Ice storm damage to trees in mixed Central European forests: damage patterns, predictors and susceptibility of tree species

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Abstract

In northern temperate forests, ice storms are a common disturbance agent, though climate change may alter their occurrence patterns. Their impact on forest ecosystems is complex, as they influence both structure and processes. In 2014 an ice storm of high intensity and large spatial extent occurred in Slovenia, Central Europe, which enabled a detailed study of ice damage to individual trees across a broader spatial scale. Pre- and post-ice storm measurement data on 11,414 trees on 960 permanent plots were used to examine ice damage patterns on trees in the disturbed forest area ($\approx 8,700 \text{ km}^2$) to determine the predictors of ice damage to trees and to investigate the relative susceptibility of eight groups of tree species in mixed Central European forests. We used a novel approach to modelling ice storm intensity across the region based on measured data on air temperature, precipitation amount and duration, precipitation intensity and wind speed. The ice storm damaged

31 % of the analysed trees; high variability in the damage rate was observed across the disturbed area. For the tree species, a susceptibility to ice damage index (SI) ranging between 0 (no damage) and 1 (complete damage) was calculated based on terrestrial assessment of trees. Tree species differed significantly in susceptibility to ice damage: *Abies alba* (SI=0.14) and *Quercus* sp. (SI=0.11) were rather resistant; *Picea abies*, *Fagus sylvatica* and *Acer* sp. (SI=0.23-0.28) were moderately to very susceptible; and *Pinus* sp. (SI=0.62) was extremely susceptible to ice damage. Eight predictors and three interactions were included in an ordinal logistic regression model of tree damage: ice damage on trees depends mainly on ice storm intensity, elevation, and tree species, while tree dbh and social status, tree size and tree species diversity indices, and slope were relatively less important. Our study illustrates the complexity of damage patterns on trees due to ice storms and the significance of ice storm intensity and tree species as predictors when modelling ice damage on individual trees.

Keywords

natural disturbance; ice storm damage; ice storm intensity; susceptibility index; ordinal logistic regression; Slovenia

1 Introduction

Disturbance significantly influences the dynamics of natural and managed forests across the globe. Among disturbance agents, fire, insects, snow and wind have been thoroughly studied, but less is known about ice accumulation. An ice storm can be separated into two unique components: 1) the meteorological event that produces glaze and 2) the response of the biota to ice accumulation (Bragg et al., 2003). The first occurs when a moist air mass of above-zero temperature lies above a colder surface layer of subzero temperature air. Droplets falling from the upper air layer become supercooled as they pass through the layer of cold air and freeze upon contact with objects on the surface (Carrière et al., 2000). There is no generally accepted definition of an ice storm; the National Weather Service in the USA defines an ice storm as an occurrence of freezing precipitation, resulting in either structural damage or at least 6.35 mm of ice accumulation on exposed surfaces (Irland, 2000). Ice storms can cause massive damage to human infrastructure, as well as to agricultural crops and forests (Zhou et al., 2011).

In forests of the northern temperate zone, ice storms are a common natural disturbance agent, but their intensity and frequency differ within and between continents. They are relatively more frequent in the temperate zone of North America (e.g. Oliver and Larson, 1996; Frelich, 2002), but less so in East Asia (Zhou et al., 2011) and Europe (Kämäräinen et al., 2017). In European forests, ice storms are a common disturbance agent, but far less important than fire, insects, snow or wind (Schelhaas et al., 2003). In some parts of Europe (e.g. the Dinaric Mountains, some areas of the Alps), however, ice storms are frequent and may periodically cause extensive damage (Carrière et al., 2000; Nagel et al., 2017). Ice storms can be local or regional, even affecting millions of hectares in a single event. Usually they cause minor damage, but periodically they can result in a catastrophe. The return interval of ice storms varies greatly with location and can range from a few months to several years, decades, or even centuries for catastrophic ice storms. In Europe, freezing rain typically appears between November and February (Carrière et al., 2000) and is more frequent in Central and Eastern Europe (typically 2-3 events annually) than in Northern Europe (typically 0.5-2

events annually) (Kämäräinen et al., 2017). In many parts of Europe, ice storms appear to be much more frequent than reported by observers (Bernstein et al., 2009), since they are mostly of low intensity and cause no or minor damage. Climate change may alter the frequency and intensity of ice storms; both increasing (Klima and Morgan, 2015) and decreasing (Seidl et al., 2017) frequency and intensity of ice storms have been forecasted.

When an ice storm occurs, several components of forest ecosystems, as well as many processes of forest dynamics, may be significantly affected (Oliver and Larson, 1996; Ge et al., 2015); for example, forest stands and individual live trees suffer damage, woody debris loads increase due to tree injuries and higher mortality of trees, and wildlife may experience mortality and habitat modification. Ice accumulation can cause tree damage ranging from the loss of tissue to fatal injury (Lemon, 1961). The most frequent tree injuries are minor to major twig and branch breakage and subsequent crown loss, crown bending on a temporary or permanent basis, trunk breakage or split within or below the crown, and root system damage with possible uprooting (Miller-Weeks et al., 1999).

Tree damage results from the complex interactions among disturbance intensity, biological factors related to the tree and stand attributes, physical site conditions and other external aggravating factors (e.g. Jones et al., 2001; Kenderes et al., 2007). In general, disturbance intensity is the physical measure of a disturbance over a given area (Frelich, 2002); in the case of an ice storm, this measure can be the ice load thickness on trees. However, due to the lack of reliable data, the measured ice load thickness has rarely been examined as an explanatory variable for tree damage (e.g. Proulx and Greene, 2001). It is possible to measure ice thickness in ice storm manipulation experiments, but such measurements are rare (e.g. Rustad and Campbell, 2012; Nock et al., 2016). Thus, most studies have included proxies for ice storm intensity that are for the most part assessed indirectly from damage on studied plots (e.g. Nagel et al., 2016). However, when an indicator of ice storm intensity has been included in analyses, it has been recognized as an important predictor of tree damage

occurrence or even the type of tree damage, including broken twigs, branches or tree-tops or snapping, bending or uprooting of a tree (Proulx and Greene, 2001; Aubrey et al., 2007).

The biomechanics of trees may play a major role in damage occurrence and type (Bragg et al., 2003).

Tree species and tree size should capture most of the relevant traits contributing to tree damage due to ice loads (Bragg et al., 2003). In studies from North America, tree susceptibility to ice damage as well as inflicted tree injuries have often been considered to be species-specific (e.g. Bruderle and Stearns, 1985; Rebertus et al., 1997; Hopkin et al., 2003; Priebe et al., 2018), but the genotype within species can also be relevant. For instance, narrow crown genotypes may experience less ice storm-induced damage than broader crown genotypes of the same species (Pile et al., 2016). The literature, however, offers only minimal agreement on species' susceptibility to ice load injuries (e.g. Boerner et al., 1988).

In addition, the silvicultural treatment of a stand prior to an ice storm may also influence ice damage on trees. The exact effect of treatment is difficult to determine due to many interrelated variables (Bragg et al., 2003). In general, managed stands should not be more prone to ice damage than unmanaged stands (e.g. Nielsen et al., 2003); however, the intensity of thinning has been recognized as a factor negatively influencing the resistance of stands and trees in the short run (Zarnovican, 2001).

