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Effects of topography and tree stand characteristics on susceptibility of forests to natural disturbances (ice and wind) in the Börzsöny Mountains (Hungary)

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Abstract: We analysed the role of topography, tree stand characteristics and management on the susceptibility of forest stands to abiotic natural disturbances. In 1996, stands of Börzsöny Mts, Hungary were hit by a severe ice storm, then by strong winds three years later. Affected areas were mapped on aerial photos, and we built a GIS database containing variables describing topography and tree stand characteristics. The role of variables in predicting ice break and windfall was investigated by non-parametric statistical tests and by a series of C&RT (Classification and Regression Tree) analyses. Elevation, aspect and slope proved to have strong statistical relationships with the distribution of both ice break and windfall, with misclassification error (MER) of 18% and 15%, respectively, if studied without stand descriptors. Mixing ratio and age of beech were the most important stand descriptors to explain the distribution of ice break (MER=15%), whereas that of windfall was best described by the age and height of the two dominant tree species (MER=11%). The explanatory power could be increased if all variables (topographic + stand descriptors) were considered, though the increase in explanatory power was higher in the case of ice break (MER decreased from 15% to 11%) than for windfall (MER decreased from 11% to 10%). Since management related stand variables (beech mixture ratio, age, height, amount of recently felled stock, slenderness) and susceptibility to disturbance events seemed to be related, our results suggest that the sensitivity of tree stands could be decreased by increasing compositional and structural heterogeneity.

Abbreviations: C&RT – Classification and Regression Tree, MER– Misclassification Error Rate, GIS – Geographic Information System, DEM – Digital Elevation Model, RelAgeSlen – Relative Age-specific Slenderness, fs – amount of felled stock, totcut – total cut, plancut – planned cut.

Introduction

In temperate broadleaved forests of Europe and North America, the most common form of natural disturbance is fine scale gap dynamics driven by the death of individual (or a few) canopy trees (Peterken 1996, Splechtna et al. 2005). Less frequent natural disturbances that affect larger areas are responsible for shaping the natural coarse pattern of forests. In Europe, this group of natural disturbances includes windthrow and ice break which, depending on their size and intensity, may result in the destruction and renewal of individual forest stands or entire woodlands (Pickett and White 1985, Peterken 1996, Ulanova 2000, Splechtna et al. 2005, Nagel and Diaci 2006). Unfortunately, there is limited quantitative information on the natural disturbance regimes of European forests, because unmanaged old-growth forests are scarce after a long history of intense forest use and exploitation (Glatzel 1999, Parviainen 2005). In Eastern Central Europe, where more remnants of natural forests survived, scientific traditions focused on describing forest stand structures and on distinguishing forest community types, hence much less emphasis has been put on studying processes (Standovár and Kenderes 2003).

Much more information is available on the natural disturbance regimes of North American forests (Van Dyke 1999, Bragg et al. 2003). Ice break and windthrow occur at a medium (decade) frequency in the deciduous woodlands of the temperate zone (Foster and Boose 1995). The time rotation for catastrophic windthrow and ice break varies greatly with location. For ice it can be as short as a few months, whereas it can be longer than a thousand years for catastrophic wind (e.g., Canham and Loucks 1984, Proulx and Greene 2001, Bragg et al. 2003 and references therein). The spatial extent of large scale disturbances can be huge, reaching several million hectares (Bragg et al. 2003 and references therein).

The importance of natural disturbances in maintaining original forest biodiversity is widely accepted and most modern strategies of biodiversity conservation in forests rely on mimicking natural processes (e.g., Peterken 1999, Angelstam 2002, Lindenmayer and Franklin 2002). Natural disturbances are not only necessary but also unavoidable, even in a world of active control against them (e.g., fire prevention, pest control, etc.).

Intensive large scale forest disturbance events have caused serious problems in European forests in recent decades. In spite of the uncertainty that surrounds the available figures (e.g., Schiesser et al. 1997, Dorland et al. 1999, Lässig and Močalov 2000, Smits et al. 2005), the general impression suggests an increasing trend in frequency and/or severity of disturbances at the continental scale (Schelhaas et al. 2003). Available data at the national and regional scales have proved this trend: the increase of storm damage was demonstrated for Denmark (Holmsgaard 1986) and Switzerland (SFSO and FOEFL 1996), whereas a sharp increase in sanitary cuts was shown for Bayern (Germany) and the Czech Republic (Mosandl and Felbermeier 1999). On a European scale strong winds and storms were responsible for 53% of the total damage to forests during the second half of the last century (Schelhaas et al. 2003).

Changes in climate and management which induced alterations in forest structure and conditions are among the possible major causes behind this increase in forest damage due to natural disturbances. Several authors have stressed that the increased damage could be explained by an increase in susceptibility brought about by forest management. In general, the prevailing uniform shelterwood system may be viewed as a wide-ranging, intensive and frequent (constantly present) disturbance, which homogenizes the structure, composition and processes of forest communities in many ways. It creates relatively large, even-aged and often pure stands. Heavy thinning makes stands more vulnerable to wind (Lohmander and Helles 1987, Dobbertin 2002) and snow (Nykänen et al. 1997) damage; however, these effects disappear after a few years. Newly clearcut areas also expose the edges of the remaining stands to the force of the wind. Pellikka and Järvenpää (2003) found that a recently thinned forest was more likely to be damaged than an unmanaged dense forest stand.

As opposed to the above papers that studied the effects of individual forestry operations, in this study we analysed if stand characteristics that developed as a cumulative result of long term management played any role in making stands more susceptible. Tree species composition, stand density (hence tree shape) are affected by the frequency and intensity of precommercial thinning and later tending cuts.

