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The radial growth-competition relationship in *Picea abies* stands affected by windfall

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Abstract: Actual status of mountain forests especialy, of Norway spruce (Picea abies Karst. (L)) stands is a result of combined action between forest management measures and biotic and abiotic risk factors. In this context, tree growth dynamics is a result of multifactor interaction (competition, disturbance, management practice, climate etc.). Wind damage affect the stand structure and normal ecosystem functions including the relationship between individual tree growth and competition processes. Though, it is recorded a diminishing of productive capacity for affected stands as well as a significant diameter increment for remaining standing trees. The correlation between tree growth (cumulate basal area increment in the last 10 years) and competition (Hegyi and Schutz competition indices) was analysed in stands with different windfall intensity. No relationship between tree growth and competition was observed in highly affected stands. Schutz competition index explains better individual tree growth comparing with Hegyi index in low or no-affected stand by windthrow. The variability of the basal area increment ($ln\Delta g_{10}$), explained by competition indices, is rather low (<2%) in the stand that had been highly affected by windfall, regardless of the selected competition index. Thus, significant reduction of the stand density related to number of trees (low density), as a consequence of high intensity windfalls, crown competition has a very small influence on the basal area increment comparing with situations met in low (high density) and moderate (medium density) affected stands.

Additional key words: Norway spruce stand, competition index, basal area increment, windfalls risk factors

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Introduction

In terms of structure and functional relationships, the dynamics of mountain forest ecosystems is the product of specific internal processes, correlated with the enforcement of forest management measures and with the effects of the biotic and abiotic risk factors (Castagneri et al. 2008). The specific competitive processes in forest ecosystems have a significant influence on both the diameter and height growth. Growth processes are high correlated with light conditions. Crown shape and morphology is influenced by the availability of light. Light condition depends on topographic factors and local competition between trees (Lang et al. 2010).

Tree growth depends on the size, shape and functioning of the foliar system, i.e. of the crown parameters. The size and shape of the crown is a direct result of the interaction between neighbouring trees. The dynamics of radial, height, basal area or volume increment is directly related to the inter-tree and inter- specific competition. Competition is a result of negative interaction between trees for aboveground (e.g. light) or belowground resources (e.g. water) (Larocque et al. 2013). The competition for resources between neighbouring individuals is one of the main predictors of tree growth (Tome and Burkhart 1989). The effects of the competition on the individual trees growth has been the subject of numerous research studies, while the competition indices were included in various increment models (e.g. Pretzsch et al. 2002).

Wind is an importance disturbance factor in mountain ecosystems, and manly in Norway spruce artificial monoculture (Panayotov et al. 2011). The impact of a windthrow is reflected in the significant changes occurring in the structure of the stands, through a systematic stand density reduction process (Popa 2007). Reduction of stand density, by human intervention (e.g. thinning) or disturbance factors (e.g. wind, insects) induce an increase of light availability and reduce competition for nutrients and water (Larocque et al. 2013). The occurrence of gaps or the relatively even reduction of stand density influences the intra- or inter-specific competition, with direct effects on the growth processes (Aakala et al. 2013).

The main objective of the study is to measure the statistical relationship between the competition indices and the trees growth in Norway spruce (*Picea abies* Karst. (L)) stands affected by windfall of different intensity. Our hypothesis is that a decrease of stand density due to wind damage will reduce the influence of competition on tree growth.

Materials and methods

The research has been conducted in the north of the Eastern Romanian Carpathians in two artificial Norway spruce stands aged 65 (plot 43H) and 80 years (plot 48A). In 2002 the study region was affected by a high intensity wind damage been felled over 400.000 m^3 in an area of 7000 ha (Popa 2008). According with local topography the wind damage intensity varies between 10 to 100% of stoking volume. Two 0.5 ha permanent plots have been established in each stand, with different stand density levels, induced by windfall. The wind damage intensity was established comparing actual number of tress per ha (after removal of felled trees by wind) with normal number of trees per ha according with yield tables (function of specie, age and stand index) (Table 1).

