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ORIGINAL PAPER

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Vulnerability of spruce (*Picea abies*) and beech (*Fagus sylvatica*) forest stands to storms and consequences for silviculture

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Abstract The form and magnitude of storm damage and stand disclosure patterns were assessed in 332 randomly chosen pure and regular stands of spruce (*Picea abies* L.) and beech (*Fagus sylvatica* L.) after storm LOTHAR, within a region of the Swiss Midlands. This data was analysed in relation to maximal wind speed, measured with Doppler radar techniques and other influential factors such as relief, allometric characteristics, silvicultural history, and neighbourhood. In addition, storm damage, assessed from aerial photographs over an extended perimeter (about 70,000 ha) was considered. A storm of the magnitude of LOTHAR (December 26 1999), with an average maximal wind speed of 45 m s^{-1} (160 km h^{-1}) appears to have a highly chaotic wind field structure, with great spatial and temporal variation of wind gusts. Wind speeds were not a significant predictor for damage in spruce stands and only weakly influential for beech. The consequences of this high randomness were analysed to estimate the return time of such a storm at the stand level. It lies between 86 and 113 years for spruce, 357 and 408 for beech. Only a few independent variables were significant and the overall explanatory strength of the model was unexpectedly low ($R^2 = 0.07$ for spruce and 0.30 for beech). Among the more reliable predisposing factors were mixture and aspect combined with gradient. An admixture of 10% or more broadleaved tree species or wind-firm conifers like Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco] significantly reduced the vulnerability of spruce stands (by a factor of more than three). On wind-exposed aspects, damage was more than twice the average. Steeper slopes caused a significant reduction in susceptibility (by a factor of six for slopes over 50%, in comparison to gentle slopes $< 20\%$). Other factors such as height to diameter ratio of trees or time since last thinning did not appear to be significant predictors.

Keywords Storm damage · Stability · Risks · Return time · Thinning

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Introduction

On December 26 1999, the winter storm, LOTHAR, dramatically hit western Central Europe with a magnitude of about 45 m s^{-1} (160 km h^{-1}), causing about 185 M m^3 of timber damage in northern France, southwestern Germany and northern Switzerland. The Swiss Midlands, situated on the southern flank of the storm, where turbulence is considered to have been particularly strong (Mayer and Schindler 2002) were also at risk, as well as regions on the main axis of the storm (Paris–Nancy–Frankfurt). A maximum wind speed of 241 km h^{-1} was recorded at Uetliberg Hill (900 m asl) in the Zurich region. As a consequence, about 3% of the forest's standing crop was broken or uprooted, mainly over large areas.

For many years, Swiss forestry has applied a relatively pragmatic "close to nature" silviculture (Schütz 1999). This is based on an intensive thinning regime from above with regular interventions, on average every 10 years, the promotion of mixed stands, and the application of small-scale regeneration in an irregular shelterwood system with extending gaps (Femelschlag). Spruce (*Picea abies* Karst.) and fir (*Abies alba* Mill.) dominate at medium elevations on sites where pure beech (*Fagus sylvatica* L,) represents the climax forest. These two conifers species, which are considered to be particularly sensitive to wind storm damage, account for 57% of the standing crop of the Swiss Midlands (spruce alone comprises 41% of the standing volume).

The problem of studying the response of forest stands to storms is twofold: it is impossible to determine the exact pattern of damaging wind speeds, in particular, the occurrence of destructive gusts and their temporal and spatial variability; secondly, there are no exact figures for stand breakdown, and in particular the critical point at which cohesive stand forces due to promiscuity of neighbours cease to operate, leading to collapse. What we observe afterwards is a posterior effect: the form and the magnitude of damage. How is it that some stands with particular structural characteristics are severely damaged over large areas, whereas similar stands in the vicinity are untouched or show only dispersed damage (Preuhsler 1991)? It seems that the chaotic character (randomness) of such an event is much greater than previously thought. It is especially unclear if the large spatial variation of observed damage is due to the temporal dimension or spatial structure of the heterogeneous wind field structure. Another question is: can the behaviour of trees within a stand and their interactive lateral networking help us to understand the breakdown? Some observations (witnesses, film records) suggest, as working hypotheses, at least for spruce stands, that stand collapse does not generally occur after a single destructive gust, but after the successive impact of several heavy gusts (Schütz and Götz 2003; Bosshard 1967). Inner stand cohesion (collective stability) could be the decisive factor until the destabilisation threshold is reached. This would mean that successive loosening of cohesion would leave a stand in such an unstable state that it is no longer able to withstand even less damaging gusts.