However, as many previous studies showed the effect of topography on the sensitivity of trees to disturbance (Foster and Boose 1992, Seischab et al. 1993, Warillow and Mou 1999, Mou and Warillow 2000, Duguay et al. 2001, Dobbertin 2002, Rhoads et al. 2002, Bragg et al. 2003, Millward and Craft 2004), we needed to include the study of variables describing topography as well, so that we can separate these two groups of possible causes.

By performing this study, we took the possibility the Királyrét area in the Börzsöny Mts. gave us, as it was hit by two serious disturbance events within three years (ice in 1996 and wind in 1999). The area has a varied topography, and is covered by forests managed rather intensively in the past 200 years. Specifically, we wanted to answer the following questions:

1. How big area was affected by the two disturbance events?

2. Under what topographic conditions did trees fall at a higher probability due to ice and wind effects?

3. What special stand characteristics and/or previous forest operations do the affected areas have?

4. What is the importance of topographic, stand and management characteristics in determining the sensitivity of stands to disturbances?

Materials and methods

Study area

The study area covers 4830 hectares (48.3 km^2), in the Börzsöny Mountains, Northern Hungary (47^{o}55'20'' N, 18^{o}58'0''E). The bedrock is mainly andesite agglomerates and tuffs of the Miocene volcanism (Gyalog 2005). The study site includes two geomorphologically distinct areas (Figure 1). The southern lower part (300-500 m a.s.l.) contains gentle slopes climbing from Királyrét to the higher (500-900 m a.s.l.) northern part, which is characterised by steep, rocky slopes and deep valleys of north-

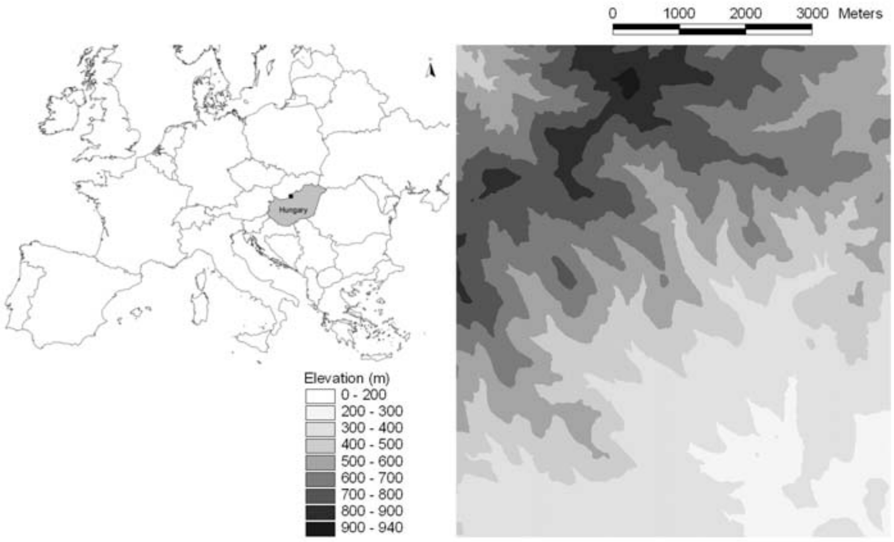

Figure 1. Map of the study area showing elevation 'belts'.

west-southeast direction. This dichotomy in geomorphology is also manifested in the vegetation. The stands dominated by sessile oak (*Quercus petraea* (Mattuschka) Lieblein) occur at the lower, whereas those dominated by beech (*Fagus sylvatica* L.) at higher elevation, and beech is more abundant on northeasterly slopes than on southwesterly ones. Turkey oak (*Quercus cerris* L.) and hornbeam (*Carpinus betulus* L.) also appear at lower elevations as associate species in sessile oak dominated stands. Ash (*Fraxinus excelsior* L.) is locally dominant on sharp ridges and on the steepest part of the caldera. The forest stands have been managed by the uniform shelterwood system with short regeneration period (Matthews 1991).

As a result of the intensive forest use in the early 1900's, the age distribution of the forests in the Királyrét region is rather uneven: 70 to 100 year old stands have high share, whereas middle-aged stands (around 50 years) give only a small proportion of all forests. The mixture ratio of sessile oak and beech is varying, but the majority of the stands is dominated by one of these species.

Ice break and windthrow in the Börzsöny Mountains

Forests of the Királyrét Forest Directorate were hit by two intense disturbance events in 1996 and 1999. On 9 January 1996, warm air masses reached the Carpathian basin and were topped over the cold air masses that filled the Carpathian basin. As the relatively warm rain reached the cold surfaces, thick ice crust started to develop on tree branches. It grew thickest in the cold microclimate corners, sometimes reaching 6 cm in thickness. Many trees could not bear the great burden: their crowns and trunks broke, some even uprooted. Some of the falling trees also knocked against their neighbours, resulting a domino-effect, which led to the complete demolition of huge areas.

Three and a half years later, the heavy rainfall in June 1999 was followed by a heavy windstorm. The trees slipped on the soaked soil, and fell over huge areas, according to the domino-effect.

Data collection

Airborne photos taken in 1995 (before the disturbances) and in 1999 (immediately after the windthrow) were used to assist in accurate localisation of patches produced by disturbance. The locations of the disturbed patches were delineated in the scanned and geocoded images of the photos taken in 1999 (resolution = 60 cm by 60 cm). The patches engendered by ice could be well differentiated from those due to wind. The lack of fallen trees (they had been removed), and the presence of recovering vegetation characterised patches hit by ice, whereas fallen trees and bare ground were still visible in patches that were hit only in 1999. To check the accuracy of this visual assessment, we made ground-truthing together with local foresters, and also consulted the photo set from 1995.