Additionally, the interaction of ice with other disturbance agents, especially wind and snow, may cause increased susceptibility of stands and trees to ice damage (Coder, 2015), but relations among disturbance drivers may be modified by climate change (Seidl et al., 2017).

Studies on the impact of ice storms on European forests are rather rare relative to studies on other disturbance agents. There are two main reasons for this: 1) ice storms are usually low-severity, local-scale events, and 2) massive ice storms are rare relative to windthrow, fire or breakage due to snow load. Consequently, relatively little is known about the susceptibility of tree species to ice damage in Europe. In addition, no model has been developed so far to show the mutual influences of ice storm intensity, tree and stand attributes, and site characteristics on ice damage to trees.

In 2014 an ice storm of the largest intensity and spatial extent ever recorded occurred in Slovenia and Croatia (Nagel et al., 2017), causing extensive damage to more than half of Slovenian forests. This represented an opportunity to study ice damage patterns for trees in various forest stands across a broad range of site conditions and at different ice storm intensities. Studies of this event assessed the general damage rate in forests (Šimić Milas et al., 2015) or were limited to some localities of unmanaged forests (Nagel et al., 2016) or to a single tree species and consecutive disturbances (de Groot et al., 2018). However, a detailed study of ice damage to individual trees across a broader range of forests together with an evaluation of tree species susceptibility to ice damage on a regional spatial scale is missing. The aims of our study were thus to 1) examine ice damage patterns on individual trees in relation to different ice storm intensities in managed mixed forests at the regional scale, 2) determine the predictors of ice damage occurrence and severity with the main focus on tree and stand attributes, and 3) quantify and examine the relative susceptibility of tree species to ice damage.

2 Methods

2.1 Study area

The forests of Slovenia, which cover approximately 11,800 km², were used as the study area (Figure 1). The area is characterised by considerable variation in relief and climatic conditions. The mean annual temperature is 7.8 °C, and ranges from -2 °C in the Alps to 14 °C in the coastal region, while the total mean annual precipitation is 1734 mm, and ranges from 800 mm in the eastern part to almost 4000 mm in the northwestern part of Slovenia. Elevation ranges from 0 to 2864 m, with the majority of forest lying in the belt between 400 and 1200 m. Approximately half of forests grow on limestone and dolomite, and the another half grow on silicate or mixed parent material on which both cambisols and leptosols of different depths evolved.

Forests cover 60% of the area. The main tree species are *Fagus sylvatica* (European beech; 32 % of total growing stock), *Picea abies* (Norway spruce; 31 %), *Abies alba* (silver fir; 7 %), *Quercus* species (7 %), *Pinus* species (6 %) and *Acer* species (5 %). In addition, a number of minor tree species are admixed in these forests (see Table A1 in the Appendix). The forests are characterised by small-scale natural regeneration-based forest management, with the irregular shelterwood system being the prevailing silvicultural system. This system creates a horizontal mosaic of stands of different ages (i.e. developmental phases). The mean stand basal area nationwide amounts to around 30 m² ha⁻¹ (Slovenia Forest Service, 2014).

Between January 29 and February 5, 2014, an extensive ice storm affected a large part of Slovenia. Over this period, much of the affected area received more than 90 mm of precipitation. A sizable area received more than 150-200 mm (Vertačnik et al., 2015), and the highest registered amount of precipitation reached 300-400 mm (ARSO, 2014a). Due to high air temperatures in the upper atmospheric layers and a subzero air mass near the surface, the falling rain converted to supercooled freezing rain which created 20-60 mm, and at times even up to 90-100 mm, of ice accumulation (Sinjur et al., 2014). There were no reports of significant winds during the studied disturbance event, indicating that wind did not meaningfully contribute to forest damage (ARSO, 2014a). Although the ice storm affected almost the entire area of Slovenia, its severity differed across the country (Figure 1). Approximately 8,700 km² was impacted, and in total 5.76 million m³ of timber was harvested in 2014-2017 due to ice damage, with a large number of damaged trees left in the forests (Slovenia Forest Service, 2018).

2.2 Data

The study is based on individual tree data (n=11,414) from 960 permanent sampling plots that were inventoried in the year before the ice storm and re-inventoried a few months after the ice storm (Slovenia Forest Service, 2014). The Slovenia Forest Service annually surveys approximately 10 % of

forest area of the country, and repeats the inventory every ten years. The inventory is carried out in a systematic grid of permanent sampling plots of 200 m², on which all trees ≥ 10 cm dbh are surveyed. Plots are located on a 250 × 500 m grid with known longitude and latitude coordinates of each plot centre.

Figure 1: Forest cover in Slovenia with locations of selected permanent sampling plots (left) and the 2014 ice storm intensity (ARSO, 2014b) with locations of meteorological stations used in the study (right)

For the analyses, we used four groups of variables: 1) ice storm intensity, 2) tree variables, 3) stand variables and 4) topographic variables.

2.2.1 Ice storm intensity

Ice storm intensity (DINT) was assessed based on ice thickness, which was estimated based on the liquid rainfall amount during temperature conditions favourable for ice formation. Glaze ice occurrence is a meteorological variable that is systematically observed at the manned meteorological station network of the Slovenian Environment Agency. The main deficiency of ice observations is the lack of information on ice thickness. Therefore, we assessed ice thickness based

on measured meteorological variables: 1) air temperature, 2) precipitation amount and duration, 3) precipitation intensity and 4) wind speed.

The area affected by ice was modelled using daily surface air temperature, the vertical temperature profile and precipitation measurements during the eight-day ice storm period. In the first step, maps of spatial distributions of surface temperature and precipitation amounts were produced (see also Figure SM1 in the Online Supplementary Material). From point measurements, both air temperature and precipitation values were interpolated into a regular 100 m grid using the residual kriging spatial interpolation methodology (Cressie, 1993). Previous studies (Dolinar, 2005, 2014; Tveito et al., 2008) have shown that, with the given measurement network density on the Slovenian territory, the best results in spatial interpolation are obtained with the residual kriging methodology using geographical variables (i.e. longitude, latitude, and elevation) and, in the case of precipitation, also radar measurements as explanatory variables. The same studies have shown that the highest spatial resolution in which the spatial variability of an interpolated climate variable could be explained by a given spatial network density is between 1000 and 100 m. Based on automatic precipitation measurements (37 weather stations), the daily time period of precipitation was determined for each day of the ice storm. The spatial distribution of mean surface air temperature (measured at 153 stations; Figure 1) was calculated only for daily time periods in which liquid precipitation was observed and registered.

The vertical temperature profile is a key element for ice formation (Vertačnik et al., 2015); a distinct temperature inversion with a cold near-surface air mass and a layer of relatively warm air at higher altitudes must exist for ice load to occur. During the 2014 ice storm, the vertical temperature profile changed noticeably across the study area. It was calculated regionally based on *in-situ* temperature measurements at different elevations and radiosonde measurements over Udine (Italy), Ljubljana (Slovenia), Graz (Austria) and Zagreb (Croatia) and was used as a vertical temperature gradient twice in the DINT modelling: firstly, in the surface air temperature spatial interpolation procedure as a part of the linear model describing the relationship between temperature and elevation, and secondly as

a binary layer (i.e. ice formation possible or not possible) to determine the potential area for ice formation (see step 2 below).

