plot (Fd; a density of 2,044 trees/ha) and 11.0 m on the "sparse" one (Fs; a density of 1,652 trees/ha). The measurements of wind speed profile were realized at six levels on 26-m-high towers situated near the centre of each plot. The winter 2005/2006 was characterized by continuous snow cover (from November 2005 to April 2006) with a high water value in the investigated locality. The damage to the forest caused by this snow blanket was noticeable, mainly in Fd. The stand density decreased by about 29% on Fd and by about 14% on Fs plot. It witnesses entirely new airflow conditions within and over this forest stand and connected changes in its aerodynamic characteristics.

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 in European forestry. The damaged forest, in its turn, influences the airflow and meteorological characteristics of the atmospheric layer affected by this stand. It has been recognised that a freshly thinned forest is more likely prone to damage than an intact dense forest stand. Low stand density seems to increase the probability of damage, especially from windstorms. Snow can cause damage to a forest also deep inside the stand (Pellikka and Järvenpää, 2003). The severity of snow damage depends on the tree characteristics. Stem taper and crown characteristics are the most important factors controlling the tree mechanical stability (Nykänen et al., 1997).

The majority of forest ecosystems in the Czech Republic consist of Norway spruce stands with a share exceeding 80%. The climate of Norway spruce monocultures is subject of an intensive research carried out at the Experimental Ecological Study Site (EESS) of the Institute of Systems Biology and Ecology (ISBE), AS CR, Bílý Kříž in the Moravian-Silesian Beskydy Mts (Kratochvílová et al., 1989). The research comprises:

measurements of solar radiation, measurements of soil temperature, profile measurements of the wind speed, air temperature and humidity inside and above the forest stand. The microclimate of the spruce stand at the site has been studied since the growing season 1997 (Rožnovský, 1998; Matejka et al., 2000). The winter 2005/2006 was characterized by a long period of continuous snow blanket with high water value, and it caused damage to the forest. The consequence was the changes in the microclimatic characteristics.

The aim of this contribution is to inform about our research on influence of snow damage on the airflow above and the aerodynamic characteristics of the examined spruce stand, particularly on the roughness length and zero plane displacement. These characteristics are very important in studying interactions between the vegetation cover and surface layer of the atmosphere. Therefore, growing seasons (May–October) 2005 (ie before damage) and 2006 (ie after damage) were compared from this point of view.

Experimental site and data

The experimental data for this study were provided by measurements within and over the spruce stand in the EESS. This experimental site is situated on a mild slope with SW orientation in the locality Bílý Kříž (49°30' 17" N, 18°32'28" E, 908 m asl; Janouš and Schulzová, 1995). The investigated forest consists of a Norway spruce monoculture (*Picea abies* [L.] Karst) established in 1981 with four-year-old seedlings.

To obtain two plots with different stand densities for further continual research, there were performed two thinning interventions in autumn 1996 and 1997. Each plot has an area of 0.25 ha. Later, in early May 2001, an additional thinning was carried out on Fs plot. In the growing season 2005, the density on Fd plot was 2,044 trees/ha and the mean tree height (*h*) was 11.9 m. Fs plot had the stand density 1,652 trees/ha and $h = 11.0$ m. Automatic measurements of wind speed profile within and above the plots started in 1997 (Fd) and 1998 (Fs).

The locality Bílý Kříž is classified as a cool and humid climatic region with abundant precipitation. The mean annual air temperature is 5–6 °C, the mean annual precipitation total is 1,000–1,200 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).

In general, north and west airflow predominates in the Beskydy Mountains, the south and south-southwest wind direction, however, is prevailing above the investigated spruce forest stand. It is a result of the highly diversified broken terrain (Havránková et al., 2001).

The wind speed and direction were measured continuously by an InSituFlux system (Sweden). The system enables us to measure the flux of energy and substances between the vegetative surfaces and boundary layer of the atmosphere, providing with the eddy-covariance method. At the same time, microclimatic profile measurements of the wind speed, air temperature and humidity inside and above the investigated forest stand were realized at six levels on a 26 m high tower in both experimental plots. The wind speed values were continually measured with an automatic measuring equipment with data logger (DL3000, Delta-T, U.K.) and anemometers (AN1, Delta-T, U.K.) at 10-minute intervals and recorded at 30-minute intervals.

