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Vulnerability of uneven-aged forests to storm damage

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Uneven-aged forests are assumed to have a high stability against storm damage but have rarely been analysed for vulnerability to storm damage due to a lack of a sufficient empirical database. Here we model storm damage in uneven-aged forest to analyse major factors that may determine the sensitivity of this type of forests to storms based on a broad database. Data are derived of public forests in the canton Neuchâtel in West Switzerland that are dominated by silver fir and Norway spruce and managed since the beginning of the 20th century following a single-tree selection system. A unique dataset of periodical (every 5–10 years) full inventories measuring the diameter of every single tree including salvage cuttings was available for the investigation. The time series reached back until 1920 and covered an area of 16 000 ha divided into 3000 divisions. The effect of a major winter storm ('Lothar') in December 1999 on these forests was investigated using a subset of 648 divisions. The influence of the vertical stand structure on the vulnerability of storm damage was studied using logistic regression models. To facilitate the analyses, an index of closeness to a J-shaped distribution (LikeJ) based on the number of trees in different diameter classes was developed. Besides structural indices, variables representing stand characteristics, soil-related and topography-related variables were included. The results of our study show that the overall damage level of the investigated forests was rather low. The variables that entered the model for the uneven-aged stands were different to those that are normally significant for even-aged stands. While variables like stand structure, the timing of the harvesting and topographic variables entered a multivariate statistical model as significant predictors, standard predictors for storm damage in even-aged stands such as stand density, thinning intensity or species composition were not significant. We hypothesize that the uneven-aged structure of the investigated forests may be one reason for the low damage level we observed but emphasize the need for more detailed research to support this conclusion.

Introduction

Stand structure is assumed to have an influence on the vulnerability of forests to storm damage. Nolet *et al.* (2012) developed an approach in which information on stand structure in wind damaged sugar maple poles was used as bio-indicator for wind intensity. Bonnesoeur *et al.* (2013) investigated windfirmness of two different stand structures in beech forests and found that the increase of risk with the increase of the bending moment coefficient was higher for high forests compared with coppice with standards. Mason (2002) hypothesizes lower storm damage vulnerability in uneven-aged forests due to a potentially higher individual stability of the trees. This is supported by Kenk and Guehne (2001) who show that especially large trees in irregular forests have favourable relations between height and diameter (<80) indicating high individual stability. In a study on the economic performance of uneven-aged forests in the Black Forest area of Southwest Germany (Hanewinkel, 2001), uneven-aged forests showed a lower percentage of salvage cuttings than adjacent even-aged forests (Hanewinkel, 2002). While there is an extensive literature

on storm damage vulnerability and storm damage modelling (recently reviewed in Hanewinkel *et al.* (2011)) that mainly deals with even-aged forests, empirical information on storm damage in uneven-aged forests is rare. Only few regional case studies with a limited database (Dvorak *et al.*, 2001) specifically deal with the vulnerability of uneven-aged forests on the stand level to storm damage. This is a major research gap, as one of the main reasons for the conversion of even-aged to uneven-aged forest within 'close-to-nature' silvicultural programs that are currently ongoing in large forest areas in Central Europe (Spiecker *et al.*, 2004) is an assumed lower vulnerability of the targeted highly structured forest stands to abiotic disturbances such as storms. Additional information on the stability of uneven-aged forests under the influence of storms – including events with high wind speeds – is therefore urgently needed.

Goal of the study and research questions

The goal of the study is to investigate how stable uneven-aged forests that are characterized by trees of different sizes (diameter

and height) on a limited area (so-called typical 'Plenter' – forests after Schütz (2006) dominated by conifers) against storm damage. Specifically, we investigate the following research questions:

(1) What is the influence of the vertical stand structure on storm damage in uneven-aged stands?
(2) What is the influence of other stand characteristics (tree species, stand density...) on storm damage in uneven-aged stands?
(3) What is the influence of harvesting (intensity and timing) activities ?
(4) What is the influence of soil characteristics (moisture and acidity) and of the topographic situation (exposure, shape of terrain, slope and elevation)?

Thus, the study focuses on the analysis of uneven-aged forests and does not provide for a comparison between even-aged and uneven-aged stands in terms of windthrow probability.

Material and methods

Database

The study is based on repeated inventories in public forests in the canton Neuchâtel in the Jura region of West Switzerland that are dominated by silver fir (*Abies alba* Mill.), Norway spruce (*Picea abies* Karst) and European beech (*Fagus sylvatica* L.). Since the beginning of the 20th century, these forests have been managed following a single-tree selection system ('Plenterwald'). Since 1920, the diameter at breast height (dbh) of all trees with dbh ≥ 17.5 cm has periodically (every 5–10 years) been measured, and salvage cuttings separately recorded, for 3000 divisions of 0.3–20 ha (mean 6 ha) in an area of 16 000 ha. A division is an inventory unit that may encompass several stands that can be separately described in a qualitative way (i.e. by a verbal stand description). However, the quantitative description (i.e. the inventory) and the management planning both take place on a division level. Thus, the divisions in our case are comparable to forest stands and are treated as such in our investigation. Callipering was done in 5-cm-dbh classes, e.g. the 25-cm class includes all trees with dbh of ≥ 22.5 cm and <27.5 cm. For this study, we analysed the effect of a major winter storm ('Lothar') in December 1999 that caused >200 million m^3 of damage in Europe. We selected 648 divisions based on the criteria: constant area, data consistency and inventory immediately before the storm. Divisions that had significantly changed their area, those with missing data or were the last inventory was >10 years before the storm were thus excluded from the dataset.