The severity of disturbance was recorded by distinguishing two levels: a disturbance patch was labelled as *intensive* if most tree individuals were flattened and the cover of remaining canopy was less than 20%. All other cases were treated as *sporadic* disturbance. The reason for applying this simple description of a much more complex phenomenon was that the distinction of more categories just by the assessment of the aerial photographs would have introduced more error. As a result we distinguished four disturbance types: intensive ice break, sporadic ice break, intensive windthrow, sporadic windthrow (Figure 2).

For the purpose of this analysis, we built a GIS database which contains: *i)* the geocoded aerial photographs; *ii)* digital elevation model (DEM) created from the digitised contour lines (raster with 5 by 5 meters resolution, 220-920 m); *iii)* Two raster layers – derived from the DEM – describing topography of the study area: slope (0-40°), aspect (original degree (0-360^{o}) values were converted to a nominal scale: N, NE, E, SE, S, SW, W, NW); *iv)* Four polygon layers containing the digitised contour lines of the patches hit by the four disturbance types; *v)* polygon layer showing the boundaries of forest subcompartments *vi)* raster layers (5 by 5 m resolution) that were derived from data linked to the forestry map showing variables describing tree stand characteristics.

Of the many possible descriptors of forest stands, we used the following variables:

- Mixture ratio of sessile oak and beech (0-100%);
- Age of sessile oak and beech (1-188 year);
- Mean height of sessile oak and beech (0-33 m);
- Relative age-specific slenderness of beech for stands where age of beech > 20 years and mixing ratio of beech > 40%:

  *RelAgeSlen = (Slenderness-AgeSlen)/AgeSlen*100*,

  where *Slenderness = tree height (cm)/dbh (diameter at breast height in cm), AgeSlen* = mean age-specific slenderness, which was calculated by fitting a polynomial function

  ($AgeSlen = 89.1715 + 0.1267 * BeechAge - 0.0034 * BeechAge^2$)

  to data of all subcompartments containing beech in the Királyrét Directorate;

- Amount of felled stock between 1995 and 1999 (0-200 m^3/ha) for stands where age of dominant tree species > 50 years. Both total cut and planned cut (total cut - sanitary cut) were calculated to assist correct interpretation of results. In these calculations the felled stock was weighted by years then summed and calculated for one hectare:

  $fs = ((0.7*f95) + (0.8*f96) + (0.9*f97) + f98 + f99)/area$,

  where *fs* = amount of felled stock between 1995 and 1999 in m^3/ha; *f95*, *f96*, etc. = amount of felled stock in the given subcompartment in 1995, 1996, etc.; *area*: area of the given subcompartment.

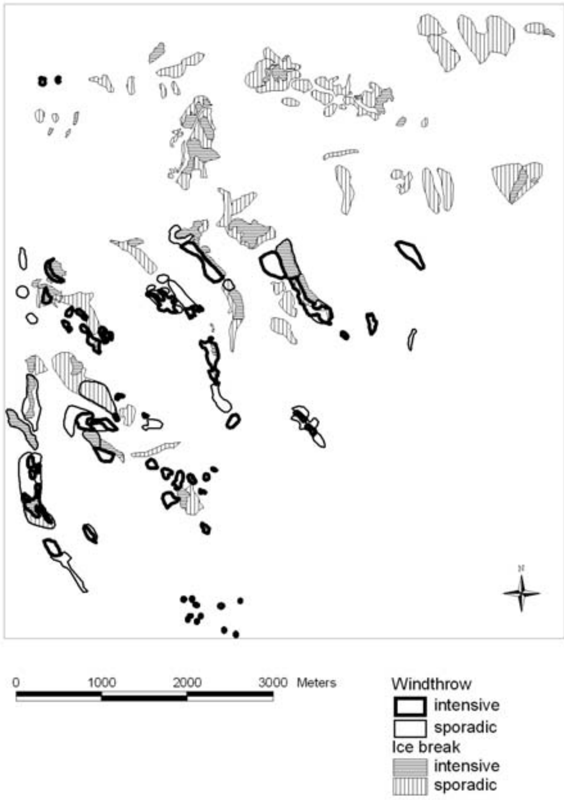

Figure 2. Map showing the distribution of patches hit by intensive ice break, sporadic ice break, intensive windthrow, sporadic windthrow.

Data analyses

To study the relationships between the occurrence of disturbance and potential explanatory variables, we performed different statistical analyses using a sample of all data (1,756,772 pixels with forest stand descriptors). A stratified random sampling was applied to all raster layers containing the explanatory variables. We applied the restriction of having at least 10 m between neighbouring sample points to prevent the inclusion the same pixel several times. Altogether, 10.000 sampling points were allocated both for studying ice and wind disturbance. For ice break, 7500 random points were selected with no disturbance and 2500 with intensive ice break. For studying wind disturbance, we excluded those patches that were hit by either intensive or sporadic ice damage so that interdependence of these two events does not complicate our analyses. Hence, 7500 random pixels with no disturbance at all, and 2488 random pixels with intensive wind break were selected. The disturbed areas were over-represented in both samples, because complete random sampling

Table 1. Descriptive statistics (number, total area, average size) of patches hit by ice break and windthrow in Királyrét.

