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PÔVODNÁ PRÁCA – ORIGINAL PAPER

Modelling height to diameter ratio – an opportunity to increase Norway spruce stand stability in the Western Carpathians

Modelovanie štíhlostného kvocientu – možnosti zvýšenia statickej stability smrekových porastov v Západných Karpatoch

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Abstract
Norway spruce is one of the most widespread and economically important coniferous species in Europe and is also one of the tree species most mechanically sensitive to windthrow and consequently, is frequently damaged by storms. As height-to-diameter (HD) ratio has long been identified as an indicator of stand static stability, the main factors affecting the ratio in Norway spruce stands in the Western Carpathians were analysed to assess their general susceptibility to storm damage. A model was developed to assist forest managers in deciding on levels of thinning intensity for increasing the stability of such spruce stands, while still maintaining productivity. Data from the National Forest Inventory (260 plots) and previously existing research projects (48 plots) were used. Plots were distributed over the major part of the Western Carpathian range covering most variability in forest site factors. The final model incorporated the most relevant characteristics; those indicating ecological conditions: altitude and site index; and others related to stand properties: crown ratio, stand density, and mean stand height. The results indicated that intensive early thinnings must be applied, specifically on very rich sites at low altitudes, to decrease the HD ratio to a more stable range.
Keywords: static stability; *Picea abies*; site index; stand density; wind damage risk

Abstrakt
Smrek je jednou z najrozšírenejších a ekonomicky najdôležitejších ihličnatých drevín v Európe. Taktiež je drevinou veľmi často poškodzovanou vetrovými kalamitami. Štíhlostný kvocient (pomer výšky a hrúbky stromu) sa považuje za vhodný indikátor statickej stability jednotlivých stromov a porastov. Preto cieľom práce bola identifikácia hlavných faktorov, ktoré majú významný vplyv na hodnoty kvocientu. Jednoduchý model bol vytvorený ako pomôcka pre lesníka pri rozhodovaní o intenzite prebierok v smrekových porastoch s cieľom potenciálneho zvýšenia statickej stability a zachovania optimálnej produkcie. Využili sa údaje Národnej inventarizácie a monitoringu lesov SR (260 plôch) a taktiež údaje z predchádzajúcich výskumných projektov (48 plôch) tak aby reprezentovali čo najširšie rozpätie ekologických podmienok, v ktorých smrek v súčasnosti rastie. Výsledky ukázali, že najvýznamnejšími ekologickými faktormi boli: nadmorská výška a bonita stanovišťa. Taktiež niektoré porastové charakteristiky sa významne podieľali na variabilite kvocientu: podiel koruny z výšky stromu, hustota porastu a stredná porastová výška reprezentujúca rastovú fázu porastu. Výsledky ďalej preukázali, že ekologické podmienky sú významnejšie ako porastové charakteristiky, a preto tieto treba brať do úvahy pri rozhodovacom procese. To znamená, že ak sa porast nachádza na pre smrek veľmi bonitnom stanovišti, sú potrebné silnejšie prebierky od mladých rastových fáz, aby sa ovplyvňovaním hrúbkového prírastku vyrovnal vplyv rýchleho výškového rastu. Zároveň je dôležitá rozdielna intenzita výškového a hrúbkového rastu počas vývoja porastu.
Kľúčové slová: statická stabilita; *Picea abies*; bonita stanovišťa; hustota porastu; riziko rozvrátenia vetrom

1. Introduction

Norway spruce (*Picea abies* [L.] Karst.) is one of the most common and economically important coniferous species in Central Europe. Because of its widespread occurrence and mechanical sensitivity to storm damage, it is often one of the species most widely affected by wind and snow damage (Rottmann 1985). In Slovakia, as much as 62% of total windstorm damage in the years 1996–2003 occurred in spruce stands. In the same period, 51% of all forest snow damage was to Norway spruce (Konôpka et al. 2005). The importance of this issue was highlighted by findings of Schelhaas (2008) who stated that by volume, wind was responsible for more than 50% of reported primary damage to European forests from catastrophic events resulting from both abiotic and biotic agents.

Many works (Wang et al. 1998; Päätalo et al. 1999; Kamimura & Shiraishi 2007; Schelhaas 2008; Vospernik et al. 2010) have pointed out the utility of height to diameter ratio (HD) as an important measure of tree or forest stand stability, especially in the case of coniferous species. Significant differences have been observed in the average HD ratio of damaged and undamaged trees (following wind storms) for many species, for instance in Douglas fir by Schelhaas et al. (2007). In general, a low value of the HD ratio represents a