In addition to the information from the forest inventories, we used information on soils issued from site mapping in the region (Richard, 1965) and a digital elevation model with 25-m grid (DHM25) to analyse the topography of the study area in terms of exposure, slope, curvature and elevation.

Figure 1 shows a map of the study area (canton Neuchâtel) with the different forest areas.

The forests are mostly concentrated on the slopes and ridges of the Jura mountain ranges between 700 and 1300 m a.s.l.

Statistical modelling approach

Target variable

As the target variable (dependent variable), we selected the damage severity S at the division level. The damage severity was defined as the sum of the basal area of all damaged trees divided by the total basal area of the division according to the most recent inventory before the storm 'Lothar', i.e. in the years from 1990 to 1999. In our analysis, we use a logistic regression technique with a binomial response, in which stands with a damage severity S of <5 per cent are classified as not damaged ($n =$
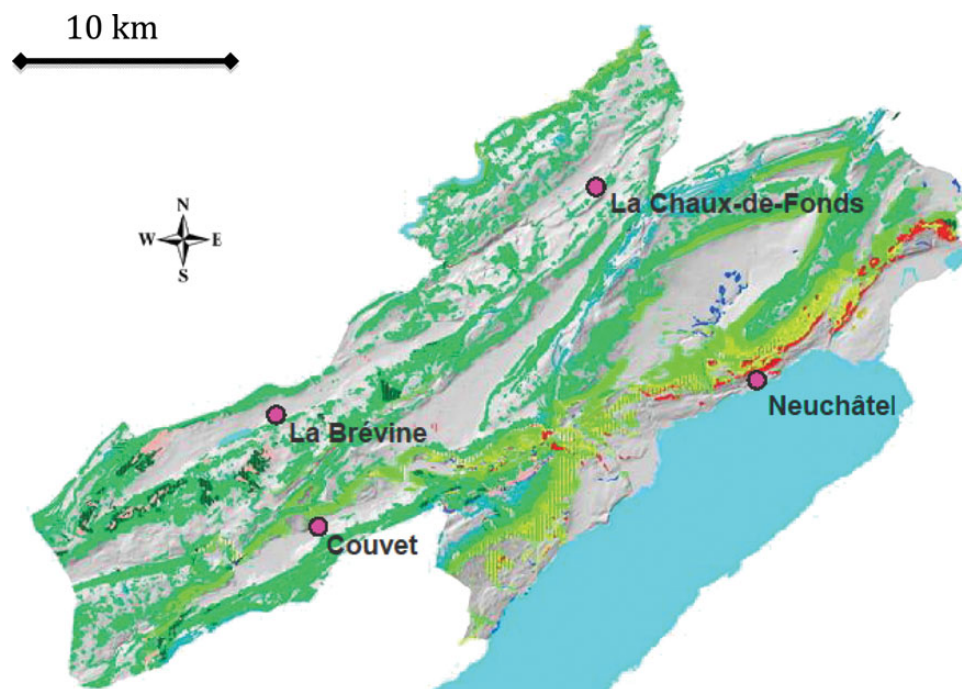
Figure 1 Study area in the canton Neuchâtel. Different colours show the forested areas with the forest associations according to the regional site map (Richard, 1965).

509), and stands with a damage severity S of >5 per cent are considered damaged ($n = 139$).

Predictors (independent variables)

We started with an initial set of 15 different predictors (independent or explaining variables) to analyse the vulnerability of the forests to storm damage in the study area. The initial selection was based on previous investigations of storm damage to forests that showed that, besides stand characteristics, terrain- and site-related parameters may affect damage (König, 1995; Fridman and Valinger, 1998; Jalkanen and Mattila, 2000; Mitchell et al., 2001; Dobbertin, 2002; Mason, 2002; Hanewinkel, 2005; Mayer et al., 2005; Schütz et al., 2006; Schmidt et al., 2010; Klaus et al., 2011; Valinger and Fridman, 2011; Albrecht et al., 2012; Albrecht et al., 2013). As reliable meteorological data such as high-resolution wind- or gust-speeds were not available for the study area, we did not include these parameters in our model. However, we checked whether there was a correlation between elevation and damage intensity, which was not the case.

The 15 initial predictors consisted of 9 variables describing stand characteristics, 4 variables concerning the topographic situation, 1 referring to soil conditions and 1 to the spatial distribution of the damage. We put special emphasis on describing the stand structure and investigated several indices on structural diversity of forest stands.

Soil and terrain characteristics

The variables describing soil characteristics were derived from the site map of the canton Neuchâtel. Using ArcGIS, the forest maps were intersected with the site maps, and each division was assigned to the site unit with the largest area in the division. Based on a regional description of the site units (Richard, 1965), the forest sites in the study area were grouped into four categories according to their position within the ecogram (Ellenberg and Klötzli, 1972): 1 – acid, 2 – central, 3 – moist and 4 – dry. These categories are standard categories that are used to classify soils and related plant associations in Europe. Forest sites of Category 2 (central) are thus in the centre of the ecogram, i.e. they occur on soils that are neither very moist nor dry and are in a pH range between slightly acid and neutral.