All living trees have been subject to dendrometric measurements such as species, diameter at breast height DBH (cm), tree height (m), length of the crown (m), two crown diameters (m) (along and perpendicular to the slope) and x and y coordinates (m). A radial increment core from the 1.3 m height has been extracted from each tree. The increment samples have been processed, measured and checked according to classical dendrochronological procedures (Cook and Kairiukstis 1990).

The quantification of the basal area increment has been conducted starting the measurements from the cambium rather than from the pith (Huang et al. 2013). The DBH was converted into diameter at breast height without bark (DBH_c) according to the equation suggested by Giurgiu et al. (2004) for Norway spruce.

$$DBH_c = DBH - (0.278 + 0.0398 \times DHB - 0.000156 \times DBH^2)$$

The cumulate basal area increment for the past 10 years (Δg_{10}) has been derived from the radial increment data set.

$$\Delta g_{10} = \pi (DBH_c - ir_{10}) \times ir_{10}$$

where ir_{10} represents the cumulated radial increment within the past 10 years period.

In order to identify the relationship between competition and tree growth, we have selected two individual based competition indices, distance dependent, as follows: the Hegyi index (Mailly et al. 2003) and the Schütz competition index (Ung et al. 1997).

Table 1. Summary statistics for Norway spruce plots

Variable	43H1	43H2	48A1	48A2
Trees per ha	268	452	294	392
Basal area ($m^2 \times ha^{-1}$)	28.6	35.8	38.2	42.1
Volume ($m^3 \times ha^{-1}$)	413.9	550.4	662.1	719.6
Age (years)	65	65	80	80
Mean DBH (cm)	40.1	36.9	44.2	40.5
Mean h (m)	34.1	33.2	39.7	36.5
Mean individual tree basal area increment Δg_{10} (cm^2)	189.5	139.9	159.5	167.6
Normal trees per ha*	887	887	549	549
Stand density	0,30	0,51	0,54	0,72
Wind damage level	High	Moderate	Moderate	Low

* number of trees per ha from yield table at stand density equal with 1

The Hegyi index is based on the ratio between the DBH of the competing tree and the one of the subject tree, weighed by the distance between them. Hegyi index is recommended as a very good predictor for basal area increment and is widely used in competition studies (Contreras et al. 2011). The selection of the competitor trees has been conducted depending on the influence area, i.e. from a circle with a radius that equals one third of the height of the subject tree (Mailly et al. 2003).

$$ICH_i = \sum_{j=1}^{N} \frac{d_j}{d_i} \cdot \frac{1}{L_{ij}}$$

where: ICH – the Hegyi competition index; d_i – DBH of the subject tree; d_j – DBH of the competitor tree; L_{ij} – the distance between the subject and the competitor tree.

To include the crowding effect we chose the Schütz competition index (Ung et al. 1997) with two components: a horizontal one, defined by the closeness between the crowns of the two trees under analysis and a vertical one, depending on the height difference. Mathematically speaking, this competition index is measured by means of the formula:

$$ICS_i = \sum_{\substack{j=1 \\ j \neq i}}^{n} 0.65\, \frac{h_j - h_i}{r_i + r_j} + 0.5 - \left| \frac{E_{ij}}{r_i + r_j} \right|$$

where: ICS – the Schütz competition index; r_i – radius of crown of the subject tree; r_j – radius of crown of the competitor tree; h_i – height of the subject tree; h_j – height of the competitor tree; E_{ij} – distance between the crown outer edges of the subject and competitor trees.

Schütz competition index has its own criterion for the selection of competitor trees for a given subject tree. Thus, a competitor tree is identified according to the formula:

$$E_{ij} \leq 0.5\,(r_i + r_j) + 0.65\,(h_j - h_i)$$

The analysis has been conducted for each plot excluding a 5 m buffer area in order to prevent underestimating the competition for outer edge trees.

Since the basal area increment has asymmetric distribution, we have normalised it by means of a logarithmic conversion. In order to test the effects of the competition on tree growth, we have used the following linear model:

$$ln\Delta g_{10} = a + b \times CI$$

where CI is either the Hegyi or the Schütz competition index.