The spatial distribution of liquid precipitation was calculated based on hourly (measured at 37 stations) and daily (measured at 212 stations) precipitation measurements. The proportion of liquid precipitation was determined based on the hourly temperature course and on daily observations of precipitation type. As explained above, the spatial distribution of the amount of liquid precipitation was calculated on a 100-m regular grid using residual kriging (Cressie, 1993).

In the second step, the potential area of ice formation was determined as the territory where the mean temperature during the rainfall event was below the freezing point (0 °C), reduced by the area where the vertical temperature profile described above did not meet the criteria for ice formation. For the potential area of ice formation, the ice storm intensity was assessed on the basis of measured daily rainfall amount and additional consideration of precipitation intensity measurements, wind speed and mean air temperature.

The next step was to produce the daily ice storm intensity maps. In these maps, only two ice storm intensity categories were determined (i.e. ice storm occurred or did not occur), and the threshold was between 10 and 20 mm of the daily precipitation amount. A shifting threshold of ice load occurrence was used due to high local variation in air temperature and wind velocity, which, together with rainfall intensity, primarily determine the collision efficiency of raindrops with cold objects and thus ice formation (Jones, 1996; Makkonen, 2000). Collision efficiency increases with higher wind velocity and rainfall intensity; thus, the threshold between two ice storm intensity categories is lower. The exact threshold was thus determined empirically, considering the information on ice damage.

Lastly, the final map of ice storm intensity for the whole ice storm event (hereafter the final map) combined individual daily ice storm intensity maps for the entire eight-day duration of the ice storm. The final map of the predicted ice storm intensity classified ice storm intensity (DINT) into four categories (Figure 1):

- DINT0 – no ice (≤ 0.1 mm),
- DINT1 – low intensity with thin ice accretion (> 0.1 -5 mm),
- DINT2 – moderate intensity with thick ice accretion (> 5 -20 mm),
- DINT3 – severe to extreme intensity with very thick ice accretion (> 20 mm).

The ice thickness range for a single category was assessed empirically, based on the precipitation sum during the entire eight-day event and on field reports on damage and ice thickness.

Finally, the field observation data on ice occurrence were used for validation of the model of the ice storm intensity. The map of the actual ice storm affected region (hereafter validation map) was determined by spatial interpolation of ice occurrence observations (presence/absence of ice observed at 212 stations) using the indicator kriging methodology (Cressie, 1993). This validation map was compared to the final map. Only two categories could be compared between both maps – ice-affected and non-affected areas. The ice-affected area covered 15,098 km² and the non-affected area covered 5,169 km² on the final map. The two maps, namely the final map and the validation map, do not match only on an area of 319 km² (1.6 % of the entire country), exhibiting rather small spatial interpolation error.

2.2.2 Tree variables

On each sampling plot, individual tree data were recorded a few months before the ice storm. Forty-two tree species were identified in the inventory (see Supplementary material, Table SM1). According to similarities in species characteristics, their dominance in stands (i.e. dominant species were treated separately, co-dominant (minor) species were grouped into larger groups), and frequency (i.e. $n > 200$), species were classified into six groups of species (SPEC) to make the analysis feasible and transparent: 1) *Abies alba* (hereinafter *Abies*), 2) *Picea abies* (hereinafter *Picea*), 3) *Pinus sylvestris* (Scots pine) & *Pinus nigra* (Austrian pine) (hereinafter *Pinus*), 4) *Fagus sylvatica*

(hereinafter *Fagus*), 5) *Quercus petraea* (sessile oak) (hereinafter *Quercus*), and 6) *Acer pseudoplatanus* (sycamore maple) & *Acer platanoides* (Norway maple) (hereinafter *Acer*). Other tree species were treated as two additional groups, namely other broadleaves and other conifers, and were included into some analyses, but not the modelling. This was because of the great heterogeneity in characteristics of tree species included in both groups, which might significantly influence the results and make their interpretation difficult. For each tree, dbh was measured with a calliper rounded to the last completed cm. Social status (SS) was assessed for each tree based the relative height of the tree and its position within the vertical structure of the stand (Klopčič and Bončina, 2010) and classified into three categories: SS1 – predominant and dominant trees, SS2 – co-dominant and intermediate trees and SS3 – understorey suppressed trees.

The individual tree data gathered on 960 plots before the ice storm were supplemented by a field-based estimation of the ice storm damage of individual trees on the plots eight months after the ice storm. This survey was done by the Slovenia Forest Service (Poljanec, 2014) to estimate the amount of damaged wood and the proportion of trees able to survive the ice damage, which was important for decision making on sanitation of the damaged forest stands. Trees were classified into four categories based on a visual assessment of damage, hereafter referred to as tree damage class (TDAM) (adapted after Miller-Weeks et al., 1999):

D0) Trees with no visual damage.

D1) Trees with moderate damage: broadleaves with less than 50 % crown damage and conifers with a broken top of less than 1/3 of the crown length, moderately leaning trees ($< 45^\circ$).

D2) Trees with severe damage: broadleaves with 50-75 % crown damage and conifers with broken tops between 1/3 and 2/3 of the crown length.

D3) Trees with total damage: broadleaves with ≥ 75 % crown damage and conifers with a broken top of more than 2/3 of the crown length, trees snapped below the crown, cleaved trees, severely leaning trees ($> 45^\circ$) and uprooted trees.

2.2.3 Stand and site variables

At the plot level, data related to the site and stand conditions were compiled. Site variables (elevation, slope and topographic position) were derived from a digital elevation model (12.5 m resolution) (GURS, 2014). Stand conditions were represented by three variables: quadratic mean diameter (QMD) (Curtis and Marshall, 2000), the Gini index (Weiner and Solbrig, 1984) and the Shannon-Wiener index (SWI) (Spellerberg, 2008). The Gini index expresses the tree size diversity and is measured on a scale from 0 to 1; it is 0 if all trees on a plot are of equal size, while it has a theoretical maximum of 1 in an infinite population in which all trees but one have a size of 0 – the ultimate in inequality (Weiner and Solbrig, 1984). A higher Gini index indicates uneven-sized stands, while a value near 0 indicates an even-sized structure of forest stands. In our study, the Gini index was calculated using the number of trees and their basal area per plot and was calculated only for plots on which more than five trees were registered. For plots with less than 50 trees, the calculated Gini index was corrected by the quotient $n/(n-1)$ to reduce bias due to small sample size (Weiner and Solbrig, 1984). SWI was applied to assess tree species diversity; in order to be consistent with the variable SPEC, it was calculated based on the basal area proportions of the eight groups of tree species per plot, namely the six target species, other broadleaves, and other conifers.

2.3 Data analyses

For each analysed tree species, we calculated the susceptibility index SI using equation 1 (adapted after Rebertus et al., 1997; Jones et al., 2001):

$$SI_j = (\sum p_{i,j} \cdot W_{i,j}) / 300 \quad [\text{eq. 1}]$$

where $p_{i,j}$ is the percentage of trees classified in a certain damage class, $W_{i,j}$ is the damage scalar (0 for no damage D0, 1 for D1, 2 for D2 and 3 for total damage D3), i is the damage class and j is the

tree species. SI ranges between 0 and 1; the higher the value, the more severe the damage experienced by the tree species.