Charactersitics of disturbed patches	Intensive ice break	Sporadic ice break	Intensive windthrow	Sporadic windthrow
Number	45	51	57	28
Total area (ha)	93.69 ha	227.33 ha	68.33 ha	89.21 ha
Average size (ha)	2.08 ha	4.46 ha	1.2 ha	3.19 ha

would have produced low amount of sampling points from the disturbed patches.

The Mann-Whitney U-test was used to compare the distribution of the applied descriptors of topography and tree stand between patches of intensive disturbance versus no disturbance. For aspect (a nominal variable), chi-square test was used (Zar 1999).

To define the importance of a certain explanatory variable in the development of the disturbances C&RT (Classification and Regression Tree) analyses were used (Breiman et al. 1984). The C&RT model is a hierarchical classification tree. It defines step by step the value of the variable (rule) that possesses the highest efficiency in producing a 'pure' classification of cases into disturbed versus undisturbed groups at the given hierarchical level. The explanatory power of the rule can be expressed by the 'impurity' of the two obtained groups of cases. The number of cases belonging to the two child branches (shown in the figures for each split) indicates the overall importance of that branch. The dominant class of observations (not disturbed – *ND*; intensive ice break – *II* or intensive windfall – *IW*) is given for the terminal nodes (indicated as boxes in the figures). The number of terminal nodes for each C&RT analysis was set to allow for reasonable interpretation of the results.

Sensitivity-analysis was carried out by defining several C&RT analyses for each disturbance type. Separate analyses were carried out by including groups of explanatory variables describing *i)* topography, *ii)* stand characteristics, *iii)* both. Extra analyses were carried out to test the importance of management-related variables: age-specific slenderness, amount of recently felled stock (both total and planned).

The explanatory power of a variable group was defined by the misclassification error rate (MER):

*MER = ((number of misclassified cases)/ total number of cases)*100.*

Misclassified cases belong to two groups. Cases with observed disturbance but no prediction (type I error), and cases with predicted occurrence, but without real disturbance (type II error). Ten-fold cross-validation was used to check how well unused samples were classified by the obtained rules. This means that ten random subsamples – as equal in size as possible – were formed from the learning sample. The classification tree of the specified size was computed ten times, each time leaving out one of the subsamples from the computations, and using that subsample as a test sample for cross-validation (StatSoft 2004). Than the "right-sized tree" was selected automatically with a technique called minimal cost-complexity cross-validation pruning (Breiman et al. 1984).

To show the overall importance of a variable as a predictor, the cumulative predictor value (Relative Importance Rank) was calculated by summing – over all nodes in the tree – the drop in node impurity, and expressing these sums relative to the most important (having the largest sum) variable found over all predictors (StatSoft 2004).

Results

Extent of disturbance

In 1996 and 1999 altogether 431.5 hectares were hit by ice break and/or windthrow (Fig. 2). This equals 8.9% of the study area (4830 ha). Basic descriptive statistics of disturbed patches for each of the distinguished disturbance types are shown in Table 1. Ice hit roughly twice as large area as wind, and on average ice break occurred in larger patches than windthrow (Table 1). However, the patches hit by the two disturbance types partly overlap (Fig. 2).

Topographic characteristics of disturbed patches

Both intensive ice break and intensive windthrow appeared at significantly higher elevations and on significantly steeper slopes than patches that were not hit by the corresponding disturbance (Tables 2-3). As Figure 3 shows (also c.f. Tables 2-3), intensive ice damage occurred at characteristically higher elevations (mean= 603.1 m) than intensive wind damage (mean=533.4 m). As chi-square tests proved, we observed intensive ice damage on NE-E-SE facing slopes significantly more often than expected (chi-square=1366.489, $p<0.001$, N-*ND*=7500, N-*II*=2500). Intensive windthrow occurred in an even narrower range of aspect, almost exclusively on E-NE facing slopes (chi-square=2260.606, $p<0.001$, N-*ND*=7500, N-*IW*=2488).

Table 2. Results of Mann-Whitney U-test comparing the distribution of the applied descriptors of topography and tree stand between patches of intensive ice break (*II*) versus no disturbance (*ND*). The mean is also given for both *II* and *ND* patches as illustration. ELEV – elevation (m); SLOPE – slope steepness (°); B_MIX – mixture ratio of beech (%); B_H – height of beech (m); B_AGE – age of beech (year); O_MIX – mixture ratio of sessile oak (%); O_H – height of sessile oak (m); O_AGE – age of sessile oak (year); RELSLEN – relative age-specific slenderness of beech (%).

Variable	Z	p	N-*ND*	N-*II*	Mean - *ND*	Mean - *II*
ELEV	-22.4437	<0.001	7500	2500	527.5	603.1
SLOPE	-32.4775	<0.001	7500	2500	16.3	22.3
B_MIX	-39.4070	<0.001	7500	2500	38.7	75.9
B_H	-39.9875	<0.001	7500	2500	11.7	21.1
B_AGE	-33.6401	<0.001	7500	2500	41.7	70.9
O_MIX	30.4582	<0.001	7500	2500	40.1	14.7
O_H	11.8703	<0.001	7500	2500	9.7	7.6
O_AGE	14.1977	<0.001	7500	2500	41.3	30.1
RELAGESLEN	-12.1460	<0.001	3109	2279	-2.3	4.2