Aerodynamic characteristics of vegetation cover can be described by the following parameters: roughness length z_0 and zero plane displacement d. The d values were determined by processing the results of measurements of the vertical wind speed profile 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 measurements above an active vegetation surface under different conditions of thermal stratification of the atmosphere (Monin and Obukhov, 1954; Matejka et al., 2000). According to the Monin-Obukhov similarity theory, each vertical wind speed profile $\bar{u}_k(z_i$ can be approximated by the relation:

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

where k is the profile number. The values of A_k, γ, and C_k parameter are calculated using the least squares method for all profiles. Then the values of z_0 are obtained from the following relationship (Monin and Obukhov, 1954):

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

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

Results and discussion

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

The mean monthly values of total snow blanket height and the mean monthly values of its water value are listed in Table 1 (data provided by the Czech Hydrometeorological Institute).

Forest damage from snow was noticeable, mainly on Fd plot. Many trees were seriously damaged and then removed. Towards the end of the growing season 2005 was the stand density 2,044 trees/ha on Fd and 1,652 trees/ha on Fs. In 2006, the stand density decreased to 1,444 trees/ha on Fd (ie about 29%) and 1,428 trees/ha on Fs (ie about 14%). Canopy openness, quantified through DIFN value ("by-product" of LAI-2000 Plant Canopy Analyser; Li-Cor, Nebraska, USA, during the leaf area index estimation as the visible proportion of sky), increased after the winter 2005/2006 by about 3.7% (ie from 1.1% to 4.8%) on Fd and by about 5.3% (ie from 2.2 to 7.5%) on Fs. Furthermore, some other trees had breaks in upper halves of their crowns. Tree height was measured on 514 exemplars on Fd and on 414 exemplars on Fs plot. On Fd plot, the mean tree height (h) in 2006 was 13.1 m and h value of broken trees was 5.5 m. The mean tree height including broken trees was $h^* = 10.8$ m. On Fs plot $h = 11.9$ m, h value of broken trees 4.0 m, and $h^* = 10.9$ m. This documents occurring of new conditions for airflow inside and above this forest stand, and also suggests about changes in its aerodynamic characteristics.

Table 1. Mean monthly values of total height of snow blanket (h_s) and of snow water value (SWV) in the locality Bílý Kříž during the 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

The analysed set, complying with the above mentioned conditions, consisted of 474 wind speed profiles obtained in the growing season (May–October) 2005 and 856 profiles obtained in 2006 on Fd plot. From the same growing seasons we analysed 1,899 profiles (2005) and 1,747 (2006) from plot Fs. We can see that there were differences in selection of profiles to be analysed between Fd and Fs plot in the same growing season. More wind speed profiles complying with the condition were analysed from Fs than from Fd plot also in all the investigated growing seasons (1997–2006). Consequently, the airflow above Fd plot is weaker than elsewhere in the surroundings. It can be explained by the influence of the local broken terrain on the airflow on these experimental plots (Havránková et al., 2001).

On Fd the wind speed was measured at six levels: 9, 11, 12, 14, 18, and 26 m above the ground during the growing season 2005 when the mean tree height $h = 11.9$ m and at 10, 12, 13, 14, 18, and 26 m during the season 2006 with $h = 13.1$ m. On Fs plot we measured at 8, 10, 11, 13, 18, and 26 m in 2005, $h = 11.0$ m and at 9, 10, 12, 13, 18, and 26 m in 2006 with mean tree height $h = 11.9$ m. These profiles were separated into the following range intervals:

$$\begin{array}{rl}
\text{I} & 1.0 < u(z) < 2.0 \text{ m s}^{-1} \\
\text{II} & 2.0 \leq u(z) < 3.0 \text{ m s}^{-1} \\
\text{III} & 3.0 \leq u(z) < 4.0 \text{ m s}^{-1} \\
\text{IV} & 4.0 \leq u(z) < 5.0 \text{ m s}^{-1} \\
\text{V} & 5.0 \leq u(z) < 6.0 \text{ m s}^{-1} \\
\text{VI} & 6.0 \leq u(z) < 7.0 \text{ m s}^{-1} \\
\text{VII} & 7.0 \leq u(z) < 8.0 \text{ m s}^{-1} \\
\text{VIII} & 8.0 \leq u(z) < 9.0 \text{ m s}^{-1}
\end{array} \tag{3}$$