Ordinal logistic regression (OLR; Kleinbaum and Klein, 2010; Harell, 2001) was used for modelling the probabilities of each of the four ice damage categories (D0 – D3) in the dependence on the three groups of explanatory variables (Table 1). The meteorological estimate of ice storm intensity (DINT) was included in the model as the main explanatory variable. The second group of explanatory variables considered individual tree attributes: tree species (SPEC), diameter at breast height (DBH) and social status (SS). The third group of explanatory variables considered the stand and geographic properties of each examined plot: Gini index (GINI), Shannon-Wiener index (SW), quadratic mean diameter (QMD), elevation (ELV), slope (SLP) and topographic position of the plot (TOP). After including these variables in the OLR mixed model as fixed effects, the random effect of plots was not statistically significant. Thus, we assumed that this group of variables explain between-plot variability well enough that there was no need to consider the random effect of a plot in the model. The OLR assumptions testing and the model fitting were applied in the R statistical software (R Core Development Team, 2019) using the rms package (Harrell, 2017).

The tree ice damage (TDAM) was an ordinal response variable with four categories. With the OLR model, the probabilities of each ice damage category were estimated considering the presented explanatory variables. The OLR model enables simultaneous estimation of the probabilities of occurrence and severity of ice damage. We fitted the OLR with a proportional odds model. For the response variable Y with levels 0, 1, ..., k , the cumulative probability for the j -th damage class, where $j = 1, \dots, k$, occurs conditionally on $\mathbf{X}$, and is expressed as:

$$P(Y \geq j|\mathbf{X}) = \frac{1}{1 + \exp(-(\alpha_j + \mathbf{X}\beta))} \quad , \quad [\text{eq. 2}]$$

where α_j is a category specific intercept, $\mathbf{X}\beta = \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_p X_p$ where β_i are regression coefficients for each of regressors X_i ($i=1, \dots, p$). The OLR model was fitted to our data using the `lrm()` R function (Harrell, 2017).

Table 1: Variables included in the modelling procedure measured or evaluated on the sampling plot or tree level; for continuous variables the mean and range values and the coefficient of variability (CV) were calculated on the plot level, and dbh was measured on the single-tree level; for categorical variables, categories are given

Variables		Variable type	Categories / statistics			Data scale
Response variable						
Tree ice damage	TDAM	categorical	D0 – trees with no visual damage, D1 – trees with moderate damage, D2 – trees with severe damage, D3 – trees with total damage,			tree
Categorical independent variables						
Disturbance intensity	DINT	categorical	DINT0 – no ice (≤ 0.1 mm), DINT1 – low intensity with thin ice accretion (>0.1 -5 mm), DINT2 – moderate intensity with thick ice accretion (>5 -20 mm), DINT3 – severe to extreme intensity with very thick ice accretion (>20 mm),			plot
Tree species or group of species	SPEC	categorical	1 – <i>Abies alba</i> , 2 – <i>Picea abies</i> , 3 – <i>Pinus sylvestris</i> & <i>P.nigra</i> , 4 – <i>Fagus sylvatica</i> , 5 – <i>Quercus petraea</i> , 6 – <i>Acer pseudoplatanus</i> & <i>A. platanoides</i> ,			tree
Social status of the tree	SS	categorical	SS1 – predominant or dominant tree, SS2 – codominant or intermediate tree, SS3 – suppressed understorey tree			tree
Topographic position of the plot	TOP	binary	0 – plane & foot of the hills, 1 – slope & ridge			plot
Continuous independent variables			Mean	Min - Max	CV	
Elevation of the plot center ($\times 100$ m a.s.l.)	ELV	scale	6.41	2.03 – 13.00	0.385	plot
Slope of the plot (°)	SLP	scale	18.2	0 – 50	0.574	plot
Diameter at breast height (cm)	DBH	scale	28.6	10 – 112	0.506	tree
Quadratic mean diameter (cm)	QMD	scale	29.8	12.3 – 66.3	0.318	plot
Gini index	GINI	scale	0.3025	0.005 – 0.790	0.372	plot
Shannon-Wiener index	SWI	scale	0.6515	0 – 1.6543	0.606	plot

In order to fit the OLR, the data have to meet the proportional odds assumption (Harell, 2001). This means that the logit transformation of the ordinal dependent variable Y has to express a linear response on a continuous explanatory variable X_i . This assumption was graphically tested, and if the response was not approximately linear, restricted cubic splines were used to adequately transform the continuous explanatory variable. A nonlinear response was found for ELV, SLP and SWI. The suitable number of knots at restricted cubic splines for each of three explanatory variables was chosen on the basis of the likelihood ratio test of nested models using the function `lrtest()`. Our assumption was that the influence of ELV, SLP and DBH on the probabilities of TDAM categories is not the same across all DINT categories; thus, the interaction terms between DINT and the three listed continuous variables were included in the model. In the process of the model validation which was performed by the application of the bootstrap procedure and the k -fold cross-validation method using the function `validate()`, two explanatory variables TOP and QMD were excluded from the final model. The relative importance of the predictors in the final model was presented on the basis of the ANOVA analysis with the partial χ^2 Wald statistics, testing the association of each predictor with the response variable, adjusted for all other predictors. The measure of relative importance of each component in the final model was computed as (χ^2 -statistic – degrees of freedom) (Harrell, 2001).

3 Results

The ice storm damaged 31 % of trees in the study area. A similar proportion of trees experienced moderate and total damage (12.2 % and 13.9 %, respectively), while severe damage was less frequent (5.2 %). Based on the results in Table 2 and Figure 2, the most resistant species appeared to be *Quercus* among broadleaves and *Abies* among conifers; some tree species experienced a lower SI than these two tree species (Appendix, Table A1) but were rare and appeared only sporadically. *Quercus* and *Abies* experienced similar damage rates of 17.6 % and 19.4 %, respectively. Whereas

more than half of damaged *Abies* trees were totally damaged, *Quercus* trees mainly experienced a much higher proportion of moderate damage. However, when damage rates per ice storm intensity categories were considered (Figure 3), *Abies* was the most resistant species, with the lowest damage rates across all ice storm intensity categories, while *Quercus* experienced similar damage rates to *Fagus* at severe to extreme ice storm intensity (DINT3), but lower damage rates at lower ice storm intensities. By comparison, *Fagus*, the most frequent tree species, experienced higher proportions in all damage classes than *Abies* and partly *Quercus*, while *Picea* experienced a much higher proportion of total and moderate damage, but a similar proportion of severe damage. The highest SI of 0.62 was observed for *Pinus*, making it the most susceptible tree species to ice damage.

Table 2: Ice damage per tree species, showing the number of surveyed trees N, the calculated susceptibility index SI for different ice storm intensities – low intensity DINT1, moderate intensity DINT2, severe to extreme intensity DINT3 – and S_{OVERALL} irrespective of ice storm intensity

Tree species	N	SI _{DINT=1}	SI _{DINT=2}	SI _{DINT=3}	S _{OVERALL}
<i>Abies alba</i>	836	0.01	0.19	0.13	0.14
<i>Acer</i> sp. *	571	0.12	0.17	0.43	0.24
<i>Fagus sylvatica</i>	4216	0.13	0.27	0.42	0.23
<i>Picea abies</i>	3108	0.07	0.28	0.47	0.28
<i>Pinus</i> sp. *	290	0.16	0.13	0.83	0.62
<i>Quercus petraea</i>	330	0.09	0.09	0.33	0.11
other broadleaves**	2029	0.12	0.14	0.37	0.18
other conifers***	34	0.00	0.20	0.25	0.21
All species	11414	0.11	0.22	0.43	0.23

* *Acer* sp. = *Acer pseudoplatanus* & *A. platanoides*; *Pinus* sp. = *Pinus sylvestris* & *P. nigra*
 other broadleaves: *Carpinus betulus*, *Ostrya carpinifolia*, *Fraxinus excelsior*, *Alnus glutinosa*,
Castanea sativa, *Fraxinus ornus*, etc.