Table 3. Results of Mann-Whitney U-test comparing the distribution of the applied descriptors of topography and tree stand between patches of intensive windthrow (*IW*) versus no disturbance (*ND*). The mean is also given for both *IW* and *ND* patches as illustration. ELEV – elevation (m); SLOPE – slope steepness (°); B_MIX – mixture ratio of beech (%); B_H – height of beech (m); B_AGE – age of beech (year); O_MIX – mixture ratio of sessile oak (%); O_H – height of sessile oak (m); O_AGE – age of sessile oak (year); RELAGESLEN – relative age-specific slenderness of beech (%); PLANCUT – amount of planned harvest (mł/ha); TOTCUT – total (sanitary+planned) amount of harvest (mł/ha))

Variable	Z	p	N-*ND*	N-*IW*	Mean - *ND*	Mean - *IW*
ELEV	-4.4287	<0.001	7500	2488	526.8	533.4
SLOPE	-26.5542	<0.001	7500	2488	16.1	20.8
B_MIX	-19.6956	<0.001	7500	2488	37.9	57.3
B_H	-31.8655	<0.001	7500	2488	11.9	18.8
B_AGE	-29.9155	<0.001	7500	2488	43.5	70.9
O_MIX	-1.8080	ns	7500	2488	39.4	38.2
O_H	-36.8419	<0.001	7500	2488	10.1	16.8
O_AGE	-34.7774	<0.001	7500	2488	42.8	73.9
RELAGESLEN	-13.4032	<0.001	3205	1773	-0.8	6.2
PLANCUT	-22.1277	<0.001	5366	2438	6.8	23.5
TOTCUT	-53.1410	<0.001	5366	2438	10.6	60.7

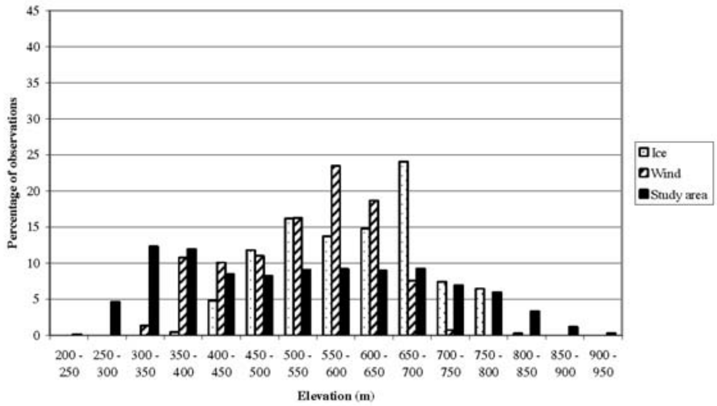

Figure 3. Comparison of areas hit by intensive ice break and windthrow by the relative distribution of elevation categories (m).

Tree stand characteristics of disturbed patches

Of the many possible descriptors of the tree stand we studied those related to tree species composition, stand age and tree height. Mixture ratio of the two possible dominant tree species (sessile oak and beech) seemed to have strong relationship with the occurrence of studied disturbances. Beech was significantly more dominant in patches hit by intensive ice break than in intact ones (Table 2), and more than 40% of the intensively broken stands contained more than 90% beech (Fig. 4). Similar, but less contrasting difference was observed for wind damaged patches (Table 3). The importance of sessile oak in ice versus wind damaged patches was different, mean mixture ratio was 14.7% and 38.2%, respectively. Patches without intensive ice damage contained significantly more sessile oak than those hit intensively (Table 2), whereas the difference between patches with intensive wind damage versus no damage at all was just not significant ($p<0.07$). All this together indicates that sessile oak was more sensitive to wind than to ice damage. More than 55% of patches with intensive ice break contained no sessile oak, whereas the same proportion for wind damaged patches was below 15%. Roughly half of the patches with intensive wind damage were characterised by oak mixture ratio between 10% and 50%. Stands of older and consequently taller trees were more often hit by these disturbances (Tables 2-3).

In addition to the above mentioned basic stand descriptors, we also studied the distribution of two – directly or indirectly – management related characteristics. The amount of recently felled stock seemed to have strong relationship with the sensitivity of stands to strong wind. As data in Table 2 show, cumulative planned (according to regular forest management plan) harvest – PLANCUT – was higher in patches with intensive wind damage than in intact ones (mean PLANCUT = 23.5 m^3 and 6.8 m^3, respectively). We also tested if the amount of all (sanitary and planned) harvest – TOTCUT – showed any relationship with the occurrence of intensive wind damage. We found an even larger difference between wind damaged versus intact patches (mean TOTCUT = 60.7 m^3 and 10.6 m^3, respectively).

Since we assumed that tree shape is related to stability, we tested if the slenderness of beech trees was related

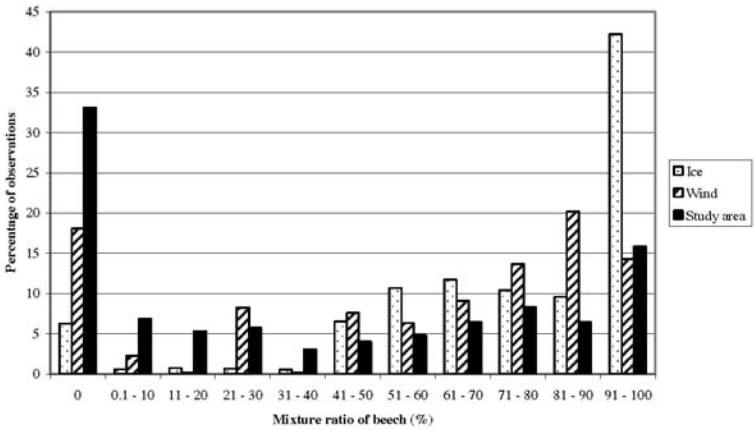

Figure 4. Comparison of areas hit by intensive ice break and windthrow by the relative distribution of mixture ratio of beech (%).