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

Table 2. Percent representation of analysed wind speed profiles in ranges I–VIII according to Eq (3) measured on both plots in the locality Bílý Kříž during the growing seasons 2005 and 2006

Range	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 the airflow in the growing season 2006 was stronger on both plots, mainly on Fd, with more than 50% of the analysed profiles classified to intervals III and IV. On Fs plot, more than 70% of the analysed profiles were within lower wind speed intervals (I and II). It was caused by different conditions for airflow due to damage to forest on these plots.

The mean vertical wind speed profiles obtained according to Eqs (3) are graphically presented in Figs 1–2. Stronger airflow is also evident from the mean wind speed profile courses on both plots during the growing season 2006.

There were analysed the values of zero plane displacement (d) and dynamic roughness length (z_0). These characteristics of vegetation aerodynamic properties play an important role in the interaction between vegetation cover and lower layers of the atmosphere. The zero plane displacement increased with increasing stand density and increasing height of the centre of gravity of the vegetation. It can be expected that the penetration of airflow into the forest can be reduced as a result of gain of the biomass at this developmental stage of the forest (Jeager, 1984). Simultaneously, the ratio d/h varied during the investigated growing seasons in dependence on spruce stand characteristics (Table 3). Since 1997, the specific architecture of this spruce forest, being thin in the upper part and dense near the ground, started to appear more expressive. The values of d as well as of d/h ratio were quite high on both plots during the investigated growing seasons, except of 2006 (Table 3).