In order to describe the topographic situation of the study area, the variables exposure, slope, elevation (height above sea level) and curvature were calculated for each division, using ArcGIS and a digital elevation model with 25-m resolution (DGM25). Exposure was defined as a categorical variable with two categories: 1 – NE–E–SE–S and 2 – SW–W–NW–N, according to the major wind direction (SW–W–NW) in the study area. The curvature of the divisions describes forest areas with a positive curvature as convex (i.e. ridges) and those with a negative curvature as concave (i.e. hollows). The curvature was calculated as the (horizontal) curvature at the right angle in the direction of the maximum slope (for details of the calculation see ESRI (2012)).

We made no effort to include wind-related parameters like wind speed or gustiness in our model. We know from a reanalysis of the wind speeds on 26th of December 1999 (Meteoswiss, 2009) that the wind speeds in the study area were particularly high and that they did not much differ between lower and higher elevations. The cold front of the winter storm hit Switzerland at ~09.00 UTC in the area of the Neuchâtel Jura and crossed the mountain range within half an hour. In La Brévine (1043 m a.s.l.), maximum wind speeds of 157 km h^{-1} were measured, in Delémont (413 m) even 170 km h^{-1} and on the Chasseral at 1600 m a.s.l. only marginally higher 177 km h^{-1}. The rather high spatial resolution of our data (the average size of a division is ~5 ha) would have required a grid of 200 × 200 to 300 × 300 m for wind data of the storm Lothar, a resolution that is at the moment impossible to reach, even with very advanced meso-scaled models (see e.g. Schmoeckel and Kottmeier (2008)).

Stand characteristics

Besides basal area (m^2 ha^{-1}), standing volume (m^3 ha^{-1}), tree species composition (per cent of basal area of Norway spruce, silver fir and European beech), the intensity of harvesting (per cent of basal area removed in the 8 years before the storm) and time (years) without harvesting (calculated as the mean of the time difference between the year(s) of the intervention(s) and the year 2000, weighted with the intensity of the intervention when more than one intervention had taken place) were used as predictors. A co-linearity between the three predictors describing the tree species is likely (because they sum up to 100 per cent in most stands); therefore, we tested also two orthogonal contrast, i.e. indictor variables for stands with a percentage of broadleaves (beech) of >25 per cent vs. stands with a percentage of broadleaves of <25 per cent, and a second variable indicating stands with a proportion of spruce that is higher than the proportion of fir vs. stand with a proportion of fir being lower than the proportion of spruce. The proportions are defined on the amount of basal area in both variables.

Stand structure

We tested several indices to describe the stand structure of uneven-aged stands. In a first approach, we tried the coefficient of variation of the diameter distribution (C_{DBH}) according to Sterba and Zingg (2006), a distance-independent indicator for the vertical structure of a forest stand that is calculated as follows:

$$C_{DBH} = 100 \times s_{DBH}/\bar{X}_{DBH}, \tag{1}$$

with s_{DBH} = standard deviation of the DBH classes and $\bar{X}_{DBH}$ = mean DBH. However, we found that this coefficient, as many other indices that we initially analysed, does not really characterize the diameter distribution that is used as a guideline for forest management in the study area that is strictly based on an inverse J-shaped distribution of the diameter classes. For an analysis testing structural diversity in a very broad sense, a simple, model-free index would have been better. However, our aim was to investigate how the management leading to a very specific type of structural diversity (i.e. the typical inverse J-shaped diameter distribution) that guarantees the necessary equilibrium to keep the steady state of the uneven-aged stand would influence storm damage vulnerability. We therefore developed a simple index describing the vertical structure of an uneven-aged stand based on the number of stems per hectare in different diameter classes that we called index of closeness to J shape (LikeJ).

This index is based on the diameter distribution (number of stems displayed as a function of diameter classes) of the stands, which describes the vertical stand structure of uneven-aged forests. LikeJ includes three different criteria that are combined using a scoring system:

(i) the number of small trees, i.e. in the diameter classes 20, 25 and 30 cm
(ii) the number of large trees, i.e. trees in the diameter classes ≥55 cm
(iii) the diameter class with the maximum number of trees

For each of these criteria, a scoring system was developed based on reference values for uneven-aged forests in a 'Plenter'-equilibrium according to the model by Schütz (1975) from the municipal forests of Couvet (Favre and Oberson, 2002). The forests of Couvet grow in the centre of the study area and have been managed as model 'Plenter'-forests over the last century. The reference number of stems for criterion (i) (small trees – diameter classes 20, 25 and 30 cm) is between 150 and 170, and for criterion (ii) (large trees ≥55 cm) is between 25 and 45 per hectare (Favre and Oberson, 2002), which resulted in a maximum score of 4 for both criteria (Table 1).

Table 1 gives a detailed overview of the scoring system. The highest index of LikeJ is reached at a score of 10 in divisions with a structure resembling a model Plenter-forest structure, while divisions that deviate from

Table 1 Scoring system for the index of closeness to J shape (LikeJ)

Number of small trees (20–30 cm)		Number of large trees (>55 cm)		Dbh class with max. N	
(N ha^{-1})	Score	(N ha^{-1})	Score	Dbh class (cm)	Score
≥170	4	≥65	0	≥30	0
160–170	4	60–65	0.8	25	1
150–160	4	55–60	1.6	20	2
140–150	3.6	50–55	2.4		
130–140	3.2	45–50	3.2		
120–130	2.8	40–45	4		
110–120	2.4	35–40	4		
100–110	2	30–35	4		
90–100	1.6	25–30	4		
80–90	1.2	20–25	3.2		
70–80	0.8	15–20	2.4		
60–70	0.4	10–15	1.6		
<60	0	5–10	0.8		
		<5	0		