The performance level of the regressive model has been measured by means of the root mean square error (RMSE) and of the adjusted coefficient of deter-

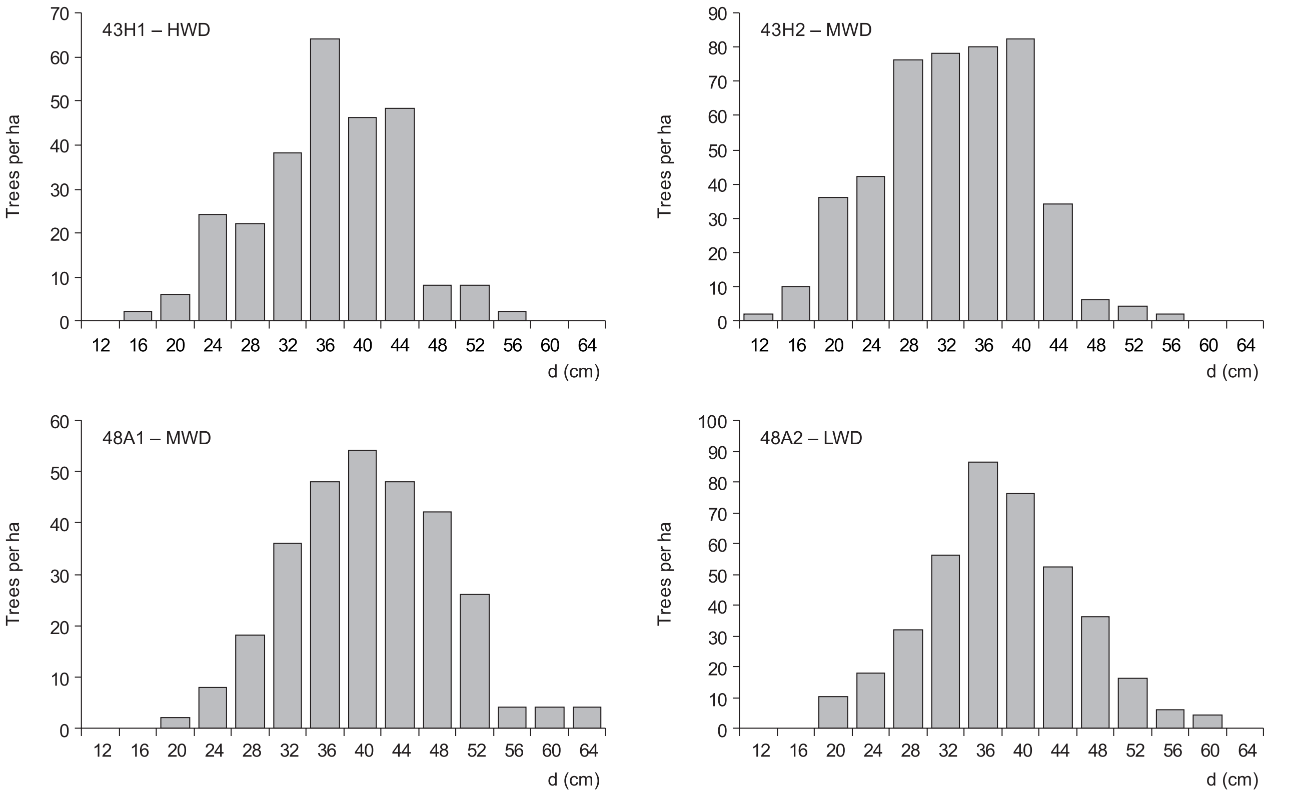

Fig. 1 Distribution of number of trees per diameter classes (LWD – low wind damage intensity, MWD – moderate wind damage intensity, HWD – high wind damage intensity)