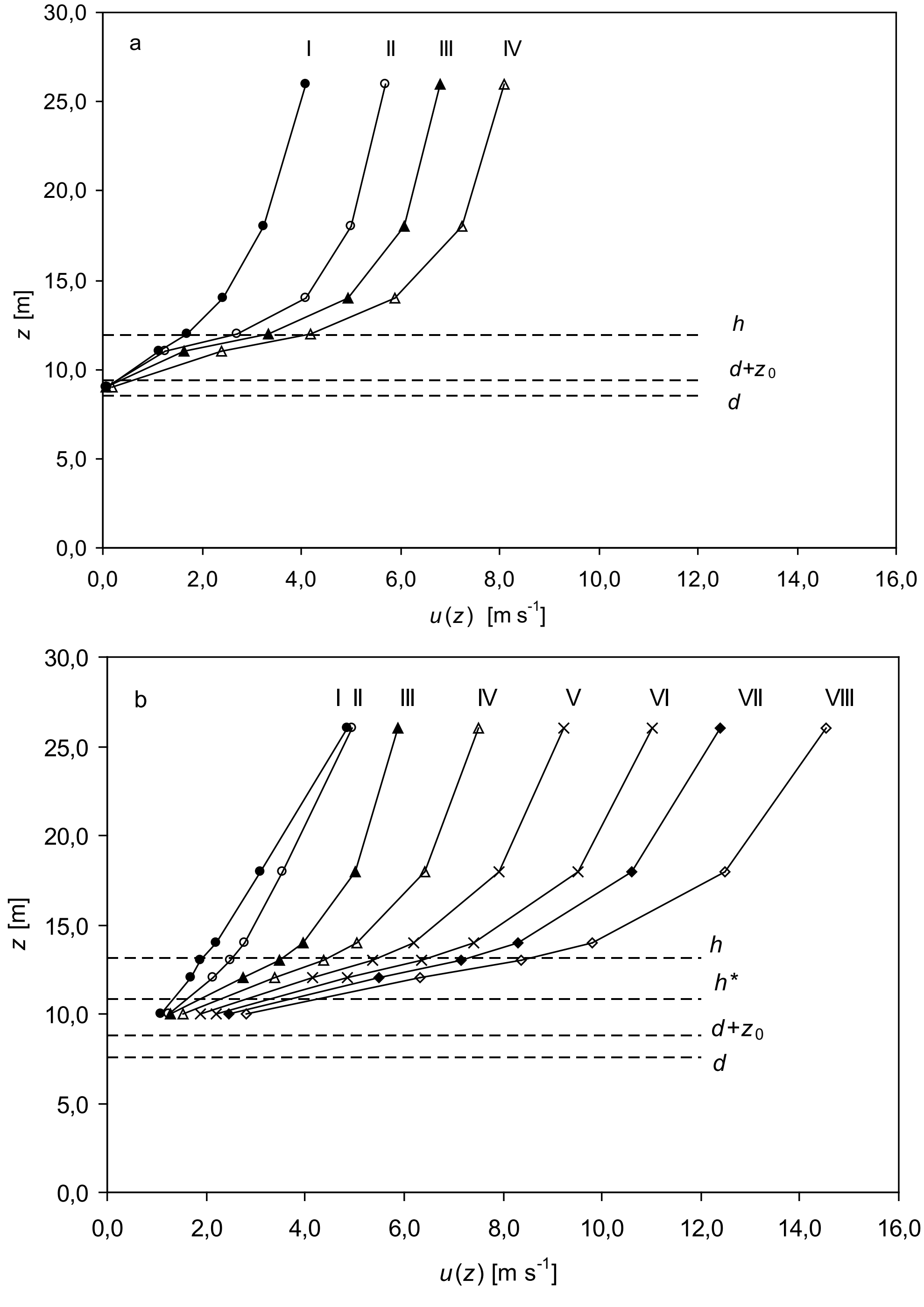

Fig. 1. Mean vertical wind speed profiles in and above spruce stand in Fd plot during growing season 2005 (a) and 2006 (b) h – mean tree height, h^* – mean tree height including broken trees, d – zero plane displacenemt, z_0 – dynamic roughness length, ranges I–VIII by Eqs (3)