The overall score is calculated by summing up the sub-scores for the three different columns (number of small trees, number of large trees and diameter (dbh) class with the maximum number of trees (max. N)). Maximum score (max. closeness) is 10. References numbers for the number of trees in the sub-scores are based on Favre and Oberson (2002).

such model structures, e.g. by fewer or more large trees, have lower scores. Table 1 shows that criteria (i) and (ii) are weighted twice compared with criterion (iii). For criterion (iii), only divisions with the maximum number of trees in the smallest diameter classes (20 or 25 cm) scored to guarantee the typical inverse j-shaped diameter–distribution curve. Divisions with >170 small trees per hectare also achieved the maximum score for criterion (i). The index – including the scoring and weighting system – was developed in an iterative process such that stands with a reverse J-diameter distribution according to the model by Schütz (1975) should get the maximum scores whereas uniform forests should achieve the minimum scores.

Spatial distribution of the damage

As storm damage cannot be expected to be evenly distributed over the whole study area, we tested the spatial autocorrelation of the damage severity *S* (see the target variable section) with two different definitions of neighbour divisions and two test statistics. Both neighbour definitions were based on distances between division centroids, once including the next (closest) $k = 3$ divisions and on the other hand including divisions within a distance between 100 and 2100 m, the latter resulting in an average number of 33 neighbours per division (4 divisions with only 1 neighbour, 1 division with 99 neighbours). The two test statistics were Moran's *I* and Geary's *C*. The statistics standard deviates are between 8.2 (Geary's *C*, $k = 3$) to 20.1 (Moran's *I*, 100–2100 m) and indicate a highly significant spatial autocorrelation between the division's damage severities *S*.

Therefore, we introduced an auto-covariate (Dormann *et al.*, 2007) in the logistic regression, which is, for each division, the mean damage severity *S* over the $k = 3$ neighbouring divisions.

Table 2 gives an overview of all variables that were initially included in the statistical analysis.

Table 2 Overview on the explaining variables (predictors) initially tested within the statistical modelling

Name	Acronym	Type – unit (Range)
Soil and terrain characteristics		
Soil type	St	Category (1–4)
Exposure	exp	Category (1–2)
Curvature	cur	Continuous[1] (−4 to +4)
Elevation	hasl	Continuous (m)
Slope	slo	Continuous (%)
Stand characteristics		
Standing volume	vol	Continuous (m^3 ha^{-1})
Basal area	ba	Continuous (m^2 ha^{-1})
% basal area beech	%be	Continuous (%)
% basal area spruce	%sp	Continuous (%)
% basal area fir	%fi	Continuous (%)
Intensity of harvesting	iha	Continuous (%)
Time without harvesting	tli	Continuous (y)
Stand structure		
Coefficient of variation of the dbh	C_{dbh}	Continuous (%)
Index of closeness to J shape	LikeJ	Continuous[1] (1–10)
Spatial distribution of damage		
Mean damage intensity of geographical neighbours	h	Continuous (%)

Detailed descriptions see text.
[1]dimensionless.

Choice of the model

In order to investigate the influence of the predictors on the observed stand damages, we fitted a generalized linear regression model of the form

$$\text{logit}(y) = \boldsymbol{X}\boldsymbol{\beta} + \boldsymbol{\rho}A + \boldsymbol{\varepsilon}, \tag{2}$$

where $\boldsymbol{\beta}$ is the vector of coefficients for an intercept term and the explanatory variable $\boldsymbol{X}$, and $\boldsymbol{\rho}$ is the coefficient of the auto-covariate $\boldsymbol{A}$ addressing the spatial-autocorrelation of damage severities in the study area. $\boldsymbol{y}$ is the binary response, i.e. the likelihood that a storm damage of >5 per cent will occur and an error term $\boldsymbol{\varepsilon}$.

All calculations have been done with the procedure GLM of the R statistical package R (Bivand, 2013; R_development_core_team, 2013)

To develop the final model, we started with a first model that included all predictors except for standing volume as it is strongly correlated with basal area. Checking for multiple interactions between predictors, we developed an initial set of 21 candidate models. We used Akaike's Information Criterion (AIC) (Akaike, 1974) to compare the performance of the models for best data fit (Anderson *et al.*, 2000). From the candidate models with the best AIC scores, we developed the final model by stepwise backward regression, consecutively excluding the predictors that did not improve the performance of the model.

Thus, the predictors: soil condition, coefficient of variation of the diameter distribution (C_{DBH}), basal area and standing volume, height above sea level and harvesting intensity were removed from the model. From the variables describing the tree species mixture, the percentage of beech (basal area) remained as a significant predictor for storm damage severity. We checked the residuals of the models to analyse further needs for transforming input variables, which proved to be unnecessary, and we also found that