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lower position for the centre of gravity, and often relates to a longer crown and better-developed root system (Rottmann 1985). Moreover, a high HD ratio has been associated with enhanced risk of uprooting (Urata et al. 2011). A reduction in value of the HD ratio is one of a tree's adaptive responses (i.e. for strengthened stability) to frequent wind exposure (Mitchell 2013). Trees with lower HD ratios usually have a higher maximum bending moment than trees with higher HD ratios, of a similar height (Moore 2000; Peltola et al. 2000). Highly tapering trees were also more susceptible to stem breakage than uprooting. Predictions by the HWIND model (Peltola et al. 1999 in Peltola 2006) showed that the wind speed needed to cause uprooting or stem breakage of trees will decrease as the tree height or the tree HD ratio increases or as the stand density decreases. Tree-pulling experiments (Peltola & Kellomäki 1993) and empirical modelling based on long-term observation (Albrecht et al. 2012) showed that trees of a large HD ratio have a higher probability of uprooting or breaking than trees with a lower HD ratio. Relatively few studies (e.g. Schütz et al. 2006; Valinger & Fridman 2011) have not found a significant relationship between HD ratio and vulnerability to damage. A high HD ratio can also indicate that a tree has grown in a dense stand under the influence of close mutual support (Valinger & Fridman 1997); therefore, trees with a high HD ratio can be more vulnerable because their stems have not been acclimatised to conditions of high mechanical perturbation.

Increased vulnerability to wind damage has also been shown to be related to the frequency of past thinning events (e.g. Lohmander & Helles 1987). In general, stand density reduction by thinning usually lowers stand stability for a short term (Mitchell 2013). However, in order to produce wind firm stands at maturity, a regime of systematic and frequent thinning needs to be applied from an early stage (Slodičák 1995). The probability of damage can also become high in stands with trees of low HD ratio if thinning treatments are carried out without a consideration of neighbouring stands and areas (climate and conditions of localised area e.g. slope). Spacing trials and experiments on different thinning intensities in coniferous stands have clearly demonstrated the value of a HD ratio increase with increasing stand density (Mäkinen et al. 2002; Harrington et al. 2009). The HD ratio, apart from modification by forest management and/or stand establishment, is also affected by environmental conditions, particularly soil site class (Tilman 1988) and altitude (Homeier et al. 2010). The significant effect of soil conditions on the HD ratio was further indicated by experiments simulating contrasting water and nutrient availability by Wiklund et al. (1995).

An exact quantification of forest stand stability is very complex because it depends on multiple factors, on the "weakest link in the chain" and possibly on a domino effect in the case of storm wind damage (Schindler et al. 2012). Moreover, it relates not only to the mutual position of trees in a stand (mainly with regard to stand edge, stand gaps or unstable stand fragments), but also on the location of individual stands within surrounding forest cover (see for instance Lohmander & Helles 1987; Schelhaas et al. 2007; Mitchell 2013). Even though forest stand stability is determined by a variety of internal and external factors, it can be assumed that silvicultural systems leading to trees with high HD ratios increase the risk of wind damage (Schelhaas 2008).

There have been no detailed studies focused on HD ratios using large national datasets. Only the scale of such datasets allow the interactive influence of the many factors that may potentially affect the HD ratio to be integrated using multiple statistical analyses. The first National Forest Inventory (NFI) of Slovakia was carried out during 2005 and 2006 and gathered a large database of up-to-date forest biometric information specific to the region. The main aim of this paper is to model the HD ratio of Norway spruce across the Slovak Republic by using stand and environmental variables originating from the National Forest Inventory supplemented with further data from research plots. A secondary aim is to provide graphical models suitable to guide stand density regulation (through thinning) of spruce stands to attain a safe HD ratio in an area of wind throw risk.

2. Materials and methods

2.1. Data description

Data collected by the Slovak NFI (Šmelko et al. 2006; 2008) were used to build a model to estimate HD ratio (Fig. 1). The total number of inventory plots (IP) established by the NFI was 1419. A circular (r = 12.62 m) IP enclosed an area of 500 m^2. Data were filtered for IP that contained a minimum of 10 living Norway spruce trees and to eliminate those with less than 200 trees per hectare. This selection criterion resulted in a total of 252 IP for analysis. The average proportion of spruce was 85% (from basal area) and the number of plots in which the proportion of spruce was more than 90% was 140 (55%). In addition, a further dataset which was collected by a project entitled "Reaction of forest ecosystem diversity to climate-edaphic conditions in Slovakia" (Vladovič et al. 2005) was included in the study, because it represented close-to-nature forests (i.e. generally unmanaged) at higher altitudes, mostly of lower HD ratios. The number of plots selected from this study (TRP – Typological Representative Plots) was 48. The area of the plots was 1000 m^2 and the same criteria were applied for plot selection. The NFI and TRP data were combined under the term "sample plots (SP)".