*** other conifers: *Larix decidua*, *Pseudotsuga menziesii*, *Taxus baccata*, etc.

Figure 2: Proportions of trees with different ice damage classes (D0-D3) by tree species

Figure 3: Proportions of trees with different ice damage classes (D0-D3) by tree species, differentiated by ice storm intensity categories (DINT)

The final OLR model of ice damage (TDAM) included 8 predictors: DINT, ELV, SLP, DBH, SPEC, SS, GINI and SWI. The non-linear dependence of TDAM on ELV, SLP and SWI was considered using restricted cubic splines with five knots. The interactions between DINT and ELV, SLP, and DBH were also considered in the OLR model (Supplementary Material, Table SM2). Bootstrapping the model showed no serious problems with overfitting: the original sample Somer's rank correlation between predicted probabilities and observed response (D_{xy}) was 0.6541, while the corrected D_{xy} on the basis of optimism from the bootstrap procedure was 0.6477, the corrected slope of the overall logistic calibration equation was 0.9797, and the maximum absolute difference in predicted and calibrated probabilities (E_{max}) was 0.0075. The R-square value of the model was 0.404.

The ANOVA results showed that the ice storm intensity DINT was the most important predictor of ice storm damage to trees (Figure 4); the second most important predictor was elevation and its interaction with DINT, followed by tree species, SLP, SWI, DBH and other predictors and their interactions. Considering all other predictors in the model, *Quercus*, *Picea*, *Acer*, *Fagus* and *Pinus* were 3.03, 3.09, 3.59, 4.26 and 8.03 times more likely to increase in damage class than *Abies*, respectively.

We were particularly interested in relations between ice storm intensity DINT, tree species SPEC and DBH since this relation is of utmost importance for forest practice. Thus, we calculated the cumulative predicted probabilities of occurrence of ice damage classes (Figure 5) and the predicted probabilities (Figure 6) considering all three predictors of interest, while all others were held constant at their mean or most frequent category. In a low intensity ice storm (DINT1), the damage occurrence probability was almost constant with respect to DBH. It was the lowest for *Abies* and the highest for *Pinus*. At this ice storm intensity, moderate damage was the most likely to occur for all tree species (Figure 4), but only *Pinus* exceeded the 10 % probability. The probability of total damage occurrence was lower than 5 %, while *Pinus* was the only species that exceeded this threshold probability. For all tree species severe damage was less likely to occur than moderate or total damage.

Figure 4: The relative importance of the predictors and their interactions within the ordinal logistic model estimated by the ANOVA with the difference between partial χ^2 -values and degrees of freedom df (i.e. $\chi^2 - df$) (Harell, 2001)

At an extreme ice storm intensity (DINT3), once again *Abies* experienced the lowest damage occurrence probability (at most 50 % at a DBH of 10 cm), while *Pinus* and *Fagus* experienced the highest, reaching more than 85 % and 75 % (both at a DBH of 10-27 cm), respectively. Even trees of 100 cm in dbh of these two species were subjected to more than 58 % and 42 % probability of damage occurrence, respectively, while *Abies* trees of the same size experienced only 15 % probability of damage occurrence. Small- to medium-sized trees of most tree species experienced a higher probability of total damage than of moderate or severe damage; the thresholds of mean dbh at which the probabilities of moderate damage exceeded those of total damage were 57 cm, 66 cm, 50 cm, 98 cm and 48 cm for *Acer*, *Fagus*, *Picea*, *Pinus* and *Quercus*, respectively. The exception was *Abies*, which was more likely to experience moderate damage than total or severe damage at all dbh values.

Figure 5: Cumulative probabilities of damage occurrence for predominant and dominant trees of tree species in relation to tree size (DBH) and ice storm intensity (DINT); other continuous predictors were held constant at their means

For forest practice, the influence of social status of a tree (SS) and tree size (GINI) and tree species diversity (SWI) are important as well (see Supplementary material). We observed only minor differences in the probabilities of damage occurrence and the damage types between dominant, codominant and suppressed understory trees; for all tree species, understorey trees experienced the highest damage probabilities. The influences of GINI and SWI were similar, showing decreasing probabilities of damage with increasing tree size or species diversity. At severe to extreme ice storm intensity DINT3, the probability of total damage decreased markedly with increasing stand diversity.

Figure 6: Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species in relation to tree size (DBH) and ice storm intensity (DINT); only trees with social status SS1 (predominant and dominant) were considered; other continuous predictors were held constant at their means

4 Discussion

This study is probably one of the first in Europe to assess ice storm intensity based on measured meteorological data and using it to examine species-specific susceptibility to ice damage; previous studies used proxies based on ice damage on the studied plots (e.g. Nagel et al., 2016). We considered four levels of ice storm intensity, whereas most other studies have focused on relatively small forest areas, assuming constant ice storm intensity. In addition, our approach provided an insight into the patterns of damage susceptibility of tree species in relation to ice accretion of different thicknesses.

Ice storm intensity was by far the most important predictor of ice damage on trees; its relative importance in the OLR model was much higher than that of tree species. Ice accumulation was found to be a major predictor of bending also in loblolly pines (*Pinus taeda*) in the southeastern United States (Aubrey et al., 2007) and of light and moderate to severe crown damage and uprooting in unmanaged mature forest stands in Central Europe (Nagel et al., 2016). In addition, Proulx and Greene (2001) demonstrated that ice accumulation was the primary explanatory variable of individual tree damage occurrence and damage type. Lafon (2004) showed, based on six studies on ice-storm disturbance, that the proportion of trees damaged increased linearly with ice thickness (in mm), with a slope factor of 0.0154. Our results were similar; however, our study indicated a non-linear relationship. Ice accretion of >20 mm represented the threshold for severe damage to trees in the study. Similarly, Rustad and Campbell (2012) found that ice accretion of 7-12 mm caused significant canopy damage in the northern hardwoods, resulting in a significant increase of fine and coarse woody debris and a significant increase in leaf-on canopy openness, but only 10 % of trees suffered severe crown damage or breakage. In our case this percentage was more than twice as high (Figure 3).

There are some shortcomings in the procedure for calculating ice storm intensity, especially in the assessment of ice thickness within the DINT categories. However, including the validated ice storm intensity in the ice damage model showed its high importance for damage to trees. The ice load thickness on tree crowns is strongly affected by the local environment and microclimate conditions and thus usually varies even at small scales within a stand, and to an even greater extent on a landscape scale across the ice storm track (Boerner et al., 1988).