Distribution of damage severities
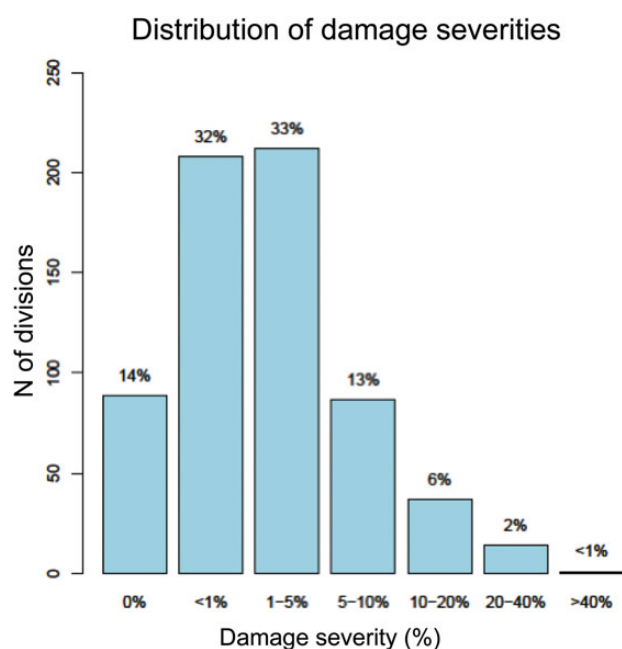
Figure 2 Damage severities in the forest divisions ($n = 648$) of the study area.

the auto-covariate completely removed the spatial autocorrelation from the residuals.

Results

Distribution of the target variable

The overall level of damage is rather low (Figure 2). In almost 80 per cent of the divisions, the damage severity is <5 per cent. Fourteen per cent of the divisions have not been damaged at all by the storm 'Lothar'. The highest damage severity is 42 per cent and occurred in only 1 division.

Statistical model

The statistical parameters (coefficients, *P*-values, level of significance) for the final selected model with the lowest AIC score are given in Table 3.

The final model with significant predictors for storm damage includes the following:

- the severity of storm damage in neighbouring stands (f): the occurrence of storm damage in neighbouring stands increases the probability for storm damage in a given stand;
- the exposure of the stand (asp): (North) West exposition (asp1) – in contrast to (South) East exposition slightly increases the likelihood of storm damage;
- the slope of the terrain (slo): the likelihood for storm damages decreases with the slope of the terrain for eastern exposed stands (less storm damage on steep slopes) and increases with the slope for western exposed stands (higher storm damage on steep slopes);

- the curvature of the terrain (cur): the likelihood for storm damage increases with a curvature of the ground surface changing from an extremely concave (ground depression) to an extremely convex surface (hill);
- the percentage of beech (ghe): storm damage likelihood decreases with a higher percentage of beech (basal area).
- number of years since the last intervention (lot): storm damage likelihood decreases with the number of years passed since the last sivicultural intervention;
- Index of closeness to J shape (LikeJ): the likelihood for storm damage decreases with increasing index of LikeJ, i.e. the stand's DBH distribution approaching the optimal DBH distribution (according to a model for uneven-aged stands developed based on long-term observations in the region).

Overall evaluation of the model

Under logistic regression, the residual deviance under the model compared with the null deviance (intercept term only) can be used as a measure for the strength of the model (pseudo-coefficient of determination $1 - $ (residual deviance/null deviance)). We get a pseudo-coefficient of determination of 0.38, which indicates a reasonable fit, but also means that some important factors may not have been available in this study.

Effect of closeness to J shape and years without harvest – descriptive statistics

In order to get a more detailed impression of the strength of the effect of some of the significant parameters, we looked into the boxplots of the predictors 'index of closeness to J shape – LikeJ' and time without harvest.

The damage severity decreases by >50 per cent from 0.2 (Index of LikeJ = 0–1) to <0.1 (LikeJ = 7–8) (Figure 3a – left). For LikeJ – values of >8, no further decrease of the damage severity can be observed. Interestingly, the damage severity already decreases to a level of <0.1 from LikeJ-class (0–1) to class (1–2). However, looking at the frequency distribution of the LikeJ-values (Figure. 3b – right), we can detect that the first two classes each makes up for <1 per cent of the divisions, which makes interpretation difficult. Looking at Figure. 3b, we concede that the distribution of the divisions is skewed towards highly uneven-aged stands and that the number of divisions with a distinct even-aged structure is low. A further analysis of the strength of the effect of the parameter unevenness using the response function of the regression coefficient showed that the effect of LikeJ is limited to a maximum of 1 per cent change of damage severity per LikeJ – class, i.e. an overall maximum impact of 10 per cent of the parameter unevenness between the lowest class (LikeJ = 0) and the highest class (LikeJ = 10).

Furthermore, damage severity decreases with increasing time elapsed since the last harvest intervention (Figure. 4).

The severity constantly decreases from 1 to 8 years without harvest before the storm event (Figure 4) showing a clear, though not strong effect of the timing of the harvest. On average, 1 year more time decreases the damage severity by ~1 per cent (s. Table 2).

Table 3 Statistical parameters of the predictors of the final selected model, including interactive effects

Coefficients		Estimate	Standard error	Z-value	Pr(>|z|)	Level of significance
Intercept		1.35290	0.71619	1.889	0.058890	****
Auto-covariate	f	0.25670	0.03111	8.250	<2e-16	***
Curvature	cur	1.95866	0.59838	3.273	0.001063	**
Closeness to J shape	LikeJ	−0.15997	0.05958	−2.685	0.007259	**
Time without harvest	lot	−0.16152	0.05813	−2.779	0.005461	**
Share of beech	ghe	−0.03563	0.01223	−2.913	0.003580	**
Exposition	asp1	−1.31395	0.65628	−2.002	0.045273	*
Slope	slo	−0.13707	0.04128	−3.320	0.000899	***
Exposition : slope	asp1:slo	0.15656	0.04502	3.477	0.000506	***