2.2. Tree and stand measurements

To obtain the variables for model building, plot statistics were compiled for each sample plot. In each, a mean HD ratio was calculated as an average ratio from measurements of dominant and co-dominant spruce trees. For this study, trees from the first and second sociological classes were considered as dominant and co-dominant trees. Only these classes were considered to determine the stability of their entire stand (Konôpka 1992). The HD ratio (dimensionless) was calculated by dividing mean tree height (m) by the mean DBH (m) of the selected trees; it ranged from 40 to 115. Mean diameter of the selected trees was calculated as a quadratic mean ($MDBH_{dom}$). The crown ratio (CR), derived as an average crown ratio of dominant and co-dominant trees in a plot, was calculated by dividing total tree height by crown

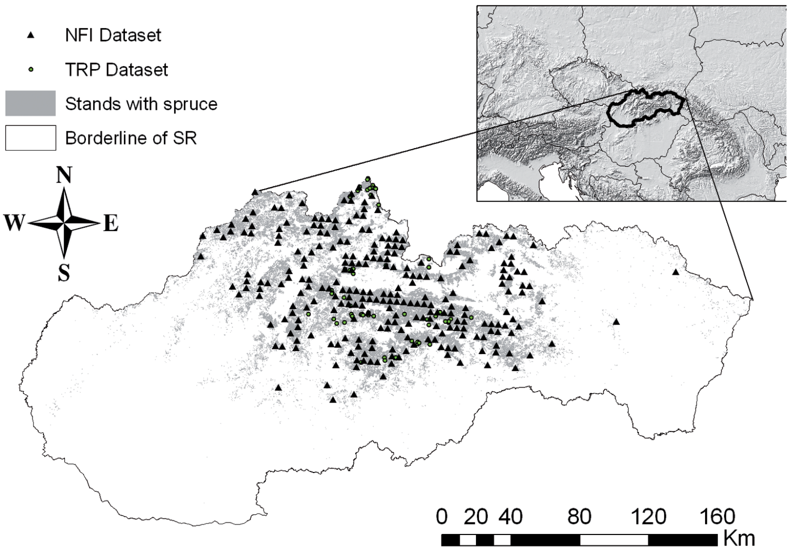

Fig. 1. Location and distribution of the plots from both the Slovakian NFI and TRP datasets.

length and was expressed as a percentage. Crown length was identified as the vertical distance from the tip of the leader to the base of the crown, measured to the lowest live whorl on the stem. The crown ratio was expected to be a useful explanatory variable in assessing the standing stability of a spruce stand. Further variables used in the study were the mean height (MH) and mean quadratic diameter (MDBH) of all the trees in each plot, stand density (SD – trees per ha), stand density index (SDI, Reineke 1933), and the sum of basal area per hectare (BA_{tot}). Mean height was preferred to top height because it is widely used for estimating growing stock in the Slovak Yield Tables (Halaj & Petráš 1998). In addition, parameters such as DBH and height variability, representing the structural irregularity of the stands were also tested.

A height-growth model developed by Halaj & Petráš (1998) was used to calculate the site index (i.e. top height at a standard age of 100 years) of Norway spruce in each SP, based on stand age and top height:

$$h = SI\,exp[(((a_3+a_4)SI*100^{a1+a2/SI})/(SI(1-a_1)-a_2))\,(age^{1-a1-a2/SI}-100^{1-a1-a2/SI})] \qquad [1]$$

where SI is site index and a_1–a_4 are model parameters. The final site index for each plot was then calculated by mathematical interpolation between the adjacent height--growth curves.

2.3. Statistical methods

Using non-linear regression, relationships between HD ratio and some independent variables were assessed. To build a complex model to include all the necessary explanatory variables, multivariate non-linear estimations using the least squares method with a Levenberg-Marquardt algorithm were used (Levenberg 1944; Marquardt 1963). As the relationships between individual independent variables and HD ratio were non-linear, a logarithmic transformation of the variables was carried out and the form of the equation used in the study was as follows:

$$ln(y) = b_0+b_1ln(x_1)+b_2ln(x_2)+\ldots+b_nln(x_n) \qquad [2]$$

where y is the dependent variable, x_1–x_n represent predictors and b_0–b_n are regression coefficients to be estimated.

The use of a linearised form required a re-transformation, so that non-transformed values of the HD ratio would be available as outputs. Hence, the following re-transformation was implemented:

$$y = exp(b_0+b_1ln(x_1)+b_2ln(x_2)+\ldots+b_nln(x_n))\lambda \qquad [3]$$

where λ is a correction factor according to Marklund (1987):

$$\lambda = 1/n\Sigma(Y_i/e^{lnY_j}) \qquad [4]$$

where Y_i is the measured value and Y_j is the predicted value.

This correction factor was preferred here to the commonly used Baskerville (1972) or Sprugel (1983) corrections because those require a log-normal distribution of the dependent variable, which if not the case tends to yield overestimates (Ledermann & Neumann 2006).

To obtain the goodness-of-fit of a model, the coefficient of determination, residual standard error of the model and standard error for the estimation of individual regression coefficients were used. A forward step-wise regression procedure was used where only the variables making a significant contribution to an explanation of the HD ratio variability were included in the model. In the step-wise regression, the best model was selected using an Akaike information criterion (AIC, Akaike 1974). AIC was used because it not only rewards goodness of fit, but also includes a penalty which increases as a function of the number of estimated parameters (Motulsky & Christopoulos 2003). A possible multicollinearity between the selected predictors was tested using VIF (O'Brien 2007; Robinson & Schumacker 2009). All statistical analyses were completed using R (version 2.15.0, R Development Core Team 2012) software.