Wind generally does not enter closed stands (Oliver and Mayhead 1974). Gardiner (1994) showed that only winds exceeding 45 m s^{-1} (162 km h^{-1}) with high rotational downwards motions (vortex) can penetrate the crown canopy of normal closed Sitka spruce stands, thus entering the stand and causing the breakage or uprooting of single trees. This means that storm damage must be considered as a dynamic process, as a phenomenon of a disturbance chain. Trees within a stand sway with different wavelengths and amplitude (according to our own swaying experiment, Vanomsen unpublished). This means that the so-called "honami" effect (synchronous swaying, after Inoue 1955) which is supposed to generate a domino effect is not generally considered to be the main phenomenon, nor to be decisive for inducing breakdown (Cremer et al. 1982; Gardiner 1994). Such synchronous swaying has never actually been observed (Bosshard 1967). This also applies to conifer stands. For broad-leaved trees, the damping effect of the main branches within the crown seems to play a greater role in reducing swaying energy. Moreover, because broad-leaved trees have better intrinsic timber properties, stem breakage is less likely to occur and inversely, anchorage seems to be the critical point. An objective genuine witness of LOTHAR observed that conifer stands broke down when maximum wind speed occurred, while broad leaved trees snapped off at a much later point, when the wind speed had diminished (Schütz and Götz 2003).

This study considers the storm vulnerability of representative stands of a sensitive tree species (spruce) at the stand scale in comparison to a wind-firm species (beech). The main aim was therefore to compare damages in more or less pure spruce stands to pure beech ones under different wind speed conditions assessed by Doppler radar technique. An analysis of the main damage patterns should provide clues towards the reasons for stand collapse, and allow the risks to be characterised. Subsidiary it aims to analyse the interaction between damage and wind indicators like topographic exposure to wind, stand structure characteristics and silvicultural history, and address the question of predisposition and vulnerability.

Materials and methods

Doppler radar techniques allow us to measure instant wind speeds under certain conditions, i.e. when precipitation occurs and the viewing angle of the radar beam is favourable (Schmid et al. 2001). This enables us to render the spatial distribution of wind speeds with a spatial resolution of about 250 m×250 m for sectors with a suitable orientation to wind direction and which are located at an appropriate distance from the radar (20 km). Although there are some limitations (measurements every 5 min corresponding to the radar measuring sequence, measurements at a certain elevation over terrain depending on range from the radar site), this allows us to emphasise the small-scale spatial variation of wind speeds and to use this data as a stratification factor for sampling forests stands. In order to reach this goal, we had to extrapolate wind speed to constant height (1,000 m elevation asl, i.e. about 400 m above forest). The ETH Doppler radar at Hönggerberg lies in the vicinity of Zurich city, in a zone threatened by LOTHAR.

The C-band Doppler radar is operated by the Institute for Atmospheric and Climate Science of ETH. Data on the plan position indicator (PPI), scans of radar reflectivity and Doppler speed at 1.5 and 20° elevation angles, are available in 5 min intervals. The Doppler wind data are "folded" to a wind speed interval of -16 m s^{-1} to $+16$ m s^{-1} and therefore need to be unfolded (dealiased) with proper methods. The restitution after dealiaising of the ETH-Doppler speed data was carried out for a perimeter of 60 km×60 km using a variational procedure (Wüest 2001). An average wind direction from sector WSW (azimuth angle 260°) was assumed. A high-resolution wind map (mesh of 250 m) was generated after restitution of the highest recorded wind speed between 10:04 and 13:29 (local time), i.e. during the culmination of LOTHAR (Schraner et al. 2002). Using a spatially averaged but time-resolved radar, wind speed profile around the radar site allows extrapolation of wind speed data from the radar measuring height to 1,000 m and 600 m asl, respectively. Comparisons with conventional wind measurements (terrestrial) using an anemometer show that the speed measured by the radar (at 1,000 m asl) corresponds with conventional maximal wind velocity peaks (at 5 m above soil). Radar measurements at 600 m asl correspond to mean wind speed (10 min intervals). In order to estimate the spatial and temporal heterogeneity of the storm, three other variables were derived:

BOE: an expression for the temporal variation, defined as the number of times different wind speed limit is exceeded (i.e. BOE45 at a threshold of 45 m s^{-1})
TURB: an expression for the spatial variation, defined as standard deviation from five adjacent wind pixels
B: an expression for storm intensity, defined as the duration of occurring wind speed at different thresholds (i.e. B45 at a threshold of 45 m s^{-1})