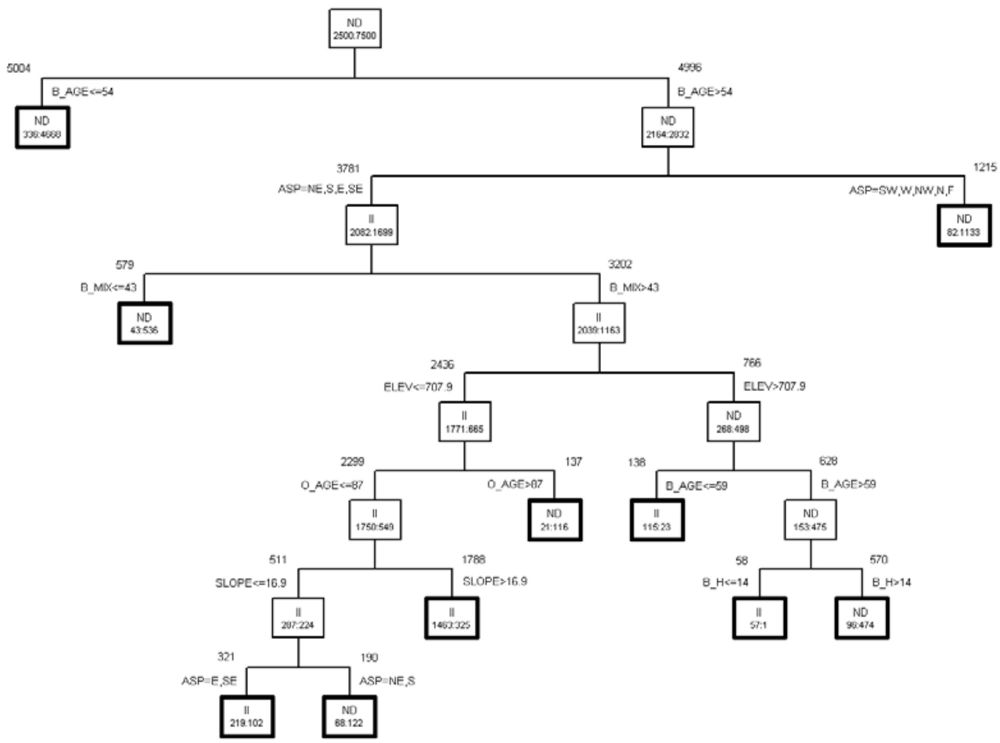

Figure 5. Classification tree for intensive ice break using variables describing both topography and the tree stand. (rectangles = nodes with number of damaged and undamaged cases, rectangles in bold indicate terminal nodes). Each node is assigned to class with majority of cases: *II* – intensive ice break, *ND* – not damaged. The variable on which the split was based is indicated above each node with the threshold value.

Table 4. Misclassification error rate (MER) and error rate of cross validation (10-fold CV %) for C&RT analyses performed to study the role of exploratory variables in the development of ICE and WIND damage. *Topo* – variables describing topography; *Stand* – variables describing stand characteristics; *Topo*+*Stand* – all variables belonging to *Topo* and *Stand*; *T*+*S*+*RelAgeSlen* – *Topo*+*Stand* + average relative age-specific slenderness of beech trees in stands older than 20 years; *T*+*S*+*PlanCut* – *Topo*+*Stand* + amount of felled stock as planned; *T*+*S*+*TotCut* – *Topo*+*Stand* + total amount of felled stock (planned + sanitary cut).

Used variables	Sample size	Number of splits	MER (%)	10-fold CV (%)
ICE				
Topo	10000	10	18	19
Stand	10000	8	15	15
Topo+Stand	10000	9	11	12
Topo+Stand	5388	9	18	19
T+S+RelAgeSlen	5388	9	18	19
WIND				
Topo	9988	7	15	16
Stand	9988	9	11	13
Topo+Stand	9988	9	10	11
Topo+Stand	4826	9	7	7
T+S+RelAgeSlen	4826	9	7	7
Topo+Stand	7804	8	13	13
T+S+PlanCut	7804	9	12	13
T+S+TotCut	7804	8	9	10