2.4. Model validation

The final model was validated employing the method of *k*-fold cross validation. The entire dataset was systematically and equally split into three subsets (the plots were arranged alphabetically and each second and third was selected to be included as a different subset). The model was first trained on one subset and then validated on the remaining two subsets, which was repeated twice more, swopping training and validating subsets. A t-test was used to evaluate the differences of mean residuals from zero for each validation. Furthermore, Kolmogorov-Smirnov tests (Massey 1951) were employed to evaluate whether the distribution of model residuals differed from normal.

2.5. Use of stand density as a practical management factor

In order to provide a practical means for forest management to apply HD as a factor in stabilising stands, the final model was solved for stand density directly (Eq. 5).

$$SD = EXP((ln(HD)-b_0-b_1{*}ln(X_1)-b_3{*}ln(X_2)-\ldots-b_n{*}ln(Xn))/b_{SD})^{*}\lambda \qquad [5]$$

where $b_0 - b_n$ are regression parameters estimated in the previous analysis, $X_1 - X_n$ are explanatory variables, and *SD* is the stand density (number of trees per hectare).

To show the differences of HD ratio at different altitudes, two instances were used; 800 and 1200 m a.s.l. The lower altitude (800 m a.s.l.) represented the majority of commercially managed stands. The higher described what is regarded as mountain spruce which is generally less intensively managed. The altitude of 1200 m a.s.l. is considered as the lower limit to the 7th altitudinal vegetation zone (Zlatník 1976), where forest structure has been recognised as differing significantly from lower vegetation zones. The 7th vegetation zone is a high-altitude (1200 – 1550 m a.s.l.) zone where spruce naturally creates homogeneous forests. According to NFI results in Slovakia, the average altitude of the zone is 1335 m a.s.l. (Bošeľa 2010). A lack of data from altitudes higher than 1200 m provides a natural limit for use of models from this work.

Table 1. Basic statistics of the sample plots used for the study.

Plot variable	Abbr.	Mean	Min	Max	SD	Skewness
Stand age [years]	Age	82	19	200	41	0.53
Altitude [m a.s.l.]	Alt	931	359	1507	247	0.20
Site index [m]	SI	30	11	51	7	-0.21
Mean HD ratio [dimensionless]	HD	79	45	111	11	-0.45
Mean crown ratio [%]	CR	56	27	93	14	0.38
Mean height [m]	MH	22	8	36	6	0.19
Mean diameter [cm]	MDBH	28	12	49	8	0.19
Stand density [trees ha^{-1}]	SD	786	180	3286	530	2.06
Stand density index [Reineke]	SDI	798	213	1954	214	0.96

The stand density required to reach a HD ratio of 80 and 90 was calculated, because trees or stands with a HD ratio of 80 or less are generally considered stable against breakage caused by wind (Konôpka 1992; Wonn & O'Hara 2001; Vospernik et al. 2010). By showing the density at the HD ratio of 90, it was possible to demonstrate the extent of thinning required to perform such a decrease in HD ratio (i.e. from 90 to 80).

3. Results

Spruce trees demonstrated different growth rates and appearance along the altitude range covered by the SP dataset. At high altitude, trees had longer crowns with more highly tapered stems resulting in lower HD ratios than trees at lower altitudes. There was a greater spread in the TRP dataset compared to NFI data as it contained more trees of larger diameter (Fig. 2). This means that if only the NFI dataset had been used for model building, it would not have covered an important cohort of variability in the HD ratio range.

Altitude, site index and crown ratio were the factors with the highest correlation with the HD ratio ($R^2 = 0.18$ to 0.30) (Fig. 3). The other factors that significantly affected the HD ratio were stand density, mean stand height and stand age. The negative relationship with age and the slightly positive one with mean height were driven by the inclusion of the TRP dataset where plots were established at high altitudes and in older stands, often in semi-natural forests or nature reserves. In these stands the structure was highly diverse (with regard to height and diameter), often resulting in trees having longer crowns and with a higher degree of taper.

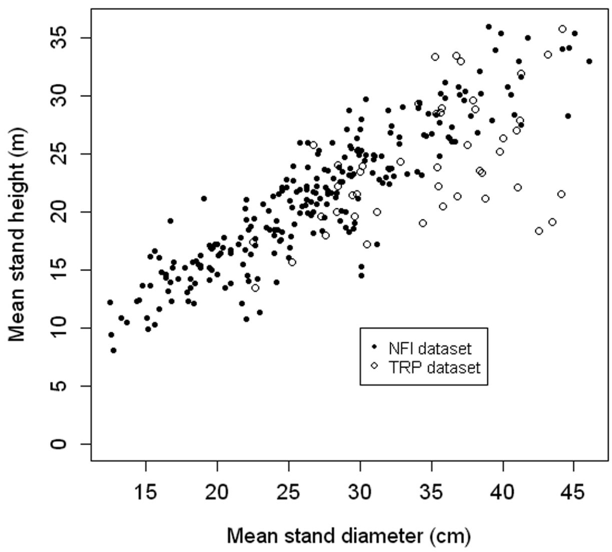

Fig. 2. Variability of stand height and diameter across the combined dataset.

