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ORIGINAL ARTICLE

Aboveground parameters of spruce (*Picea abies* (L.) Karst.) stability in the light of discriminant analysis

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Abstract

In the locality Zemská (the Low Tatras Mts.) the following aboveground parameters were measured in windthrown and undamaged Norway spruce *Picea abies* (L.) Karst. trees: stem diameter at breast height, stem diameter measured 20cm from ground level, tree height, crown length, and crown width. The stem quotients, crown proportion index, height position of the green crown, and the height of the tree centre of gravity were calculated from these data. Our results agreed with the present understanding that a wide tree crown has a negative effect on spruce stability. Paradoxically, from the view of tree stability, more favourable values of crown proportion index, stem quotients, and height positions of tree centre of gravity were found in windthrown spruce trees. In addition, the forward stepwise method of discriminant analysis identified the variable height position of the tree centre of gravity in the resulting model as the second best predictor (crown width being the first) in distinguishing between windthrown and undamaged spruce trees, although this variable had a higher mean value (less favourable) in undamaged trees.

Key words

Picea abies, static stability, windthrow, tree centre of gravity, discriminant analysis

Introduction

Forest damage by wind is a continual cause of economic loss in Slovak spruce forests. On the 19th of November 2004, large parts of the forests in the southern Slovak part of the High Tatras were damaged by a strong wind storm. More than four million cubic metres of trees were uprooted or broken. We are currently witnessing ongoing climate change on Earth, and increasingly we have registered the occurrence of extreme weather. Norway spruce is the most susceptible of all tree species to the effects of climate change. Spruce stands in Slovakia have extremely low static and ecological stability, where they are most under the threat of abiotic harmful factors. The most common cause of failure in Norway spruce [*Picea abies* (L.) Karst.] is uprooting, but stem breakage may occur if the soil is frozen and if the crown is loaded with snow (Peltola et al. 1997, 2000). Wind damage results in a loss of timber yield, reducing the yield of recoverable timber and increasing the costs of unscheduled thinnings, leading to disturbances in planned forestry management. Furthermore, broken and uprooted trees in stands can lead to detrimental insect attacks on the remaining stems because of the increased availability of breeding material.

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In tree and forest science, the definition of tree stability includes the mechanical behaviour of trees, the forces and pressures acting upon trees, the interaction between these components, and aspects of tree biology and physiology related to tree mechanics (Lundström 2010). The susceptibility of a forest stand and trees within the stand to wind damage is controlled by forest structure and tree, stand, and site characteristics. In general, the following parameters of tree growth have the biggest influence on tree stability: proportions and character of the crown (width, length, and shape), stem (height, diameter, habit and strength) and root system (depth, width and the nature of anchorage) (Konôpka 1978). Lundström et al. (2008) found that the strengths of the stem and the anchorage of Norway spruce mutually adapt to the local wind acting on the tree crown in the forest canopy. Stresses in the tree stem and anchorage result from combinations of wind and snow load, and the overhanging weight of the leaning tree. The magnitude and frequency of such loads depend on the tree and stand characteristics, climate, and season. A sufficiently heavy load will cause the stem or the tree anchorage to fail. The type of failure depends on the stem and anchorage strengths, and on where and in which direction the load is applied. The magnitude of the failure load will, in addition, depend on how well the tree, including the crown, stem, and anchorage, has adapted its growth to the particular load combination (Telewski 1995; Nicoll and Ray 1996; Di Iorio et al. 2005).

The general understanding of parameters of static stability in individual trees is well developed and many works present a simple comparison of these parameters between damaged and undamaged trees. The purpose of this paper is to take advantage of discriminant analysis methods in order to gain a new perspective on wind damage in spruce forests.

Material and methods

The aboveground parts were measured on Norway spruce (*Picea abies* (L.) Karst.) in the locality Zemská (20°03’ E, 49°06’ N) (the Low Tatras Mts). This site is even-aged, with the dominant stand layer being 80 years old, has a northern aspect, 40% slope, and an altitude of about 950 m a.s.l. According to Pal. Hab. classification, the site consists of the following forest type: 42.13 Acidophile medio-European fir forest. The forest stand analysed consists of entirely of Norway spruce.

Firstly, the aboveground parameters of windthrown spruce trees were measured in the stand. These windthrown spruce trees were scattered throughout the stand. In their surrounding areas, the aboveground parameters of undamaged (upright) spruce trees were measured. These included: stem diameter at breast height (*DBH*), stem diameter $D_{0.2}$ – measured 20 cm from the ground level, tree height (*H*), crown length (*CL*), and crown width (*CW*). The stem quotients *H/DBH*, $H/D_{0.2}$, and $DBH/D_{0.2}$ were calculated from these data. The crown proportion index was calculated according to the formula: $Cpi = CL/H \times 100$. The tree centre of gravity was calculated according to the methodology of Saniga (1985).