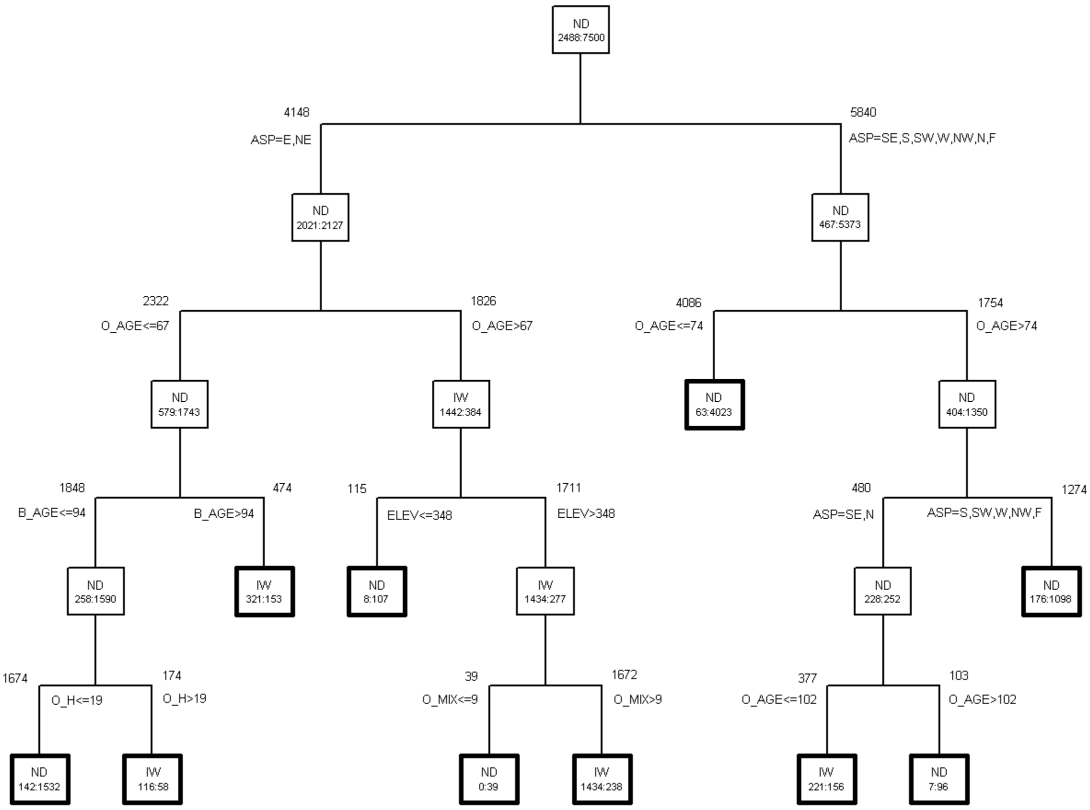

Figure 6. Classification tree for intensive windthrow using variables describing both topography and the tree stand. (rectangles = nodes with number of damaged and undamaged cases, rectangles in bold indicate terminal nodes). Each node is assigned to class with majority of cases: *IW* – intensive windthrow, *ND* – not damaged. The variable on which the split was based is indicated above each node with the threshold value.

to their sensitivity to ice and wind disturbance. Relative age-specific slenderness was higher in stands hit by intensive ice break and windthrow than in intact ones (Tables 2-3).

Factors determining the sensitivity of stands to ice and wind disturbance

Separate C&RT analyses were performed to study the effectiveness of different groups of variables in explaining the occurrence of disturbances.

The analyses of intensive ice break showed that 82% of cases were correctly classified (MER=18%) when only topographic variables were included in the analysis (Table 4). Stand descriptors alone gave slightly better results (MER=15%). The inclusion of both variable groups increased the goodness of the analyses (MER=11%). Cross-validation values were about the same as MER for these cases indicating that the created rules classified the test sample (not included in the analysis) as well as the learning sample. The inclusion of slenderness did not improve the overall goodness of the analysis. Figure 5 shows the C&RT diagram for the analysis in which patches with intensive ice break were compared with intact patches using variables describing both topography and the tree stand. 58.5% of sample points (1463 out of 2500) where intensive ice break occurred; these were older than 54 years; were located on NE-E-SE-S facing slopes; contained more than 43% beech; were located at elevations lower than 708 m (Figure 5). If they contained sessile oak, then they were younger than 88 years, and slope steepness was higher than 17^{o}. The relative importance ranks (cumulative predictor value) for the included variables in the C&RT analysis shown in Fig. 5 were as follows: *B_MIX* – 100; *SLOPE* – 95; *ASP* – 90; *B_AGE* – 83; *O_MIX* – 75; *B_H* – 72; *ELEV* – 68; *O_AGE* – 67; *O_H* – 37. This means that variables describing stand composition (mixture ratio and age of beech) and those describing topography (slope and elevation) were equally powerful in predicting the occurrence of intensive ice break.

The obtained predictive power was 85% (MER=15%) when only the descriptors of topography were included in the analysis of intensive windthrow (Table 4). Stand descriptors alone provided better results (MER=11%). The inclusion of both variable groups did not increase the predictive power considerably (MER=10%). The inclusion of slenderness of beech trees did not improve the results. However, when data on total recent harvest (planned + sanitary cuts) were included, misclassification error decreased (Table 4). Figure 6 shows the C&RT diagram for the analysis of intensive windthrow, where variables describing both topography and the tree stand were used. 57.6% of sample points (1434 out of 2488) where intensive wind break occurred; these were located on E-NE facing slopes; were older than 67 years; were located at elevations higher than 348 m; contained minimum 10% sessile oak (Figure 6). Intensive wind damage also occurred in patches, where sessile oak was younger than 67, but these patches either contained old (>94 years) beech trees (321 cases), or sessile oak was higher than 19 m (116 cases) in them. Intensive windthrow also occurred on slopes facing to SE or N. In these 221 cases, the age of sessile oak was between 74 and 102 years. Similarly to what we found for ice break, cross-validation values were about the same as MER. The relative importance ranks for the included variables in the C&RT analysis shown in Fig. 6 were as follows: *O_AGE* – 100; *O_H* – 90; *B_H* – 69; *B_AGE* – 68; *ASP* – 58; *B_MIX* – 47; *SLOPE* – 40; *O_MIX* – 40; *ELEV* – 43. This means that variables describing stand age and height were the most powerful in predicting the occurrence of intensive wind break, whereas those describing topography and tree species composition were less important.

Discussion

While interpreting our data, we were aware of the strong interplay between topography and meteorological conditions (e.g., wind strength, thickness of deposited ice). More importantly, we also had to consider the possible effects of previous forest management on tree stand characteristics.