3.1. Final model selection

From the regression analysis, five variables were found to have a significant effect on HD ratio (see Table 2). Stand age was found to have a significant impact on HD ratio, however, the age of TRP data was only estimated and therefore mean stand height was used instead of stand age. For example, in the study of Valinger & Fridman (2011), mean stand height was one of the three factors included in the logistic model for damage prediction. The first model is the simplest, including only crown ratio as the predictor. It's residual standard error

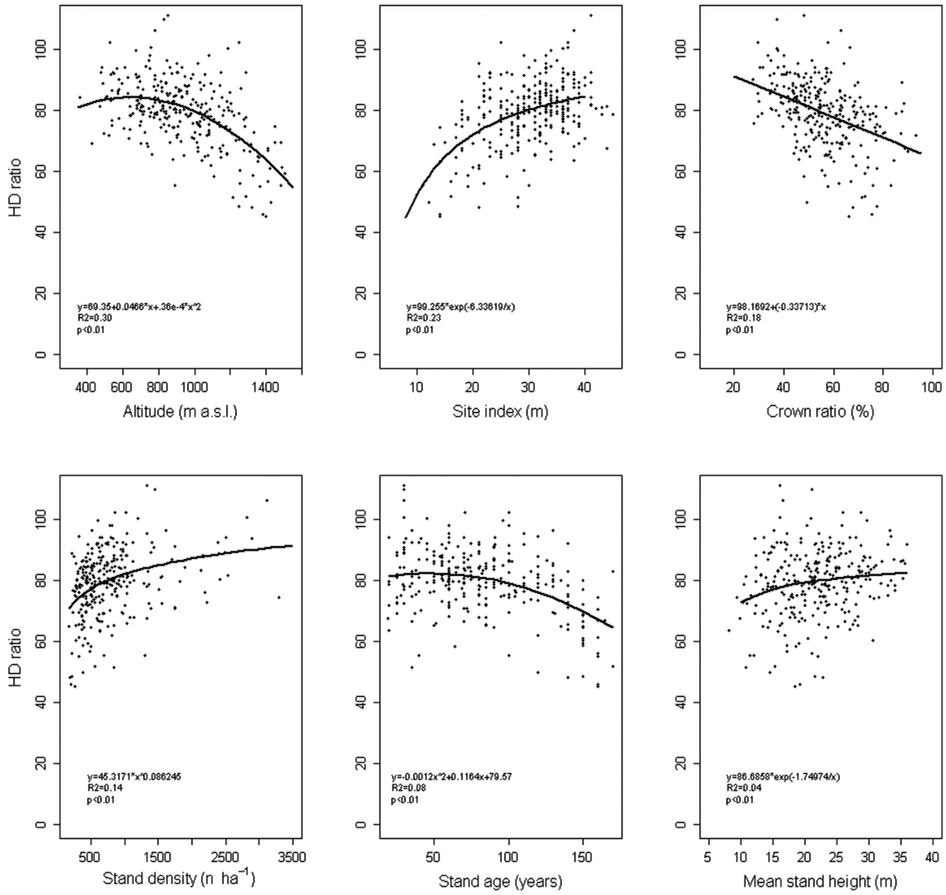

Fig. 3. Relationships between HD ratio and ecological and stand factors.

(RSE) as well as AIC value were the highest. Inclusion of other variables such as stand density (the number of trees per hectare), altitude, site index and mean stand height into the model resulted in an increase in the degree of variation explained (R^2) and a decrease of the residual standard error (RSE) to 7.4. The two variables that described stand density were found to explain the same amount of variability, therefore the simpler count of trees per hectare was used, instead of the SDI, because of its greater practicality for forest managers. Moreover, interactions between variables were tested, but it did not contributed to variance explanation at all.

In the final model (Table 3), the crown ratio had a significant relationship with the HD ratio. It could be seen from the data that the longer a tree's crown, the smaller the HD ratio,

Table 2. The contribution of predictors to the final model.

Model	Res.Df	AIC	ΔAIC	RSE	R^2
1 HD=Intercept+CR	281	−336.362	180.041	9.9	0.18
2 HD=Intercept+CR+SD	280	−397.151	119.253	8.9	0.34
3 HD=Intercept+CR+SD+Alt	279	−449.059	67.344	8.3	0.43
4 HD=Intercept+CR+SD+Alt+SI	278	−470.107	46.296	8.0	0.47
5 HD=Intercept+CR+SD+Alt+SI+MH	277	−516.403	min	7.4	0.58
5 HD=Intercept+CR+SDI+Alt+SI+MH	277	−516.402	0.001	7.4	0.58

Note: ΔAIC is the difference between minimum AIC and AIC of the particular model.