Although *Picea* and *Pinus* are more susceptible to ice damage than broadleaved species, the opposite has been found for some other conifers, namely *Abies* and *Larix* (see Supplementary material). The rate of ice damage on *Abies* was the second lowest among the analysed tree species. However, when *Abies* is damaged, total damage quite frequently occurs, mainly due to severe crown damage (i.e. top breakage) or stem breakage. Yet, for *Abies* the probability of occurrence of at least

moderate damage to trees was the lowest among all analysed tree species. A similar finding was reported by Nagel et al. (2016) for unmanaged mature forests. In Nebraska, USA, *Abies* species were also found to have exceptional resistance (Evertson, 2007). It is possible that differences in wood traits between *Abies* and other species could be a reason for its low damage rate (Nykänen et al., 1997). Another possible reason might be a higher proportion of medium and large *Abies* trees in the analysed stands compared to other tree species. We found that the probability of ice damage decreased with increasing dbh. However, the SI value, when calculated only for trees smaller than 30 cm in dbh (results not shown), also indicated much lower susceptibility of *Abies* to ice damage compared to the other main tree species of the same dbh class.

Pinus was the most susceptible tree species to ice damage; it had the highest SI value by far and experienced the highest proportion of total damage (Table 2, Figure 2). It sustained mainly small and large branch breakage as well as stem breakage resulting in severe to total damage. *Picea* experienced the second highest rate of total damage among the main species; it can be classified as a relatively susceptible tree species to ice damage. A detailed study of ice damage in a location within our study area showed that *Picea* suffered mainly tree top breakage, causing moderate to severe damage (Šink, 2015). However, this is contradictory to the findings of Nagel et al. (2016), who recognized *Picea* as a less susceptible species to ice damage in the same study area. The fundamental difference is that they studied rather uneven-aged unmanaged stands with cohorts of large canopy trees, while we analysed stands irrespective of size evenness and management. In addition, their plots were intentionally located in severely damaged forest areas, while we included plots covering the entire gradient of ice storm intensity.

Among all coniferous tree species registered in our study, *Larix decidua* and non-native *Pseudotsuga menziesii* were the most resistant ($SI \leq 0.10$; see Supplementary Material). However, their presence is limited to a few small forest areas within the studied forest stands. In addition, the ice storm occurred in February, when *Larix* was needleless, which might have additionally decreased its susceptibility to damage. Regardless, these results justify more research on both tree species.

521 *Fagus*, the most frequent species in our study area, and *Acer* were the most susceptible to ice
 522 damage among the main broadleaved species, whereas *Quercus* was among the least damaged tree
 523 species. A higher proportion of *Fagus* in forest stands was demonstrated to increase the occurrence
 524 probability and severity of ice damage in Hungary (Aszalós et al., 2012), while less damage was
 525 observed in stands with a higher proportion of *Quercus* (Kenderes et al., 2007). According to our
 526 study, several minor broadleaved tree species, which occur sporadically in forest stands (i.e. *Ulmus*
 527 *glabra*, *Sorbus aucuparia*, *Sorbus aria*), experienced heavy damage and can be characterized as
 528 highly susceptible to ice damage ($SI > 0.27$), while some other minor tree species (i.e. *Carpinus*
 529 *betulus*, *Fraxinus excelsior*, *Quercus cerris*, *Robinia pseudoacacia*, *Salix* spp., *Sorbus torminalis*, *Tilia*
 530 sp.) seem to be among the resistant tree species ($SI \leq 0.13$). As the sample for these species was
 531 rather small, these results should be interpreted with caution.

532 Several tree attributes, which were not directly studied in our analysis, can be related to species,
 533 namely deciduousness and evergreeness, growth form and crown architecture, mechanical
 534 properties of the wood, and intra-specific genetic variation. Since the majority of ice storm events in
 535 Central Europe occur between November and February (Carrière et al., 2000), the higher
 536 susceptibility of conifers may be related to their evergreen canopy and consequently larger surface
 537 area for ice accumulation (Lemon, 1961). However, for *Abies*, this factor seems to be less important
 538 in contributing to its susceptibility. Tree species differ in growth form and crown architecture,
 539 including crown form, fineness of branching, branch angle and arrangement, and crown symmetry,
 540 which may influence ice damage susceptibility (Cannell and Morgan, 1989; Smith, 2000). Nock et al.
 541 (2016) confirmed the key role of crown architecture in determining intra-crown patterns of ice
 542 accretion; higher and exterior branches accumulate more ice than lower and inner branches. If
 543 linked to differences in crown architecture between tree species, this could be a possible
 544 explanation for the differences found in our study. Furthermore, the mechanical properties of the
 545 wood determine the pliability of the limbs and stems, which importantly influence the resistance of

546 tree species to ice damage (Bragg et al., 2003); pliability, however, is closely related to the diameter
 547 of a limb or stem.

548 The probability of ice damage decreased with tree size in terms of dbh, though its relevancy in the
 549 model was quite low. In general, larger trees appear to be more resistant to ice loads than smaller,
 550 often spindly trees. However, very small trees of <5 cm dbh are often highly resilient to ice or snow
 551 damage since their supple boles are pliable enough to bend but not break under ice load, and after
 552 the ice melts, they usually straighten relatively quickly (Bragg, 2016). This pliability diminishes with
 553 increasing dbh. This finding could be related to wood properties, such as modulus of rupture (MOR)
 554 and related maximum bending moment (RC), which are of crucial importance in branch, stem or root
 555 breakage (Bragg et al., 2003). Since RC depends on dbh^3 , it is higher in large trees with stronger
 556 wood; this is species specific, however. The larger size of trees may impart structural rigidity and
 557 hence lower pliability, but greater resistance to breakage (Amateis and Burkhardt, 1996). The latter
 558 is true only if the trees are not infected by wood-decay fungi or have not experienced any other
 559 injury or wood failure in the stem, branches or root system. Our results on the influence of tree dbh
 560 on the probability of ice damage are in accordance with the findings of Rebertus et al. (1997) and
 561 Rhoads et al. (2002), but in contrast to those of Nagel et al. (2016), who analysed unmanaged stands
 562 with an abundance of large trees. Also, Jones et al. (2001) found that plots dominated by large trees
 563 were more damaged than plots dominated by small trees. Several studies (e.g. Lafon, 2004;
 564 Nadrowski et al., 2014), however, found that ice storms predominantly affect trees of 15-20 cm dbh,
 565 in contrast to smaller and larger-sized trees.

566 Our study showed that tree size significantly influences the damage class; the probability of totally
 567 damaged trees was higher among small trees. Similar results were reported by Lafon (2004), who
 568 determined higher probabilities of bent boles and severe bole damage such as snapping in small-
 569 diameter trees and higher probabilities of crown damage with increasing tree diameter. Several
 570 other studies (Proulx and Greene, 2001; Priebe et al., 2018) demonstrated that increasing tree
 571 diameter tends to shift ice damage from bending to crown loss; however, our data did not confirm

this. In addition, the probability of a tree being uprooted increases with dbh if trees are growing on a slope (Nagel et al., 2016).