Table 2. Model parameter estimates

Plot	R^2_{adj} (RMSE)	Variable	Estimate	SE	t	P
43H1	0.017	Intercept	4.995	0.098	50.67	<0.0001
	(0.555)	ICS	0.040	0.029	1.34	0.1822
	0.018	Intercept	4.920	0.145	33.73	<0.0001
	(0.580)	ICH	0.104	0.075	1.37	0.1731
43H2	0.626	Intercept	5.360	0.051	104.54	<0.0001
	(0.479)	ICS	−0.166	0.009	−17.44	<0.0001
	0.197	Intercept	5.355	0.109	48.99	<0.0001
	(0.705)	ICH	−0.214	0.032	−6.66	<0.0001
48A1	0.519	Intercept	5.390	0.064	84.52	<0.0001
	(0.453)	ICS	−0.183	0.017	−10.65	<0.0001
	0.280	Intercept	5.844	0.155	37.64	<0.0001
	(0.553)	ICH	−0.478	0.073	−6.50	<0.0001
48A2	0.517	Intercept	5.483	0.062	87.15	<0.0001
	(0.511)	ICS	−0.221	0.017	−12.58	<0.0001
	0.296	Intercept	5.949	0.142	41.94	<0.0001
	(0.616)	ICH	−0.483	0.060	−7.98	<0.0001

mination R_{adj}^2. The model parameters were estimated by means of the ordinary least square, using the REG procedure from SAS (SAS 2013).

Results

The intensity of windfall is reflected in the number of trees per hectare that are still standing (stand density) compared with normal number of trees per hectare according with yield table. Stand density is minimum in the 43H1 plot and maximum in the 43H2 plot (Table 1). The stand basal area ranges between 28.6 $m^2 \times ha^{-1}$ and 42.1 $m^2 \times ha^{-1}$. For the stand with high wind damage intensity the number of trees per hectare represent 60% from moderate affected stand and the basal area 80%.

The diameter distribution is normal in case of low affected stand and asymmetric for stand with high intensity of windthrow (Fig. 1).

The maximum value of competition index of individual trees is higher in the case of the 43H2 plot ($ICS_{max}=19.4$; $ICH_{max}=10.0$) as compared to the other plots (43H1−$ICS_{max}=7.8$; $ICH_{max}=3.6$). Mean

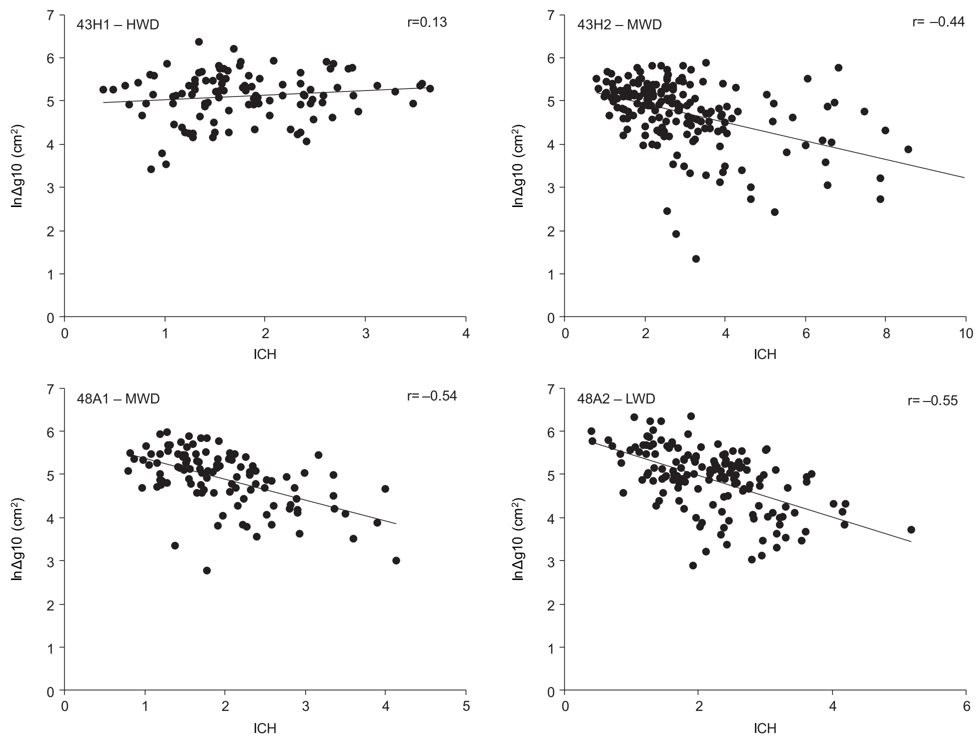

Fig. 2 Relationship between the basal area increment ($ln\Delta g_{10}$) and the Hegyi competition index (LWD – low wind damage intensity, MWD – moderate wind damage intensity, HWD – high wind damage intensity)