Two study areas were chosen (675 km^2 in the west and 234 km^2 in the east from the radar site). These fall within the utilisable zone of the ETH-Doppler-radar wind speed measurements. A list of all potential stands within this zone (in keeping with the main aim of the study) was compiled from available management plans. The quality of information on stand composition and structure before LOTHAR was also considered. The selection criteria were: stand area >0.5 ha; development stage: timber tree dimension (diameter at breast height of 100 largest trees per ha, DO > 30 cm) based on the assumption that young stages, up to pole stage, do not seem to be threatened by storms; a more or less even-sized stand structure and, in the initial phase, is relatively pure. Species: essentially dominated by spruce (*Picea abies*) or beech (*Fagus sylvatica*). A certain amount up to 10% of mixed silver fir (*Abies alba*) within spruce stands was tolerated. Stand areas varies between 0.5 and 7.4 ha (in average 0.98 ha) corresponding to the small-scale mosaic of stand distribution in Switzerland. After admixture was found to be a determining factor for stability, data from 16 additional stands with specific mixtures were recorded during a complementary campaign. Last selection criterion was no disturbances from bordering stand gaps or edges.

This resulted in 460 potential spruce stands and 252 potential beech stands. Out of this collective, 332 stands (203 spruce, 129 beech) were selected by stratified random sampling for detailed terrestrial measurement within five wind speed strata, with relatively even distribution in each class.

For this set of 332 stands, detailed terrestrial measurements were made from May to October 2002 to assess stand allometric characteristics: measure of DBH and height of about 40 dominant trees in order to assess DO and HO, dominant diameter, and top height respectively, defined as height diameter of the 100 largest trees per hectare. The exact form and width of stand openings within the stand limits and beyond were mapped with geodesic terrestrial method (traverse). As far as possible, the type of damage (broken or uprooted) was recorded, according to the progression of timber clearance. The stand situation before the storm was reconstructed, or in the case of severe breakdown, taken from management plans and verified by the incumbent forest rangers. The rangers also provided additional information on other previous damage (injuries by bark beetle, root rot) as well as on stand history (most recent thinning, thinning type and intensity, presence of disturbing unevenness like edges). In spring 2004, a second campaign provided results for 16 additional stands, using identical recording methods, randomly selected according to the question of how mixtures in spruce stands influence stability. As admixed species mostly Douglas fir [*Pseudotsuga menziesii* (Mirb.) Franco], European larch [*Larix decidua* Mill.], and Scots pine (*Pinus silvestris* L) were considered. Also recorded were aspect, slope in %, elevation asl, distance to the next forest edge in lee and luff, and the presence of disturbing hindrances, such as edges from bordering neighbouring stands or old gaps. To characterise site conditions, the phytosociologic units (according to Ellenberg and Klötzli 1972) were taken from regional vegetation maps with a scale of 1:5,000.

In addition, a large-scale assessment of severe damage from aerial photographs (scale 1:15,000) was available. Mappings of clear openings (gaps > 1 ha), as well as areas of dispersed small-scale damage (crown cover release 0.4–0.8 or remaining closure 0.2–0.6) were assessed on a large scale in a project commissioned by the Swiss Federal Agency for the Environment, Forests, and Landscape (BUWAL). These windstorm gaps within the extended radar perimeter (about 70,000 ha forests) were coupled using GIS-Software (ArcGIS) with other digital geoinformations such as forest massifs (contiguous forest areas), altitude, aspect, and slope, to allow for comparative analysis. Here, interpretation units are forest massifs ($n=661$, with an average area of 105 ha), 13 relief classes within forest massifs ($n=4{,}147$ units), and damage areas ($n=1{,}784$, gaps and dispersed damage;).

The following damage indices were considered:

IL = damage index, defined as the proportion of canopy gaps, i.e. the sum of gaps (defined as clear canopy openings in stands with a canopy closure >0.2) over 0.1 ha
IS = stand closure index, defined as stand closure before LOTHAR minus stand closure after LOTHAR divided by stand closure before LOTHAR

LIL = logistic transformation of IL as a response variable for logistic function analysis (LIL = LN ((IL + 0.01)/((1 – IL) + 0.01)).