Exposure 1 = easterly exposed sites. Estimated coefficients, including standard error and *P*-values, *n* = 648. Significance levels: *** = 0.001, ** = 0.01, * = 0.05, **** = 0.1
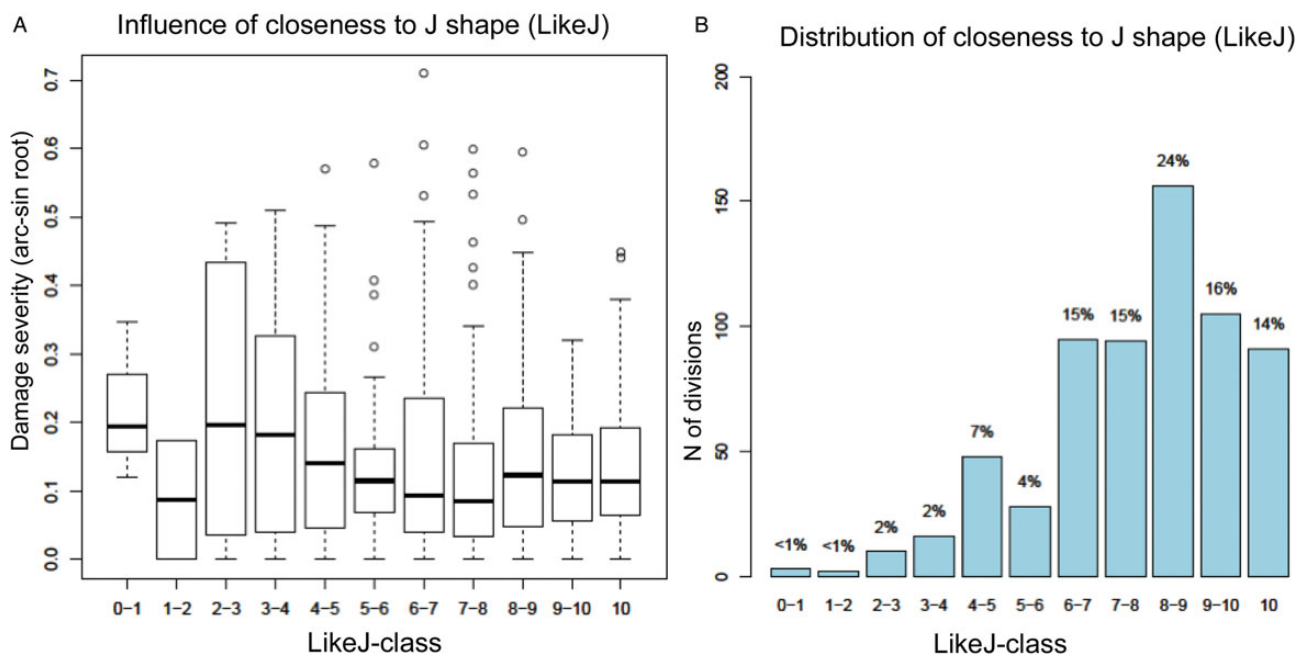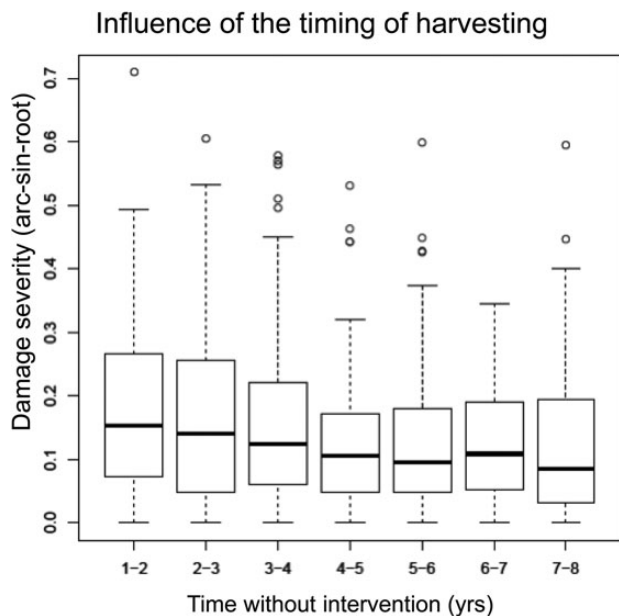

Figure 3 (a)(left): Effect of the closeness to J shape (LikeJ – see text) on the damage severity (*n* = 648). For reasons of clarity, damage severity (*y*-axis) is depicted using the arc-sine-root transformation (Mosteller and Tukey, 1977). Note: The classes for damage severities are different to those in Figure. 2. (b) (right): Number of divisions (*n* = 648) according to classes of closeness to J shape (LikeJ – see text).

Discussion

Database of the investigation

The dataset that was available for the present investigation covering 3000 forest divisions on >16 000 ha, and several decades is certainly unique. Even the reduction to 648 divisions by concentrating on one major storm event and the years 1990–1999 makes for a substantial database for the analysis of uneven-aged stands. However, because the dataset mainly originates from inventory and booking data, it has some limitations that influence the results: the inventory threshold of dbh = 17.5 cm is particularly high compared with other investigations (Fridman and Valinger, 1998;Jalkanen and Mattila, 2000; Dvorak *et al.*, 2001; Dobbertin, 2002; Valinger and Fridman, 2011). This affects structural indices

like C_{DBH} (Sterba and Zingg, 2006) as it influences the relation of mean and standard deviation. The overall damage level of the forests in this study was rather low for this storm event, which had an influence on the discriminatory power of the variables under investigation. The population of forests included in this study was biased towards uneven-aged stands. This again limits the efficiency of classical structural indices, as we were not able to cover the full range from highly structured stands – that were well represented in our dataset – to structurally more uniform even-aged stands that are underrepresented. Furthermore, the data did not contain information on tree height, a parameter that has proven to be significant in many studies (Jalkanen and Mattila, 2000; Mitchell *et al.*, 2001; Dobbertin, 2002; Mayer *et al.*, 2005; Schmidt *et al.*, 2010; Valinger and Fridman, 2011; Albrecht