In order to calculate the height (above ground level) of the tree centre of gravity, it is necessary to calculate the static moment towards the stem base according to the formula:

$$V_x = A_1 \times \frac{CH}{2} + A_2 \times \left(CH + \frac{1}{3} \times CL \right)$$

where:
V_x – static moment towards stem base (m^3),
A_1 – cross-sectional surface of stem (m^2),
A_2 – cross-sectional surface of crown (m^2).

The cross-sectional surfaces were calculated according to the formula:

$$A_1 = DBH \times CH$$

$$A_2 = \frac{CW \times CL}{2}$$

where:
DBH – stem diameter at breast height (m),
CH – height of position of green crown (m),
CW – crown width (m),
CL – crown length (m).

The centre of tree gravity was calculated according to the formula:

$$Ctg = \frac{V_x}{A_s}$$

where:
C_{tg} – the real height of tree centre of gravity (m),

V_x – static moment towards stem base (m^3),
A_s – cross-sectional area of a tree (m^2),
where:

$$A_s = A_1 + A_2$$

The mean values of the aboveground parameters were calculated. A Student's t-test was used in order to evaluate the statistical significance of differences between windthrown and undamaged spruce trees.

The forward stepwise method of discriminant analysis was used in order to determine which variables discriminate between windthrown and undamaged spruce trees. The purpose of using this analysis was to determine which variables (aboveground parameters) are the best predictors of whether a tree will be damaged by wind or not (i.e. windthrown). In forward stepwise discrimination function analysis, a model of discrimination is built step-by-step. Specifically, at each step all variables are reviewed and evaluated as to which one will contribute most to discrimination between groups (windthrown and undamaged trees). That variable will then be included into the model, before proceeding to the next step. The STATISTICA StatSoft, Inc. software (version 7.0) was used for analysis of data.

Results and discussion

The mean values of aboveground parameters for the Norway spruce trees analysed are given in Tab. 1. The mean values of stem diameters *DBH* and $D_{0.2}$ were higher in windthrown spruce trees. These results are in disagreement with the results of Peterson (2000), who stated that larger trees are more likely to be damaged, and damaged more severely, than smaller trees. Richter (1996) found that the average *DBH* of the uprooted Norway spruce trees coincided with that of their neighbours, whereas that of broken trees was 4 cm higher. On the other hand, Kohnle and Gauckler (2003) discovered that after a windstorm, Norway spruce trees that were uprooted had slightly smaller average *DBH* compared to spruce trees remaining on the plots.

In general, the higher the tree height, the more susceptible the trees are to uprooting. Unusually, a higher mean value of tree height was found in undamaged trees, although the difference was not statistically significant. Kohnle and Gauckler (2003) analysed the influence of

Tab. 1. Aboveground parameters of analysed spruce trees (arithmetic mean ± standard deviation)

Number of measured trees	Stem diameter		Tree height	Crown		Crown proportion index	Stem quotient			Height of position of green crown	Height position of centre of tree gravity
	DBH (cm)	$D_{0.2}$ (cm)	*H* (m)	width (*CW*) (m)	length (*CL*) (m)	*Cpi* = (*CL*/*H*) × 100 (%)	*H*/*DBH*	$H/D_{0.2}$	$DBH/D_{0.2}$	*CH* (m)	C_{tg} (m)
Windthrown 30	42.23 ± 8.41	54.68 ± 10.99	31.70 ± 2.85	6.52 ± 1.49	18.65 ± 3.25	58.78 ± 8.74	0.77 ± 0.13	0.60 ± 0.10	0.78 ± 0.07	13.05 ± 2.98	18.13 ± 2.14
Undamaged 63	40.60 ± 6.57	52.49 ± 9.32	32.17 ± 2.53	5.92 ± 1.14*	17.83 ± 2.95	55.48 ± 8.49	0.81 ± 0.11	0.63 ± 0.10	0.78 ± 0.07	14.34 ± 2.98*	18.89 ± 2.01
p level	0.31	0.32	0.42	0.04	0.23	0.09	0.21	0.17	0.82	0.05	0.10

* – statistical significant difference (at $p \leq 0.05$)

stand height on the vulnerability of spruce trees to wind injury. They mention that volume losses increase in conjunction with the top height of the plots. Similarly, Ni Dhubhain et al. (2001) state that an increase in top height results in a significant increase in the susceptibility to windthrow. Vicena (1964) also mentions that higher values of tree height lead to a higher intensity of wind injury.