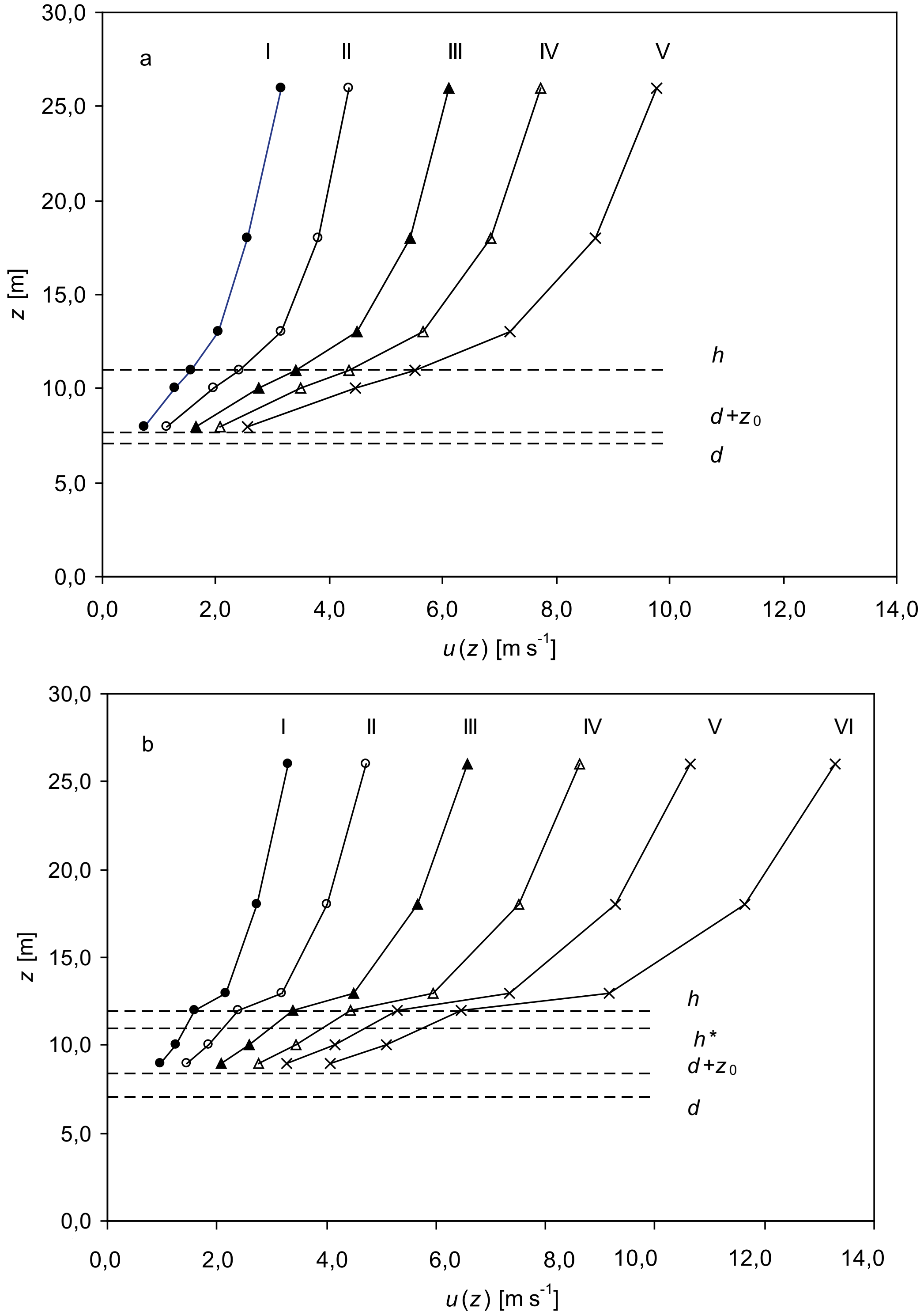

Fig. 2. Mean vertical wind speed profiles in and above spruce stand in Fs plot during growing season 2005 (a) and 2006 (b) The symbols h, h^*, d, z_0 and ranges I–VI as in Fig. 1

Table 3. Values of ratio between zero plane displacement and mean tree height (d/h) averaged over nine growing seasons on the two experimental plots in the locality Bílý Kříž

	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 in the d value on Fs during the growing season 2001 was obviously caused by the thinning performed on this plot in May 2001. The thinning has led to reduction of stand density from 2,400 trees/ha to 1,880 trees/ha. Different situation was in the growing season 2006. The strong forest damage from snow to Fd plot caused a significant fall of d values (d = 8.5 m in 2005 and d = 7.5 m in 2006). The forest damage on Fs plot was not so high and the d value was maintained stable (7.0 m) during the both investigated seasons.

In the case of a flexible vegetation cover, d and z_0 values vary with the wind speed (Hayashi, 1983; Hurtalová et al., 2004, 2006). The mean annual z_0 value of the damaged forest increased by about 0.9 m in 2005 and by about 1.3 m in 2006. Numerous authors cited by Nykänen et al. (1997) have proved that trees are especially susceptible to damage from 5 to 10 years after thinning. Snow accumulation is the highest during light winds (Pellikka and Järvenpää, 2003).

Conclusions

Airflow inside and above forest stands is dependent on aerodynamic properties of these stands. It means that a damaged forest with broken trees creates new conditions for the airflow. This was confirmed by the analysis of influence of snow damage on aerodynamic characteristics of a young spruce stand in the EESS of Bílý Kříž.

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 other factors related to landscape, especially openness of the crown layer (Nykänen et al., 1997). Synergic effects of these factors and continual snow cover with high water value maintaining from November 2005 to April 2006 in the locality Bílý Kříž caused considerable damage to the investigated spruce stand. This damage was found different on the dense (Fd) and the sparse (Fs) plots. The stand density decreased by about 29% on Fd and by about 14% on Fs plot. Furthermore, some other trees had breaks in upper halves of their crowns. These facts manifest occurring new conditions for airflow inside and above this forest stand and related changes in its aerodynamic characteristics.