For analysis of the extended perimeter, damage score indicators were:

1. The spatial percent area of gaps per forest unit (massif or relief unit)
2. the percentage of dispersed damage areas per unit
3. a + b

Results and discussion

Characteristics of the storm structure and impact

The distribution of maximum wind speeds from the Doppler radar at 1,000 m elevation shows a large variation (Fig. 1) between 32 and 70 m s^{-1} (115–252 km h^{-1}), on average 44.2 m s^{-1} (159 km h^{-1}) with a standard deviation of 3.59 (8.1%). The spatial pattern (Fig. 2) reveals the banded structure of wind speed due to several bands of heavy wind (Schmid et al. 2001). The distribution of heavy forest damage (stand breakdown over 1 ha, shown in dark in Fig. 2) presents a comparatively similar striped pattern. The banded form of severe damage was already clearly identified for the whole of the Swiss Midlands (BUWAL 2001; Schmid et al. 2001).

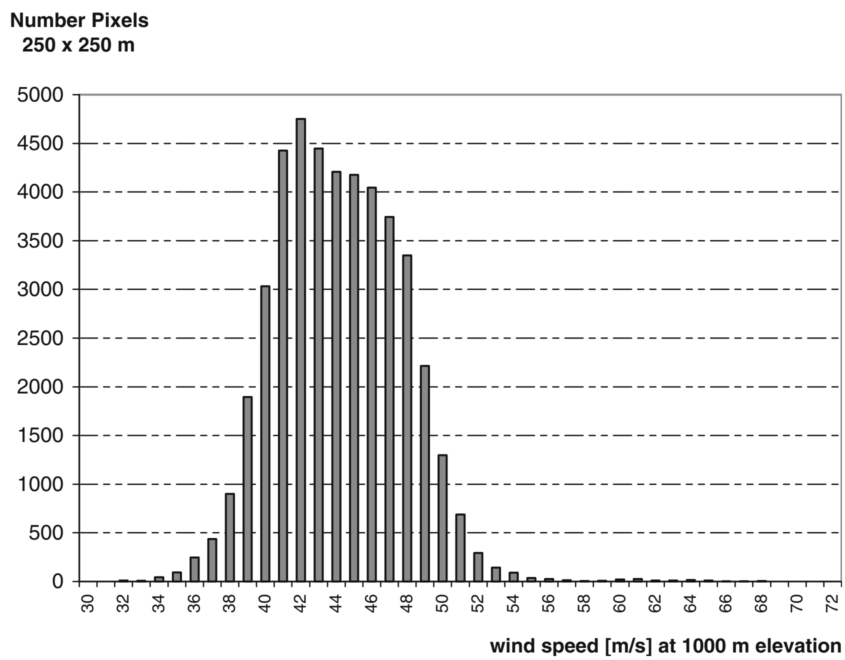
A multiple stepwise linear regression analysis of the interaction between wind speed and the occurrence of such damage emphasises unexpectedly weak correlations of $R^2 = 0.08$ for damage in the extended area. For the principal data set wind speed had no significant influence on the damage of spruce stands. For beech stands, the influence is statistically significant with an R^2 of 0.30. Furthermore, there are relatively weak correlations between different indicators of the wind field such as BOE, TURB, and B.

This shows that there is considerable inner variation during a storm event. The small-scale variation of the wind field structure in spatial and temporal distribution appears to be very chaotic. It is not possible to assess such a small-scale variation successfully using conventional wind measurements. It can be assumed that if radar wind data show the spatial variation at a certain level (1,000 m elevation), it is probably not suitable for representing the temporal heterogeneity of the wind field; nor is it prudent to extrapolate them to any other level than the one where they have been assessed.

It is therefore not surprising that, on the whole, attempts to find a clear causal relationship between wind characteristics and damage failed. One can ask if such a question is realistic at all. In other words it might be better to consider the occurring of damage, say, at a stand level as a strongly stochastic process. This confirms Preuhsler's observations (1991) of old spruce stands (87 years-old): in a thinning experiment, repeated seven times in the same forest in the Bavarian gravel plain after Storm Viviane in 1990, two replications were severely damaged and five showed only dispersed damage.

Under assumption of full randomness, as a coarse approximation one can view the forest as a partition of equal cells (stands), of which a given proportion is damaged according to pure random selection. The probability P for a stand to be damaged by the next similar event can be estimated by the proportion of the forest area damaged in the first event. Recall that under independence and stationarity the probability Ps that a storm occurs in a given year is related to the associated expected return time Ts, in years, by the equation Ps = 1/Ts. Thus, if, say, 2.5% of the forest area is damaged and

Fig. 1 Frequency distribution of maximum wind speeds from Doppler radar measurement, at 1,000 m elevation a.s.l. during the peak of the storm (26.12.1999, 10:04–13:29)