Saniga (1985) reported that tree weight is concentrated in the upper part of the tree stem, and this means that the crown is a determining factor of tree stability from the static-dynamic point of view. A higher mean value of crown width was found in windthrown trees and this difference was statistically significant. Similarly, Konôpka (1992) states that increasing crown width negatively affects the stability of a forest stand. According to his results, the crown width was statistically significantly higher in damaged spruce trees compared to the undamaged. Mickovski et al. (2005), mention that trees with narrow crowns are at very low risk to being windthrown. However, an increase in crown length positively affects the stability of a forest stand because it shifts the tree centre of gravity toward the stem base, whereby the tree stability is increased. It is better to express the crown length relatively, that is, as a ratio of crown length to tree height (Konôpka 1992). A lot of authors regard the crown proportion index as the most important component of spruce stability. However, according to our results, the windthrown spruce trees had a higher mean value of crown proportion index, although this difference was not statistically significant.

With respect to tree stability, the stem quotients are also important. Konôpka (1992) reports that in the majority of his results, the mean values of form quotients were lower (more favourable) in undamaged trees than damaged. In general, the most used form quotient is the slenderness ratio *H/DBH*. However, a lower mean value of slenderness ratio was found in the windthrown (0.77), in comparison to the undamaged spruce trees (0.81), although this difference was not statistically significant. More generally, Rottmann (1986) stated that trees with a value of *H/DBH* higher than 90 are at high risk of wind damage. Similarly Mickovski et al. (2005) considered trees with an *H/DBH* value greater than 90 to be highly threatened by wind. Mattheck et al. (2003) mention that the trees with a slenderness higher than 50 have a risk of being first bent sideward by wind, and then pulled down by the weight of their crown. Ancelin et al. (2003) found that at a wind speed of 20 m/s, Norway spruce trees with a slenderness greater than 85 and a crown ratio of less than 55% were the most likely to suffer from stem breakage, and that trees with a slenderness of between 70 and 85, and a crown ratio between 55 and 65% were the most likely to suffer overturning. Arnold (2003) found out that the mean value of stem quotient *H/DBH* was 72.9 in windblown Norway spruce trees, and 69.2 in standing trees.

Paradoxically, we found that the mean height position of the green crown and the height position of the tree centre of gravity were higher in undamaged trees. Therefore, according to our results, upright trees should be more susceptible to uprooting in comparison to windthrown trees. Therefore it seems that the aboveground parameters of spruce trees in the forest stand we analysed differ from the general understanding of tree stability, and therefore these parameters cannot be generalised.

Summary results of the stepwise discriminant analysis are given in Tab. 2. Only two variables were included in the resulting model. Wilks` Lambda is a statistical factor of overall model discrimination. A high value of Wilks` Lambda (close to 1) indicates that the discrimination of the overall model is very low. Therefore, it is disputable that we accept this model as it may not effectively discriminate between the groups examined, and it is difficult to clearly answer the research aim. Partial Lambda is the version of Wilks` Lambda that characterises a unique contribution of the respective variable to the discriminatory power of the model. According to our results, the best discriminatory contribution was from the variable *CW* (crown width), and if this is removed, the model will achieve a poorer differentiation of groups. Selection of *CW* for inclusion into the model is in accordance with the significantly higher mean value of crown width in windthrown spruce trees. However, inclusion of the variable C_{tg} into the model does not support the general consensus with respect to the effect of the tree centre of gravity on tree stability. In general, if the position of the centre of tree gravity measured above ground level is higher, the tree is at greater risk of uprooting. However, we found that upright trees possessed a higher mean centre of gravity. Therefore, it seems that it is not possible to use this parameter as an indicator of tree stability in all forest conditions. The tolerance values, as a factor of redundancy (a surfeit of information), were rather high, meaning that individual variables are not mutually redundant, and that each of these variables has its own contribution to the discrimination of the analysed groups.

Tab. 2. Results of the forward stepwise method of discriminant analysis

Variant	Wilks` Lambda	Partial Lambda	F/ remove	p/level	Tolerance
CW	0.97	0.95	4.21	0.043	0.999
C_{tg}	0.95	0.97	2.51	0.116	0.999

Conclusions

Our results are in agreement with the consensus that a wide tree crown has a negative effect on spruce stability. Paradoxically, with respect to tree stability, in the forest stand analysed we found more favourable values of *Cpi, H/DBH,* $H/D_{0.2}$, and C_{tg} in windthrown spruce trees. In addition, the forward stepwise method of discriminant analysis selected C_{tg} for inclusion into the resulting model as the second best predictor in differentiation between windthrown and undamaged spruce trees, although this variable has a higher mean value in undamaged trees. Based on our results, it seems that not all aboveground parameters of spruce stability are able to provide reliable data in determining the risk of individual trees to being uprooted by wind.