The social status of a tree had a significant but minor influence on ice damage probability. Our finding that trees occupying the predominant and dominant positions within the stand canopy experienced the lowest probability of damage was contrary to the findings of Rebertus et al. (1997) and Rhoades (1999). They reported much heavier damage in dominant trees than in suppressed trees. In our case, one of the possible explanations for the higher probability of damage among suppressed trees could be indirect damage caused by falling debris from injured canopy trees. Canopy trees increase the amount of shelter and prevent direct ice loading damage to suppressed trees, but also increase the probability of indirect damage due to the larger quantity of potential debris that could damage suppressed trees (Priebe et al., 2018). In confirmation, Boerner et al. (1988) reported that a large *Fagus grandifolia* tree toppled and uprooted a number of suppressed understory trees downslope. However, indirect damage strongly depends on the species composition of the canopy layer (Priebe et al., 2018); if ice damage prone species are present there, the likelihood of indirect damage to suppressed understory trees is greater.

Among stand variables, indices of species diversity (SWI) and heterogeneity of sizes (GINI) were included in the model of ice damage. Stands with lower species diversity (i.e. pure stands) suffered higher levels of ice damage than stands with higher species diversity (i.e. mixed stands), which is in accordance with other studies from Europe (Kenderes et al., 2007; Aszalós et al., 2012) and North America (e.g. Jones et al., 2001; Rhoads et al., 2002). The higher probability of ice damage in more homogenous stands in terms of species composition might be related to the fact that stands with low tree species diversity are usually comprised of *Picea* or *Fagus*, which are both moderately to very susceptible species, and sometimes of *Pinus*, which is an extremely susceptible tree species. In addition, pure stands are usually thinned more or less regularly to accelerate the radial growth of the remaining trees, which could add to the amount of ice damage experienced in these stands (e.g. Zarnovican, 2001). Nadowski et al. (2014), however, reported that stand species diversity may either

have no effect on single tree damage due to ice loading or may have both negative and positive effects that cancel each other out at the scale of a single tree. The Gini index, which expresses the heterogeneity of tree sizes in a stand, was also recognized as a predictor, though its relevancy was lower than that of SWI. A tree's likelihood of being damaged is lower in more uneven-sized stands than in more even-sized stands. Moreover, uneven-sized stands may also signify increased resilience to natural disturbance due to the presence of trees of all sizes in a relatively small forest area. To our knowledge, our study is the first to demonstrate this relationship between stand heterogeneity in terms of tree size and ice damage, although it should be noted that stand age and stand height were reported as important predictors of ice damage (e.g. Aszalós et al., 2012). Among other stand variables, stand density has often been recognized as a determinant of ice damage, although Bragg et al. (2003) cited many conflicting reports on the effects of stand stocking. Generally, dense stands have been found to be more vulnerable to ice storms, where collision from falling neighbouring trees is an important risk factor (Cain and Shelton, 2002).

Site conditions can be also an important determinant of ice damage severity. Higher damage rates have often been observed at higher elevations and on steeper slopes (e.g. Kenderes et al., 2007; Isaacs et al., 2014). Rhoads et al. (2002) found that ice accumulation and thus ice damage increased with elevation, but this relationship was best explained by a second-order polynomial regression. A similar result was found in our study (see Supplementary material), meaning that ice storms often impact only a specific elevation belt, which depends on the vertical temperature profile and the altitude of the border between warm and cold air layers. In our study, slope was a significant but not decisive predictor of ice damage. Steep slopes can be indicative of shallow soils, reducing the rooting depth and increasing vulnerability to uprooting. If the soil is highly saturated, the probability of uprooting is even greater (Nagel et al., 2016). The topographic position was not included in our model, but some researchers found that topographic features (e.g. valley bottoms, foothills, lower and upper slopes) are important for ice damage (e.g. Bruederle and Stearns, 1985; Rhoades, 1999). For instance, the interaction of topographic position and aspect may increase exposure to wind,

resulting in more frequent and severe damage (Warrillow and Mou, 1999). Among site variables, soil characteristics, such as soil depth and moisture, may be associated with ice damage (e.g. Rhoades, 1999), but were not included in our study because the available data were not of adequate quality.

5 Conclusions

Worldwide, there is a great deal of discussion about adaptation of forests to environmental changes. Several aspects of adaptation have been thoroughly studied, such as changes in the growth of different tree species, their health status, the impact of pathogens and insects, assisted migrations, etc., and knowledge on the resistance of tree species to natural disturbances is an additional tool for the adaptation of forests and forestry.

Our model of ice damage to trees could be used as a basis for adaptation of forest management in regions prone to ice storms. When stands in such areas are naturally or artificially regenerated, the creation of mixed stands must be a priority, and tree species resistant to ice damage should be promoted. Mixed stands with high species diversity were recognized to be more resistant to ice damage than less diverse stands. *Abies alba* among conifers and *Quercus petraea* among broadleaves seem to be the most suitable tree species to promote in Central Europe, but the same is also true for some other minority ice damage resistant species. If these species are regenerated naturally, they can be promoted through the length of the regeneration period (e.g. longer regeneration periods for promoting shade-tolerant species such as *Abies alba* or very short regeneration periods for promoting shade-intolerant *Quercus petraea*), but also through the size, shape and orientation of the regeneration areas.

In addition, the probability of ice damage decreased with tree size (dbh), larger-sized trees being much less prone to ice damage. Thus, large-sized trees may represent the basis of resistance against ice damage to stands and also of resilience since these trees usually fructify regularly and represent a continuous seed source for new stands following ice storms. Having some large-sized trees in a stand should significantly improve both the resistance and resilience to ice (and other) storms. The

size (dbh) threshold is, however, species specific, but based on our results, a threshold of 50 cm could be suggested for all analysed tree species.

In relation to large-sized trees in stands, classical selective thinning (Schädelin, 1942; Boncina et al., 2007; also termed thinning from above, while in North America Smith et al. (1997) defined it as crown thinning) should be encouraged. In this type of thinning, the favoured trees (crop trees) are mainly from the dominants, exhibiting vigour, large crown of suitable shape and good stem quality. The removed trees (competitors) are mainly from the codominants, but also dominants and intermediate trees, in order to open up the canopy and favour the growth and development of the crop trees (Schädelin, 1942; Smith et al., 1997). Such thinning has a positive long-term impact on 1) the radial growth of remaining trees, which increase faster in dbh (Boncina et al., 2007) and thus experience decreased probability of ice damage; 2) tree stability through a decreasing stem taper (i.e. h/dbh) over time; and 3) tree crown size which grows faster due to enlarged growing space as a result of harvested competitive trees. In the short term, however, selective thinning may reduce stand and tree resistance to abiotic disturbance due to the abundance of small gaps dispersed throughout the stand canopy, which reduce the support between neighbouring trees.

All of the described measures generally boost the resistance and resilience of trees when ice damage occurs. In regions where ice storms occur frequently and are predicted to be even more frequent and intense, the above-mentioned and also other adaptive measures are urgently needed in order to adequately prepare forests for environmental changes and their consequences.

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Conflict of interest statement

None declared.

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**Ice storm damage to trees in mixed Central European forests:
damage patterns, predictors and susceptibility of tree species**

Online supplementary material

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The Online Supplementary Material supplements the methodology (Figure SM1) and results of the paper (Tables SM1 & SM2, Figures SM2-7) and contributes to better understanding of the ice storm damage modelling and the obtained results.