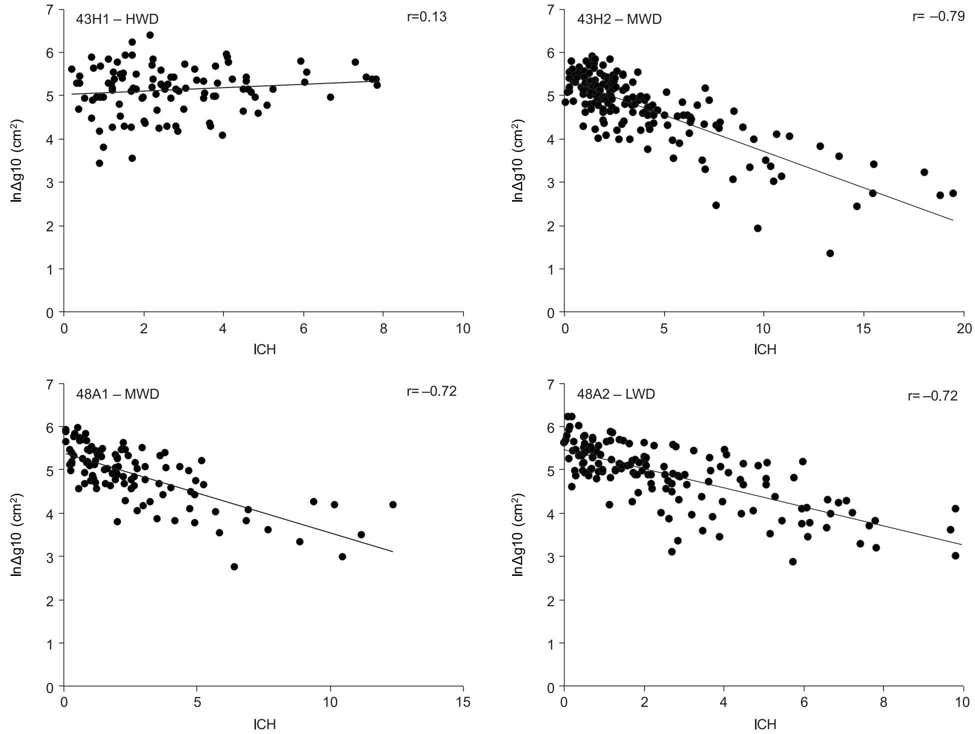

Fig. 3 Relationship between the basal area increment ($ln\Delta g_{10}$) and the Schütz competition index (LWD – low wind damage intensity, MWD – moderate wind damage intensity, HWD – high wind damage intensity)

value of competition index for stand with high and low windthrow intensity are similar, but the standard deviation is 25% lower in case of highly affected stand.

The correlation coefficient (r) between the basal area increment expressed by means of a logarithmic function ($ln\Delta g_{10}$) and the Hegyi competition index, varies between r=0.13 (p=0.17) in the case of the 43H1 (highly affected by windfall) and r=–0.55 ($p<0.0001$) for the 48A2 plot (low windthrow intensity). The correlation coefficient for moderate affected stand by windthrow varies between –0.44 and −0.54($p<0.0001$) (Fig. 1). When analysing the correlation between the basal area increment and the Schütz competition index, the intensity of the correlation is low in the case of the plot that had been highly affected by windfall (43H1 plot) (r=0.13, p=0.18) and increases significantly for the plots with low and moderate windthrow intensity (r varies between −0.72 and −0.79, $p<0.0001$) (Fig. 2).