Effects of topography

Not all the strong statistical relationships we found between topographic variables (elevation, aspect and slope steepness) and the severity of disturbance are straightforward. The major direct cause of ice damage in the Királyrét region was the unbearable weight of the thick ice deposited on individual trees. Microclimate – affected by topography – can have an influence on the severity of ice storm, e.g., by affecting the thickness of deposited ice (Bragg et al. 2003, Millward and Kraft 2004), so the importance of specific elevations in the development of ice damage can be understood. Slope steepness can increase the severity of damage because individual trees are more likely to have less stability on steeper slopes and also the development of the 'domino-effect' is more likely. These effects of slope steepness hold both for ice and wind disturbance.

In addition to these relatively straightforward effects of topography, the relationships between aspect and the severity of disturbance need more careful consideration, since tree species composition and aspect are strongly related.

Effects of stand characteristics

Tree species composition was an important factor, since ice hit mostly beech dominated stands, whereas wind damage occurred in stands where both sessile oak and beech were important components. Species specific sensitivity to ice and wind damage was shown by several authors (ice: Melancon and Lechowitz 1987, Warillow and Mou 1999, Duguay et al. 2001, Rhoads et al. 2002, wind: Foster and Boose 1992, Canham et al. 2001). Bragg et al. (2003) found that sensitivity of species depends on canopy size, canopy shape, wood strength and growth habit, while Warillow and Mou (1999) showed that wood strength was less important than canopy size and rooting depth. Heart rot was also an important factor in predisposing trees to ice break. The sensitivity of beech to ice break was reported by Melancon and Lechowitz (1987) and Rhoads et al. (2002), whereas Canham et al. (2001) found that sensitivity of beech was attributed mainly to beech bark disease.

Several studies (e.g., Foster and Boose 1992, Rhoads et al. 2002) showed that higher and older stands were more susceptible to storm damage than young ones. We also found a positive relationship between stand age and storm damage, though we found that 50-90 year old stands were the most susceptible. To explain why the expected positive relationship did not hold for older stands, we compared ice-hit versus intact points having beech trees of 90-110 years. We found that in patches where intensive ice breakage occurred beech trees had significantly higher slenderness than in intact patches. This indicates that the simple stand age – sensitivity relationship was modified in several old stands, most probably because of differences in management history.

Similarly to our results, Dobbertin (2002) showed that forests with prior damage from an earlier storm or where recent felling had taken place were particularly likely to suffer from storm damage. For similar considerations, we excluded those patches that were hit by ice in 1996 when we tested the possible effects of pre-disturbance harvest on the severity of 1999 wind damage. However, we could not recognize all patches that were hit by sporadic ice break by using the aerial photos. This is why PLANCUT (planned cut between 1995 and 1999) was not as good a predictor of intensive wind break as TOTCUT (planned + sanitary cuts).

Initial stand density, thinning regime and tree slenderness are related characteristics. Similarly to our results, several authors argue that stability of individual trees decreased with increasing slenderness (van Dyke 1999, Wilson and Oliver 2000, Canham et al. 2001, Bragg et al. 2003). A seeming inconsistency exists between the findings that *i)* high stand density enhances the development of high height:dbh ratios, and *ii)* intensive thinning increases the susceptibility to wind. Although high initial stand density and lack of early thinning increase susceptibility by giving rise to high slenderness (Wilson and Oliver 2000), thinning not only assists in the development of tall trees with small root system (Nilsson et al. 2004 for spruce plantations), but also increases susceptibility if intensive thinning takes place not long before the storm (e.g., Morris and Ostrofsky 2005).

By carrying out several C&RT analyses, we tried to explore the relative efficiency of different explanatory variable groups (topography, stand, both + management) in predicting the occurrence of the studied disturbances. C&RT results can also serve as basis for predicting endangered areas. While interpreting the obtained results, we had to face several difficulties. The spatial resolution of available data was not the same. Descriptors of topography had 5 m by 5 m resolution, disturbance patches were mapped from aerial photographs (few metres accuracy), but stand descriptors were available only for whole forestry sub-compartments (average size 4 ha) in form of averages. Another obstacle was that temporal autocorrelation might have occurred between the two studied disturbances resulting from the fact that previously ice damaged patches were more sensitive to the effects of strong wind three years later. A third difficulty arises from the fact that descriptors of topography, tree stand and management are interdependent.

We found that variables describing topography alone gave almost as good prediction as those describing tree stands. However, sensitivity of stands on easterly slopes is most probably not the direct effect of slope aspect (affecting microclimate), but the indirect effect of beech distribution, i.e., at this elevation beech prefers easterly slopes. Similarly, separating the effects of stand characteristics from those of management was hard, since descriptors of tree stand had been at least partly shaped by management (e.g., species composition, stand age, stand structure). This is why we tried to test the effects of slenderness and recent harvest by analysing sub-samples containing otherwise relatively similar stands (stands with high mixture ratio of beech, and stands older than 50 years, respectively). In this way, we managed to show that even within the framework of uniform shelterwood system, type and intensity of tending and intermediate cuts can affect the sensitivity of the remaining tree stand.

Based on the comparisons of MER values, it can be stated that variable groups describing the tree stand and management were better in predicting the evolution of both disturbances than variables describing topography.

Conclusions

In spite of the coarse scale (intensive or sporadic) used for describing the effects of ice and wind disturbances, we managed to show that forest management can have an important role in increasing or decreasing the susceptibility of forest stands to such damages. Our results suggest that by increasing compositional and structural heterogeneity, the susceptibility of tree stand could be decreased. However, more precise recommendations should be based on analyses using quantitative data on the severity of damages.

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