It was shown, that the airflow in the growing season 2006 was stronger on both plots, mainly on the denser one, when more than 50% of the analysed wind speed profiles were found in intervals: $3.0 \leq u(z) < 4.0$ m s^{-1} (34.0%) and $4.0 \leq u(z) < 5.0$ m s^{-1} (24.2%). Furthermore, the strong forest damage on Fd caused a significant fall in the zero plane displacement value, from d = 8.5 m in 2005 to d = 7.5 m in 2006. The forest damage on Fs plot was not so strong, and the d value was 7.0 m in the both seasons 2005 and 2006. The annual mean value of z_0 for the damaged forest on Fd increased from 0.9 m in 2005 to 1.3 m in 2006 (Fig. 3).

To proceed with the continual research in the investigated spruce stand, there were established two plots with different stand densities by thinning performed at autumn 1996 and 1997. Another additional thinning was performed on Fs plot in May 2001. This silvicultural treatment reduced the stand density from 2,400 trees/ha to 1,880 trees/ha. From this follows that Fs plot had a higher susceptibility to the damage. In spite of this fact, the forest damage was more severe on Fd than on Fs plot. This can be explained by the diversified terrain with a broken topography. On the other hand, the snow accumulation is the highest during light winds. And as it follows from our analysis, more wind speed profiles complying with the condition $u(h - 1) > 1.0$ m s^{-1} were analysed on Fs than on Fd plot during all the investigated growing seasons.

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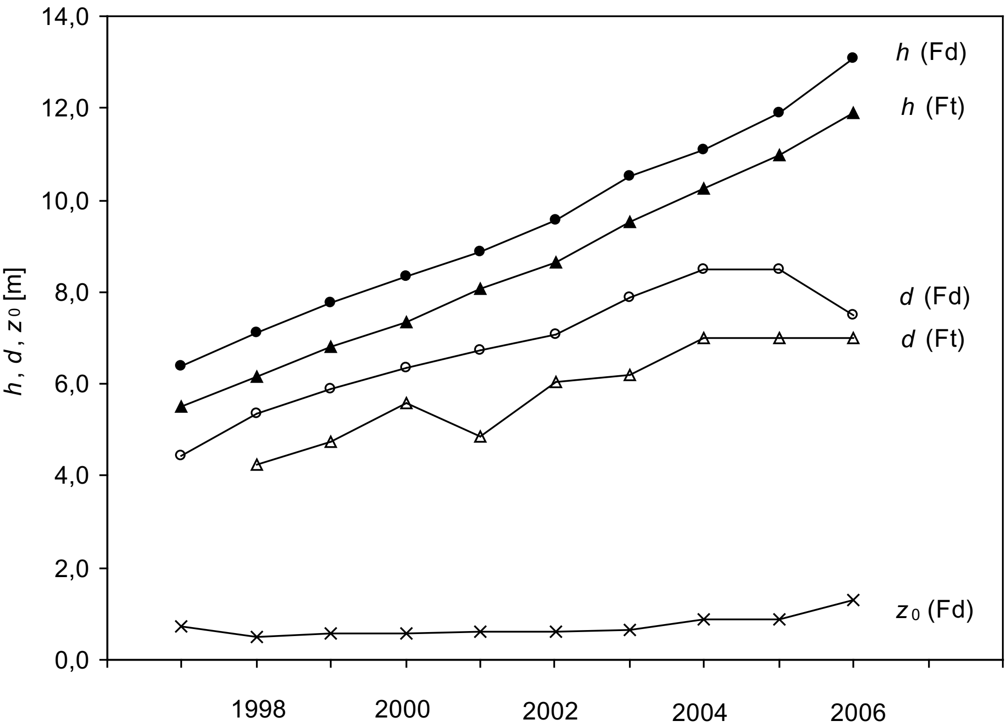