Influence of the timing of harvesting

Figure 4 Influence of the timing of harvest (time elapsed since the last harvesting intervention) on the damage severity. For reasons of clarity, damage severity (y-axis) is depicted using the arc-sine-root transformation (Mosteller and Tukey, 1977).

et al., 2012) nor on the spatial distribution of the trees. However, as we developed a stand-based model, the influence of individual tree positions as well as mean values for tree height (or for the highly correlated dbh) especially for these uneven-aged stands are very difficult to interpret. We would certainly have to expect differences in damage severities if our divisions had shown distinct differences in mean or absolute tree height.

Modelling approach

We used a Generalized Linear Model (GLM) with a logistic regression as a link function, a standard approach that has been applied in many studies on storm damage vulnerability of forests (König, 1995; Fridman and Valinger, 1998; Jalkanen and Mattila, 2000; Dvorak et al., 2001; Mitchell et al., 2001; Mayer et al., 2005; Schütz et al., 2006; Schmidt et al., 2010; Klaus et al., 2011; Valinger and Fridman, 2011; Albrecht et al., 2012). As an alternative to statistical models, 'artificial neural networks' have been used, specifically with incomplete and noisy datasets (Hanewinkel et al., 2004; Hanewinkel, 2005), which was not the case in this study. Other authors (Dobbertin, 2002; Albrecht et al., 2012) have studied storm damage in forests using 'classification and regression trees'. Besides the advantage of being easier to interpret, the great disadvantage of this approach is that you do not get any probabilities from these models. While only few studies exclusively rely on a literature analysis (Mason, 2002), mechanistic models (Peltola et al., 1999; Gardiner et al., 2008) are a common approach to investigate storm damage vulnerability of forests. However, so far these models are restricted to model storm damage vulnerability in rather uniform even-aged forests.

We used AIC as the criterion for model selection, a parameter that only delivers information on the relative strength of the winner model compared with other models but does not inform about the effective predictive power of the final model. However, the primary goal of this study was not to develop a model to predict storm damage in forest stands, but rather to analyse major influencing factors of the vulnerability of uneven-aged stands to storm damage.

Influence of the predictors

In the following sections, we discuss the influence of the different predictors on storm damage vulnerability along with the research questions that we have developed in the introduction.

Vertical stand structure

Looking at our research question 1, we can conclude that the – vertical – stand structure has a significant influence on storm damage vulnerability of uneven-aged stands. Due to the high minimum size threshold during inventories in our study, the value range of existing structural indices like the C_{DBH} is distinctly lower than that in investigations with lower thresholds. Sterba and Zingg (2006) found mean values for C_{DBH} of 38.2 for even-aged and 72.9 for uneven-aged stand, whereas the divisions in our study showed values between 23.1 and 56.9. Unlike other authors (Dvorak et al., 2001; Dobbertin, 2002) who individually grouped the stand structure of the investigated forests based on field measurements, we developed a structural index using model-based reference numbers. Our index of closeness to J shape (LikeJ) entered our model as a statistically significant variable, indicating that stands with a structure closer to a J-shaped stem-distribution are less prone to storm damage than more uniform stands, which is in line with findings of other studies (Dvorak et al., 2001; Dobbertin, 2002). However, the influence of the stand structure is rather small. Under ceteris-paribus conditions (i.e. all other influencing variables are kept constant), the maximum influence of the stand structure on the vulnerability, i.e. the difference between a stand with the highest and lowest unevenness, is at ~10 per cent of damage severity. This means that the damage level can be decreased from 20 per cent in LikeJ-class 2 to 10 per cent in LikeJ-class 10 (Figure. 3a). The potentially higher stability of uneven-aged forests is often assigned to a higher individual stability of the single trees (Mason, 2002), e.g. characterized by a lower h/d-value, a factor that we did not investigate in our study.

We did not include a comparison between even-aged and uneven-aged forests in our study, as this cannot be made at the stand level only. Even-aged management leads to the development of stands of various ages at the landscape level that will have very different susceptibilities to windthrow. A full comparison between even-aged and uneven-aged management should consider all states of development of even-aged stands.

Other stand characteristics

With respect to research question 2 of our study, the influence of other stand characteristics on storm damage vulnerability of uneven-aged stands was surprisingly low. We were not able to identify an effect of the stand density, a factor that appears to be significant in several studies (Dvorak et al., 2001; Mitchell et al., 2001; Mason, 2002; Valinger and Fridman, 2011). The overall influence of the predictor 'species' is rather low, except for a significant

influence of the percentage of beech. No influence of the percentage of Norway spruce was detected, which is partly contradictory to many studies dealing with storm damage to forests (König, 1995; Jalkanen and Mattila, 2000; Dvorak *et al*., 2001; Dobbertin, 2002; Mayer *et al*., 2005; Schütz *et al*., 2006; Hanewinkel *et al*., 2008; Schmidt *et al*., 2010; Klaus *et al*., 2011). The reason therefore might be that the distribution of the tree species in our dataset with a large amount of mixed stands and a lack of pure stands is rather uniform across the divisions in our study compared with other investigations that were able to compare pure and mixed stands of different tree species.