Table 3. Final regression model for HD ratio estimation based on the final set of predictors.

Predictor	Parameter	Estimate	Std. Error	VIF	Pr(>|t|)
Intercept	b_0	3.39354	0.32684	—	< 0.001
Crown ratio (%)	b_1	−0.07614	0.03013	1.61	0.012
Stand density (trees ha^{-1})	b_2	0.15847	0.01528	1.99	< 0.001
Altitude (m a.s.l.)	b_3	−0.11991	0.02364	1.39	< 0.001
Site index (m)	b_4	0.09069	0.02551	1.49	< 0.001
Mean stand height (m)	b_5	0.24823	0.03457	2.58	< 0.001

Note: VIF – variance inflation factor was a measure of multicollinearity.

which meant better static properties (or less risk of winter damage). The crown ratio was related to both stand density as well as to the vertical structure of forest stands. However, greater stand density was found to result in higher HD ratio. Similarly to crown ratio, the HD ratio also decreased with increasing altitude. Better site properties resulted in a higher site index, consequently influencing the HD ratio (higher site index = higher HD ratio).

HD ratio was closely related to the development of forest stands. The results showed that the HD ratio increased (nonlinearly) with mean stand height. The standard errors of individual variables were small and p-values suggested that all variables had a significant impact ($p < 0.001$ or $p < 0.05$) on the HD ratio (Table 4). Average residuals from the cross validation were not significantly different from zero ($p > 0.05$). Similarly, a Kolmogorov-Smirnov test showed a normal distribution of residuals, demonstrating the unbiased nature of the final model (Table 4).

3.2. Practical application of the final model

Less productive spruce stands at lower altitudes (Fig. 4, site index of 20 m) with a HD ratio of 90 had around 1000 trees per hectare and a mean stand height of 12 m; this stand density decreased steeply with increasing mean height. Stands with a ratio of 80 (which is the limit for spruce stands considered stable against wind breakage) had almost 2.3 times less trees per hectare, at the same mean height, demonstrating the huge contrast in density between stands with a difference in HD ratio of only 10%. Such a difference in stand density resulted in 1.4 times higher growing stock in the denser stands along the entire range of mean height. Similar relative differences were found for more productive stands, but the absolute density and growing stock were far less at the same growth stage of the stands. This suggests that trees at poorer sites grew faster at the early stages of stand development compared to those on more fertile ones, but realised less wood production by final harvest stage. Moreover, the decrease in the early stage density was faster for stands at poorer sites.

It was found that denser stands of spruce could grow at higher altitudes but yet retain the same HD ratio (as many as 5000 trees per hectare for stands with a site index of 20 m and a mean height of 12 m), since the trees there had naturally developed a higher degree of taper compared to trees at lower altitudes (Konôpka & Konôpka 2003). However, the decrease in stand density with mean stand height was higher compared to stands from lower altitudes where there was higher competition intensity.

Table 4. T-tests of mean differences of residuals from zero and Kolmogorov-Smirnov tests of residual's normal distribution.

Effect	Mean		Mean residual	t-value	p-value	K-S test	
	Train	Subset				d-statistic	p-value
Train 2 to subset 1	80.2	79.7	-0.58	-0.778	0.439	0.045	0.986
Train 3 to subset 1	80.5	79.7	-0.87	-1.098	0.275	0.043	0.991
Train 1 to subset 2	77.8	79.2	1.37	1.715	0.090	0.091	0.391
Train 3 to subset 2	79.3	79.2	-0.06	-0.079	0.937	0.069	0.736
Train 1 to subset 3	78.4	79.4	1.09	1.381	0.171	0.068	0.750
Train 2 to subset 3	78.9	79.4	0.56	0.721	0.473	0.087	0.453