Fig. 3. Average seasonal values of the mean tree height (*h*), the zero plane displacement (*d*), and the roughness length (z_0) of investigated spruce stand during ten growing seasons

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Vplyv smrekového porastu poškodeného snehom na jeho aerodynamické charakteristiky

Súhrn

Vplyv porastu poškodeného snehom na aerodynamické charakteristiky sledovaného smrekového lesa bol analyzovaný počas rastových sezón 2005 a 2006 pred a po zime 2005/2006, kedy bol tento smrekový les významne poškodený snehom. Sledovaný smrekový porast sa nachádza v lokalite Bílý Kříž (49°30'17" N, 18°32'28" E) v lesnatej vrcholovej časti Moravsko-sliezskych Beskýd. V tejto oblasti celkove prevláda severné a západné prúdenie vzduchu, avšak priamo nad experimentálnou plochou sa často vyskytuje južný a juho-juhozápadný (SSW) vietor. Je to zapríčinené miestnou morfológiou terénu, pretože experimentálny porast smreku obyčajného (*Picea abies* (L.) Karst) sa nachádza na vo výške 898−908 m na miernom SSW svahu s maximálnym sklonom 13 %. Zima 2005/2006 v sledovanej lokalite bola charakterizovaná súvislou snehovou pokrývkou od polovice novembra 2005 do konca apríla 2006 s vysokou vodnou hodnotou, čo spôsobilo na poraste významné poškodenie, hlavne na ploche s vyššou hustotou stromov (Fd). Na tejto ploche s hustotou 2,044 stromov/ha, v dôsledku poškodenia, muselo byť 29 % stromov odstránených. Odstránené boli stromy, ktoré po poškodení mali výšku menšiu ako 2 m. Na ploche s nižšou hustotou (Fs), 1652 stromov/ha, bolo 14 % stromov odstránených. Mnohé stromy zostali poškodené (zlomené a ohnuté, cca 18,5 % na Fd a 7 % na Fs), ich priemerná výška na ploche Fd bola 5,5 m a na ploche Fs 4,0 m. S cieľom sledovať vplyv tohto poškodenia na aerodynamické charakteristiky porastu, dynamickú drsnosť povrchu (z_0) a efektívnu výšku porastu (d), bolo analyzované meranie profilov rýchlosti vetra vnútri a nad týmto smrekovým porastom. Ukázalo sa, že poškodený porast vytvoril podmienky pre silnejšie prúdenie vzduchu, keď v rastovej sezóne 2006 na ploche Fd viac ako 50 % analyzovaných profilov rýchlosti vetra bolo v intervale $3{,}0 \leq u(h) < 5{,}0$ m s^{-1}. Poškodenie spôsobilo výrazný pokles priemernej hodnoty efektívnej výšky porastu (d) (hladina, kde dochádza k premene slnečnej energie na iné formy energie), z 8,5 m (2005) na 7,5 m (2006). Poškodený porast mal vyššiu priemernú hodnotu dynamickej drsnosti: $z_0 = 0{,}9$ m v r. 2005 a 1,3 m v r. 2006 (Fig. 3). Na ploche Fs vzhľadom k odlišným orografickým podmienkam a tým aj k menšiemu poškodeniu porastu bolo prúdenie vzduchu slabšie, viac ako 70 % analyzovaných profilov bolo v intervale $1{,}0 < u(h) < 3{,}0$ m s^{-1}. Priemerná hodnota d bola rovnaká v oboch sledovaných rastových obdobiach, $d = 7{,}0$ m. Z analýzy profilov rýchlosti vetra za celé sledované obdobie (1997–2006) vyplýva, že počet profilov, ktoré spĺňali podmienku $u(h - 1) > 1{,}0$ m s^{-1}, bol výrazne nižší na ploche Fd ako na Fs. To znamená, že prúdenie vzduchu vplyvom miestnej morfológie terénu je na ploche Fd slabšie. Podľa Pellikka a Järvenpää (2003) akumulácia snehu je najvyššia pri slabšom prúdení, čo vysvetľuje tiež vyšší stupeň poškodenia porastu snehom na tejto ploche.

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