Harvesting

Concerning research question 3, only the timing of the harvesting, i.e. the number of years elapsed since the last harvesting, had a clear significant influence on the vulnerability. This effect can be found in many studies on storm damage (König, 1995; Dvorak *et al*., 2001; Mitchell *et al*., 2001; Valinger and Fridman, 2011; Albrecht *et al*., 2012). Our study shows a destabilizing effect for a time of up to 8 years, whereas Albrecht *et al*. (2012) found an influence of that factor of up to 10 years. Usually this is – at least for even-aged stands – assigned to the temporary interruption of the canopy. In contrast to the results of other studies (e.g. Albrecht *et al*. (2012)), we did not detect an influence of the harvesting intensity. Here we hypothesize that harvesting in developed uneven-aged stands is a rather uniform type of intervention that does not vary in the same way as in even-aged forests where thinning intensity strongly varies according to the type of the applied thinning (e.g. high thinning, thinning from below, target diameter harvesting. . .).

Soil and topography

Our research question 4 deals with the influence of soil and topography. Soil is a predictor that is included in many investigations on storm damage (Fridman and Valinger, 1998; Jalkanen and Mattila, 2000; Dvorak *et al*., 2001; Mitchell *et al*., 2001; Dobbertin, 2002; Hanewinkel, 2005; Mayer *et al*., 2005; Schütz *et al*., 2006; Schmidt *et al*., 2010; Klaus *et al*., 2011; Albrecht *et al*., 2012). Generally soil moisture is assumed to have a significant influence on storm damage probability, specifically when highly vulnerable species such as Norway spruce grow on waterlogged soils (Hanewinkel *et al*., 2008; Schmidt *et al*., 2010). Although wet soils showed a tendency towards higher damage severity than dry soils in our study, this effect was masked by other effects in the multivariate analysis and did not enter the final model. Soil acidity, a predictor that was significant in one investigation (Mayer *et al*., 2005), did not have any effect in our study that took place in a relatively uniform region, characterized by limestone with little variation in soil acidity.

Topography is a predictor that also entered many statistical storm damage models (König, 1995; Fridman and Valinger, 1998; Jalkanen and Mattila, 2000; Dvorak *et al*., 2001; Mitchell *et al*., 2001; Dobbertin, 2002; Hanewinkel, 2005; Mayer *et al*., 2005; Schütz *et al*., 2006; Schmidt *et al*., 2010; Klaus *et al*., 2011; Albrecht *et al*., 2012). As the storm 'Lothar' was a typical winter storm that reached the study area from West (Meteoswiss, 2009), it is not surprising that westerly exposed divisions displayed a higher damage severity than those exposed to the East. However, in the multivariate statistical model, the predictor exposure entered the model in combination with the share of silver fir and slope. In combination with slope, exposure reveals significantly lower damage intensities of steep slopes, an effect that has often been observed for storm damage (Dvorak *et al*., 2001; Dobbertin, 2002; Mayer *et al*., 2005; Schütz *et al*., 2006; Klaus *et al*., 2011). However, in our study, the predictor is only significant in interaction with exposure to the East, whereas westerly exposed slopes do not show any higher damage severity than areas with less steep sites. We also detected a significant influence of the curvature of the terrain, with higher damage intensities on convex than on concave slopes, a predictor that also entered the multivariate model and that was also significant in other studies (Dobbertin, 2002; Klaus *et al*., 2011). Although increasing elevation can be generally linked to higher wind speeds, the variable was not significant in our study. Elevation as a predictor shows both directions as a predictor. In one study (Klaus *et al*., 2011), it was linked to higher storm damage, whereas in another investigation (Mayer *et al*., 2005), it was associated with lower damage intensities. The latter may be a sign of an adaptation of the root system to constantly higher wind speeds in higher elevations or simply the result of a general difficulty to get reliable information of the parameter 'wind' that includes aspects like gustiness that are very difficult to assess (Schütz *et al*., 2006; Gardiner *et al*., 2008; Albrecht *et al*., 2012; Kamimura *et al*., 2013).

Conclusions

Our investigation contributes to the knowledge of the vulnerability of uneven-aged forests to storm damage, a field of research that is currently characterized by empirical investigations dealing with either small areas (Dvorak *et al*., 2001) or with datasets containing almost no or only very few really uneven-aged forests (Dobbertin, 2002).

The results of our study show that uneven-aged stands display a specific vulnerability towards storm damage that differs in some aspects from that of even-aged stands. Stand structure (the index of closeness to J shape – LikeJ – as developed for this study,) the timing of the harvesting and topographic variables entered a multivariate statistical model as significant predictors in our investigation. However, standard variables that occur in many statistical models for storm damage in even-aged stands such as stand density, thinning intensity or species composition were not significant at all or only in interaction with other parameters. Looking at the comparably low damage level of the forests that we investigated and taking into account the rather high wind speeds in the area on the day of the storm 'Lothar' (Meteoswiss, 2009), we might conclude that long-term single-tree selection forestry has led to stable stand structures that were able to cope with a major storm event in the study area. However, in order to allow for general conclusions on the vulnerability of uneven-aged compared with even-aged forests, we intend to enlarge our database with more uniform forests stands, to investigate additional storm events and to include stand height values as predictor. The latter should be feasible by taking advantage of LIDAR information.

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Conflict of interest statement

None declared.

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