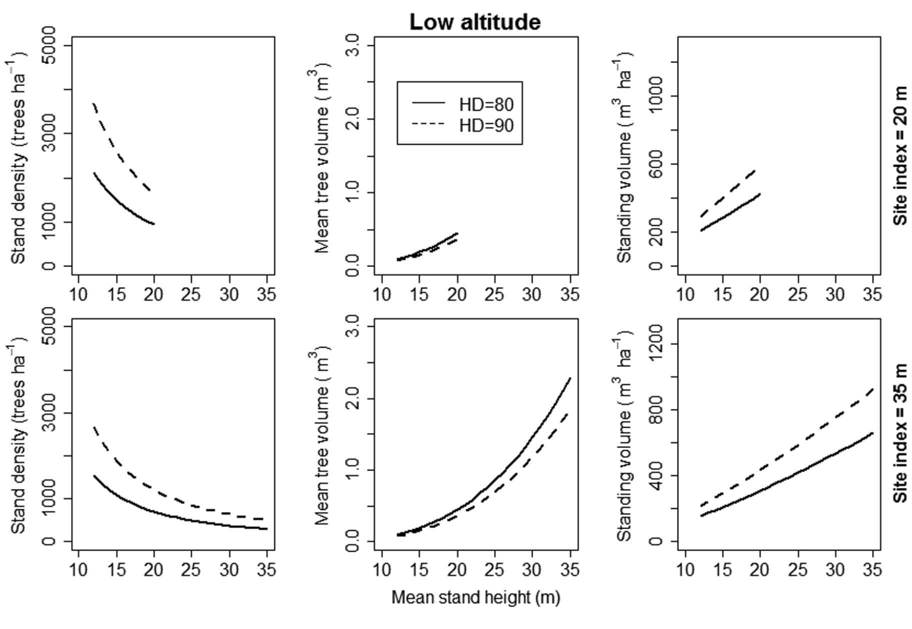

Fig. 4. Development of stand density, mean tree volume and stand volume per hectare at different HD ratios and different site indexes of spruce – at an altitude of 800 m a.s.l.

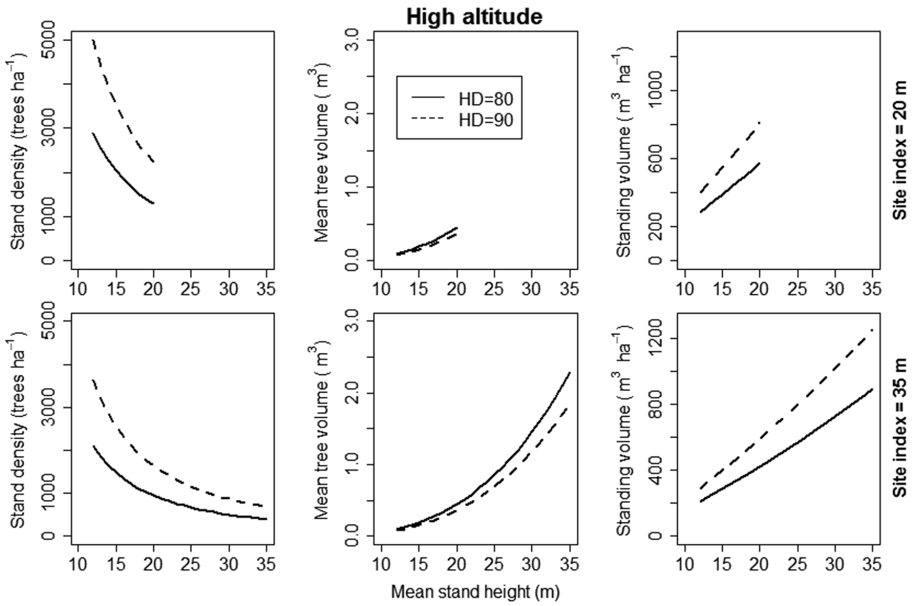

Fig. 5. Development of stand density, mean tree volume and standing volume per hectare at different HD ratios and different site indexes of spruce – at an altitude of 1200 m a.s.l.

5. Discussion

5.1. Factors affecting HD ratio

Since height and diameter increment of trees do not follow the same course (growth intensity) throughout the entire life of a tree (Oliver & Larson 1996; Šmelko 1996), a temporal change to the HD ratio is caused. In general, to predict development of the HD ratio over time, either stand age or size (mean height or diameter) can be used. For the conditions of mountain spruce forest in Slovakia (very high altitudes), the stand level HD ratio (ratio calculated from dominant and co-dominant trees) has been found to decrease with increasing mean stand diameter by Konôpka & Konôpka (2003). This tendency did not correspond exactly to the results of this paper. However, the HD ratio has also been observed to increase first with mean stand height (to circa 20 m) and to later decrease (Konôpka 1992). This corresponds to results recorded in Germany (Albert & Schmidt 2010) and France (Vielledent et al. 2010) which demonstrated that highest values of HD ratio in Norway spruce occurred in middle-size stands. It may be inferred that the initial course of HD ratio increase with stand age is most probably related to competition stress in younger growth stages. Hence, trees must invest more in height growth than in stem diameter to reach a position of dominance within a stand to enable sufficiency of light capture (e.g. Huang & Titus 1999). Later decreases of HD ratio in older growth stages might be related to reduced height increment resulting from the attainment of a dominant position within the stand and where crown surfaces are no longer limited in accessing light resources (trees do not need to expand to new space) and/or tree senescence. Moreover, HD ratio in older stands is also often reduced due to disturbances limiting tree height (especially leader breakages by ice or snow).