Table SM1: The list of tree species registered on surveyed permanent sampling plots (n = 960) with their grouping into eight main groups of tree species, showing also the number of trees (N), the share of trees per damage class (D0 – tree with no damage, D1 – trees with moderate damage, D2 – trees with severe damage, D3 – trees with total damage), and the susceptibility index $SI_{OVERALL}$, calculated irrespective of the ice storm intensity

Tree species	Group of tree species*	N	Share of trees per damage class (%)				$SI_{OVERALL}$
			D0	D1	D2	D3	
<i>Abies alba</i>	1	836	80.62	7.42	2.15	9.81	0.14
<i>Acer campestre</i>	8	56	69.64	14.29	3.57	12.50	0.20
<i>Acer platanoides</i>	6	22	68.18	4.55	4.55	22.73	0.27
<i>Acer pseudoplatanus</i>	6	549	61.93	17.12	10.02	10.93	0.23
<i>Acer tataricum</i>	8	51	76.47	19.61	3.92	0.00	0.09
<i>Alnus glutionsa</i>	8	171	61.99	19.88	8.77	9.36	0.22
<i>Alnus incana</i>	8	26	84.62	0	3.85	11.54	0.14
<i>Betula pendula</i>	8	40	75.00	12.50	0	12.50	0.17
<i>Carpinus betulus</i>	8	546	80.95	8.42	3.30	7.33	0.12
<i>Castanea sativa</i>	8	116	81.90	6.03	3.45	8.62	0.13
<i>Fagus sylvatica</i>	4	4216	67.77	12.07	6.95	13.21	0.22
<i>Fraxinus excelsior</i>	8	157	78.98	11.46	3.18	6.37	0.12
<i>Fraxinus ornus</i>	8	142	69.72	8.45	7.04	14.79	0.22
<i>Juglans regia</i>	8	13	38.46	53.85	0	7.69	0.26
<i>Larix decidua</i>	7	13	76.92	15.38	0	7.69	0.13
<i>Ostrya carpinifolia</i>	8	295	74.24	9.83	5.08	10.85	0.18
<i>Picea abies</i>	2	3108	64.77	14.22	3.02	17.99	0.25
<i>Pinus nigra</i>	3	78	80.77	6.41	7.69	5.13	0.12
<i>Pinus sylvestris</i>	3	212	25.94	14.62	9.43	50.00	0.61
<i>Populus tremula</i>	8	35	68.57	17.14	5.71	8.57	0.18
<i>Prunus avium</i>	8	57	64.91	5.26	3.51	26.32	0.30
<i>Pseudotsuga menziesii</i>	7	19	89.47	5.26	0	5.26	0.07
<i>Quercus cerris</i>	8	45	93.33	4.44	0	2.22	0.04
<i>Quercus petraea</i>	5	329	82.37	9.42	2.43	5.78	0.11
<i>Robinia pseudoacacia</i>	8	29	89.66	3.45	0	6.90	0.08
<i>Salix</i> spp.	8	26	88.46	7.69	3.85	0	0.05
<i>Sorbus aria</i>	8	89	64.04	13.48	10.11	12.36	0.24
<i>Sorbus aucuparia</i>	8	18	77.78	0	0	22.22	0.22
<i>Sorbus torminalis</i>	8	21	85.71	4.76	0	9.52	0.11
<i>Tilia</i> spp.	8	19	73.68	15.79	10.53	0	0.12
<i>Ulmus glabra</i>	8	47	46.81	21.28	17.02	14.89	0.33
other broadleaves	8	26	80.77	0	3.85	15.38	0.18
other conifers	7	7	85.71	0	0	14.29	0.14
all species		11,414	68.68	12.21	5.19	13.92	0.21

* Groups of tree species: 1 – *Abies*, 2 – *Picea*, 3 – *Pinus*, 4 – *Fagus*, 5 – *Quercus*, 6 – *Acer*, 7 – other conifers, 8 – other broadleaves

Table SM2: The ordinal logistic (OLR) model: the detailed ANOVA table with all included regressors in the model (χ^2 – partial χ^2 values, df – degrees of freedom, p – p value); the predictor was considered as significant if $p < 0.05$; see Table 1 for predictors’ abbreviations. For each explanatory variable Higher Order Factors are included in the model in the case of interactions or nonlinear relationship. The significance of interaction terms and nonlinearity for each explanatory variable is tested based on the partial χ^2 test.

Predictors	χ^2	df	P
ELV (Factor+Higher Order Factors)	953.26	16	<0.01
all Interactions	762.98	12	<0.01
nonlinear (Factor+Higher Order Factors)	658.05	12	<0.01
SLP (Factor+Higher Order Factors)	101.54	16	<0.01
all Interactions	49.07	12	<0.01
nonlinear (Factor+Higher Order Factors)	96.39	12	<0.01
DINT (Factor+Higher Order Factors)	1560.68	30	<0.01
all Interactions	866.64	27	<0.01
SPEC	202.42	5	<0.01
DBH (Factor+Higher Order Factors)	47.56	4	<0.01
all Interactions	19.15	3	<0.01
SS	29.14	2	<0.01
GINI	16.08	1	<0.01
SWI	55.86	4	<0.01
nonlinear (Factor+Higher Order Factors)	24.83	3	<0.01
DINT * ELV (Factor+Higher Order Factors)	762.98	12	<0.01
nonlinear Interaction : f(A,B) vs. AB	361.60	9	<0.01
DINT * SLP (Factor+Higher Order Factors)	49.07	12	<0.01
nonlinear Interaction : f(A,B) vs. AB	46.78	9	<0.01
DINT * DBH (Factor+Higher Order Factors)	19.15	3	<0.01
TOTAL NONLINEAR	751.52	27	<0.01
TOTAL INTERACTION	866.64	27	<0.01
TOTAL NONLINEAR + INTERACTION	1078.64	36	<0.01
TOTAL	2420.07	51	<0.01

883 **Figure SM1:** Schematic presentation of the ice storm intensity modelling procedure. Blue rectangles represent different sets of input measured data. In dark
 884 purple stages of spatial interpolation and spatial modelling are presented. The red rectangles represent the final modelling results: daily ice storm intensity
 885 maps and the final ice storm intensity map for the entire 8-days event

886

887 **Figure SM2:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species in relation to tree size diversity Gini index (GINI)
888 and ice storm intensity (DINT); only trees with social status SS1 (predominant and dominant) were considered; other continuous predictors were held
889 constant at their means

890

891 **Figure SM3:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species in relation to tree species diversity index (SWI) and
 892 ice storm intensity (DINT); only trees with social status SS1 (predominant and dominant) were considered; other continuous predictors were held constant
 893 at their means

894

895 **Figure SM4:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species for trees with social status SS2 (codominant trees)
 896 in relation to DBH of a tree and ice storm intensity (DINT); other continuous predictors were held constant at their means

897

898 **Figure SM5:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species for trees with social status SS3 (suppressed trees) in
899 relation to DBH of a tree and ice storm intensity (DINT); other continuous predictors were held constant at their means

900

901 **Figure SM6:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species in relation to elevation (ELV) and ice storm
 902 intensity (DINT); only trees with social status SS1 (predominant and dominant) were considered; other continuous predictors were held constant at their
 903 means

904

905 **Figure SM7:** Predicted probabilities of moderate (D1), severe (D2) and total damage (D3) of tree species in relation to slope (SLP) and ice storm intensity
 906 (DINT); only trees with social status SS1 (predominant and dominant) were considered; other continuous predictors were held constant at their means

907