The variability of the basal area increment ($ln\Delta g_{10}$) explained by competition indices is rather low (<2%) in the stand that had been highly affected by windfall, regardless of the selected competition index (Table 2). The Heigy index accounts between 20% (moderate wind damage intensity) and 30% (in stands that were slightly affected by windfall) of variance. However, the Schütz index accounts 63% of the basal area increment variance for 43H2 (moderate affected stand) and 52% for those plot which were low affected by wind damage.

Discussion

The analysis of the effects of the applied forest management measures is rather difficult in the case of significant wind damages, in terms of their frequency and intensity (Popa 2007). Even site condition and initial stand characteristics for all plots were similar different wind damage intensity were observed.

Wind, as disturbance factor, can affect single tree, group of tress or part of stand (Johnson and Miyanishi, 2007). Depending on the size of gap produced by trees fell the spatial structure changes. When only one tree is felled by wind, changes in competition are low. Increasing of gap size determine a decrease of competition due to high reduction of distance between subject tree and neighbors. Crown parameters are highly influence by local neighborhood competition (Lang et al. 2010). Increase of vegetation space permit trees to invest more resources in extending lateral branches and increase crown area and foliar system.

Crown morphology and area is related with growth rate (Drobyshev et al. 2007). In most cases (except for 43H1 plot) there was a negative correlation between the level of individual competition and the basal area increment. The correlation is relatively low, but statistically significant in the case of the Hegyi index, based on the ratio between the DBH weighed by the distance between trees. Other studies reveal this index to be superior because of the correlation between radial increment of the subject tree and it's

DBH (Holmes and Reed 1991, Garcia-Abril et al. 2007). In some studies for scots pine the Hegyi index explain about 50% of the variability of a 5 year radial increment (Pukkala and Kolstrom 1987). On the other hand, in the case of natural forests, the Hegyi index accounts for only 32% of the spruce radial increment variance and 14% of the silver fir radial increment variance (Duduman et al. 2010). The use of the competition indices in the growth models for scots pine has increased the explained variability by 20% (Pukkala and Kolstrom 1987).

The growth variability explained by the Schütz index, based on the crown parameters, is double compared to the one accounted for by the Hegyi index. By definition the Schütz index takes into account the lateral shading of the neighbouring trees on the crown of the subject tree (Prevosto 2005). The superiority of the distance related competition indices that take into account the crown parameters has also been noticed in mixed coniferous forests in northern California (Biging and Dobbertin 1995).

In the case of black pine, De Luis et al. (1998) have noticed the fact that the competition level is not influenced by the density of the trees in the stand, as competition indices record competition on an individual level and do not depend on the trees located outside of area of influence.

The incorporation of the competition indices in the individual growth models significantly improves their performance (Biging and Dobbertin 1995, Pretzsch 2009).

The amplitude of both competition index used is low in case of high disturbed stand comparing with low and moderate affected stand. Stand density reduction due to effect of wind damage cause a reduction of competitors and their influence area.

The strong correlation between the basal area increment and the competition indices reveals that the individual growth is highly affected by the spatial location of a tree in the stand, in relation to neighbouring trees (Coutts and Grace 1995). This statement cannot be proved in the case of stands that had been highly affected by windfalls. Thus, a significant reduction of the number of trees in the stand, as a consequence of high intensity windfalls, crown competition has a small influence on the basal area increment. The lack of windfalls or their action with a low intensity could have an effect on normal competition processes which are specific to the structure and functioning of the tree stands and which significantly influence growth. Therefore, the distance between crowns and the relative difference between height of the subject trees and competing trees (elements which have a direct influence on competition between trees in terms of canopy) influence the basal area increment to a greater extent than tree diameter (as an effect of the competition process) or the distance between the trees, in the case of tree stands that are low or moderate affected by windfalls. For studied spruce stands the Schütz index explains the size and intensity of increments better than the Heigy index, based on diameter and distance. In the case of tree stands that had been highly affected by windfall, the competition processes are very low, and both indices equally explain growth variability to a very small extent. Wind damage with high intensity (stand density under 0.3) determines a significant modification of competition and his influence on trees growth.

Further research on the topic will help collect more information on the impact of various disturbances on competition and growth processes manifested both in individual trees and within tree stands.

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