The course of temporal development of the HD ratio, as well as its value at a particular point in time, is most likely related to two groups of factors: forest stand characteristics and properties of the abiotic environment around the stand. Among forest stand characteristics, stand density (or the size and frequency of gaps between trees) has been recognised as important (e.g. Nilsson 1993; Valinger et al. 1993; Opio et al. 2000). In this study, when stand density was considered the only factor explaining HD variability, a very low correlation was found. It should be noted that stand density decreased dramatically with stand stage (age), especially in the youngest growth stages due to the high mortality rate. Often, the resistance of forests to wind and snow damage is related to the combined effect of basal area and HD ratio of the dominant trees (Martín-Alcón et al. 2010). At tree level, tree height and stand density often play an important role for prediction of snow damage risk (Valinger et al. 1993). Height growth of spruce, and thus also HD ratio, is highly modified by site priperties, and for the Western Carpathians, soil properties (nitrogen and carbon content) and climatic conditions (e.g. growing season length) have most important effect (Bošeľa et al. 2013).

The results of this work demonstrate that the HD ratio decreased with increasing crown length (crown ratio). This indicates that both parameters either react to the same external factors or influence one another. The first assumption comes from work by Nilsson (1993) who stated that both characteristics reflected stand density and therefore, both were suitable indicators of competition intensity. The second expectation is in accordance with many authors (e.g. Šmelko 1996), that longer tree crowns promoted the increment of stem diameter more than height.

The results here show that HD ratio was much influenced by altitude and site index i.e. productivity. In fact, although these two characteristics are related (average site class decreases with altitude), both contributed to improving the accuracy of the HD ratio model markedly. Decreasing HD ratio of forest stands with increasing altitude is typical for European forests (Konôpka & Konôpka 2003; Socha & Kulej 2005; Homeier et al. 2010).

The final model explained 58% of variation in the HD ratio. It combined five explanatory factors, in order of declining importance: crown ratio, stand density, altitude, site index and mean height. The most important aspect demonstrated by Figures 5 and 6 is the leftmost side of the model trajectories i.e. smaller stands. Younger trees are much more flexible to changing growth conditions (light, water and nutrient availability and growing space properties –as influenced by the removal of trees through thinning) than older ones (see also Slodičák 1995). Since the HD ratio was related to crown ratio, trees with unfavourable properties of both characteristics could be considered for removal from a stand as soon as possible. In other words, increased stand stability can best be reached by favouring spruce trees with long (deep) crowns as early as possible in a rotation.

5.2. Reliability and applicability of the stand stability model

The results of this study suggest that intensive measures (thinning) can be used to increase stability and to reduce the risk of wind damage in spruce stands by decreasing the stand HD ratio. However, there are many factors modifying the growth of spruce trees and stands such as site quality, altitude (climate), and others (Schmidt-Vogt 1977). The varying conditions over the West Carpathians demand different approaches through management measures to be applied to increase the adaptability and stability of such stands. Hence, at richer sites where spruce height growth is strongly stimulated by favorable conditions (abundant soil water and nutrient levels) and where trees reach maximum height and diameter increment far earlier than at poorer sites, it is necessary to apply more intensive thinning at earlier growth stages. Kamimura et al. (2008) suggested that top height was the most important stand characteristic for storm risk assessment and provided a critical top height for silvicultural treatments. If the top height exceeded the critical height, any treatments including thinning were avoided to minimize risk from wind damage. However, trees respond to the increased light availability with a temporal lag which should be considered before making a decision on the thinning intensity. Such a temporal lag may in the short term result in increased risk of the stand to wind damage. Accordingly a forest manager should start intensive thinning at early growth stages to continually increase the static stability of the individual trees and stands.

The final model of HD ratio proposed the removal of quite large numbers of trees or stand volume to achieve good standing stability of spruce stands. This would inevitably result in much lower volumes at older growth stages, but should ensure greater security of the standing stock. It should be kept in mind that the model is based upon a single round of NFI data, i.e. without repeated measurements. Therefore, it was not possible to infer the effect of management performed in the recent past. Such data did not include the time since the last change in stand density (management intervention), which influences the reliability of the analysis. Within the NFI data, there must have been IP where an intensive thinning had taken place shortly before the measurements were applied, not allowing the stand time to respond. However, comparison can be made to recent results of a German study (Pretzsch 2005), which was based on very long-term experimental plots for different types of thinning in Norway spruce and European beech stands. The work suggested that a heavy thinning regime which kept a stand permanently at maximum annual increment did not ensure either a maximum cumulative merchantable volume or a maximum standing merchantable volume. Clearly heavy thinning causes severe losses of increment, especially in older stands. However, a heavy thinning regime applied to support spruce stand stability should not necessarily need to be implemented on a large-scale basis. The regime could be used preferably for the sites most highly exposed to strong winds (this kind of site could be identified through historical forest records concerning repetitive wind damage). Such decision making should also be made at a forest level rather than purely at a stand level.

For making more precise recommendations on how intensive the interventions in a forest stand should be to significantly decrease the HD ratio (and in tandem increase stand stability), as well as the timing of those treatments during the stand life, a long-term set of measurements with associated information on past management treatments would be needed. However, it is anticipated that the Slovak NFI will be repeated at regular intervals in the future (most probably every 10 years), which will allow the model to be verified, updated and modified to increase precision.

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