References

Ancelin P., Courbaud B., Fourcaud T. 2003. A population approach to study forest stand stability to wind: individual tree-based mechanical modeling. In: Wind Effects on Trees. Proceedings of International Conference 16–18 September 2003, Karlsruhe, Germany (eds: B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, G. Wilhelm), 239–246.

Arnold M. 2003. Compression failures in wind-damaged spruce trees. In: Wind Effects on Trees. Proceedings of International Conference 16–18 September 2003, Karlsruhe, Germany (eds: B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, G. Wilhelm), 253–260.

Di Iorio A., Lasserre B., Scippa G.S., Chiatante D. 2005. Root system architecture of *Quercus pubescens* trees growing on different sloping conditions. *Annals of Botany*, 95, 351–361.

Kohnle U., Gauckler S. 2003. Vulnerability of forests to storm damage in a forest district of south-western Germany situated in the periphery of the 1999 storm (Lothar). In: Wind Effects on Trees. Proceedings of International Conference 16–18 September 2003, Karlsruhe, Germany (eds.: B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, G. Wilhelm), 151–155.

Konôpka J. 1978. Optimum and extreme limit of growth properties of spruce trees from the viewpoint of stand resistance against wind in the region of the Low Tatras (in Slovak). In: Poznatky z ochrany lesov. Scientific works of forest research institute in Zvolen (eds: A. Hešková et al.). Príroda, Bratislava, Slovakia, 13–41.

Konôpka J. 1992. Models of target spruce trees from the viewpoint of static stability (in Slovak). Akademie zemědělských věd ČSFR, Praha, Czech Republic, pp. 106.

Lundström T., Jonas T., Volkwein A. 2008. Analysing the mechanical performance and growth adaptation of Norway spruce using a non-linear finite-element model and experimental data. *Journal of Experimental Botany*, 59, 2513–2528.

Lundström T. 2010. Mechanical stability and growth performance of trees. PhD thesis no. 1644. University of Fribourg, Fribourg, Switzerland, pp. 141.

Mickovski S.B., Stokes A., Beek L.P.H. 2005. A decision support tool for windthrow hazard assessment and prevention. *Forest Ecology and Management*, 216 (12), 64–76.

Mattheck C., Bethge K., Kappel R., Müller P., Tesari I. 2003. Failure modes for trees and related criteria. In: Wind Effects on Trees. Proceedings of International Conference 16–18 September 2003, Karlsruhe, Germany (eds: B. Ruck, C. Kottmeier, C. Mattheck, C. Quine, G. Wilhelm), 219–230.

Nicoll B.C., Ray D. 1996. Adaptive growth of tree root systems in response to wind action and site condition. *Tree Physiology*, 16, 891–898.

Ni Dhubhain A., Walshe J., Bulfin M., Keane M., Mills P. 2001. The initial development of a windthrow risk model for Sitka spruce in Ireland. *Forestry*, 74 (2), 161–170.

Peltola H., Nykanen M.L., Kellomaki S. 1997. Model computations on the critical combination of snow loading and windspeed for snow damage of Scots pine, Norway spruce and birch sp. at stand edge. *Forest Ecology and Management*, 95, 229–241.

Peltola H., Kellomäki S., Hassinen A., Granander M. 2000. Mechanical stability od Scots pine, Norway spruce and birch: an analysis of tree-pulling experiments in Finland. *Forest Ecology and Management*, 135, 143–153.

Peterson C.J. 2000. Damage and recovery of tree species after two different tornadoes in the same old growth forest: a comparison of infrequent wind disturbances. *Forest Ecology and Management*, 135, 237–252.

Richter J. 1996. Sturmschäden in Fichtenbeständen. *Allgemeine Forst und Jagdzeitung*, 167 (12), 234–238.

Rottmann M. 1986. Wind- und Sturmschäden im Wald. Sauerländer`s Verlag, Frankfurt am Main, Germany, pp. 128.

Saniga M. 1985. Influence of the kind and grade of thinning on the stability of spruce stands against wind (in Slovak). *Lesnícky časopis*, 31 (1), 35–48.

Telewski FW. 1995. Wind-induced physiologial and developmental responses in trees. In: Wind and trees. (eds: M. Coutts, J. Grace), Cambridge University Press, Cambridge, 241–263.

Vicena I. 1964. Protection against wind calamities (in Czech). Státní zěmědelské nakladatelství, Praha, Czech Republic, pp. 178.