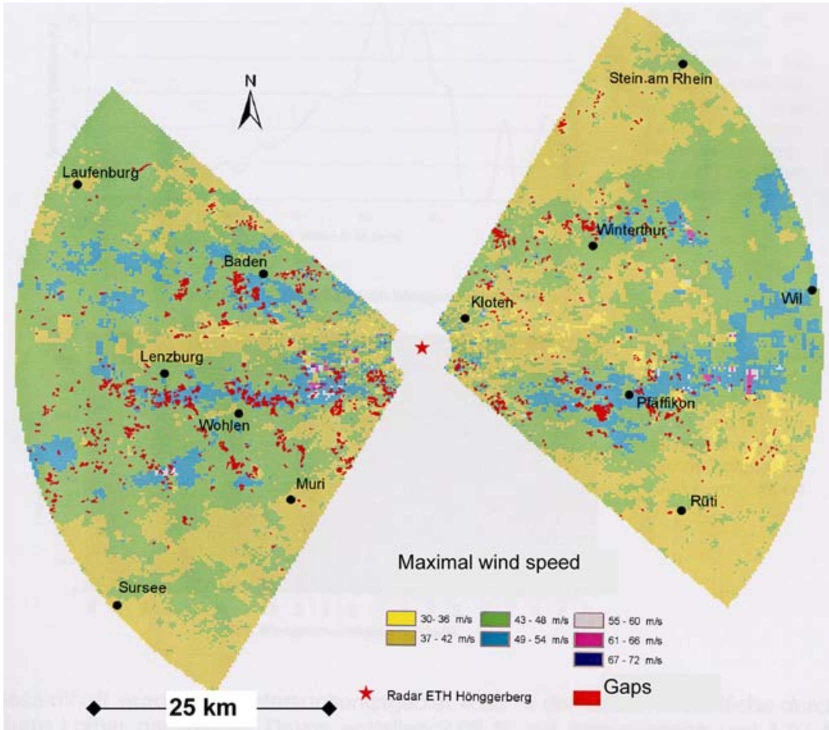


Fig. 2 Pattern of the maximum wind speeds at 1,000 m elevation, assessed from Doppler radar data during LOTHAR maximum development at Zurich Hönggerberg (neighbourhood of Zürich). The distribution of severe stand breakdown (over 1 ha width) is shown in *red*

the recurrence interval of LOTHAR is about Ts = 15 years (according to Gumbel's extreme value distribution; BUWAL 2001), then the probability that a given stand is affected in the second event, conditionally on the fact that it has been damaged in the first, is given by 0.025×(1/Ts) = 1/600, with a return time of 600 years.

Forest damages patterns

Variation

Whichever independent variable was used (development variable such as age, dominant diameter DO,or top height HO, wind field variable or topographic variable), we can observe a great variation of the damage index (IL). There was no clear correlative relationship between damage and top height in spruce and beech. (Fig. 3)

This is consistent with damage report from France (Bock et al. 2004; Angelier and Francois 2004), where a more or less random distribution of damage from a threshold of 28.5 m (for fir) and 24 m (for beech) occurred. It suggests that top height does have a discriminating effect, but that over the threshold for the first damages, there is no clear correlative effect on the phenomenon itself. It suggests moreover that pure hazard predominates. Our survey design, with the exception of young stands, does not allow the determination of such a damage threshold at least for spruce. For beech the threshold lies by DO = 40 cm (HO = 28 m).

The frequency of the damage index, split into ten classes (Fig. 4), demonstrates the unevenness of the

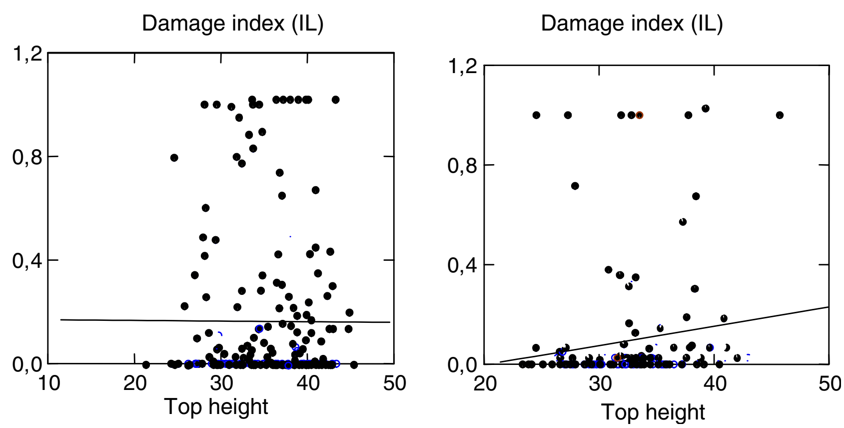
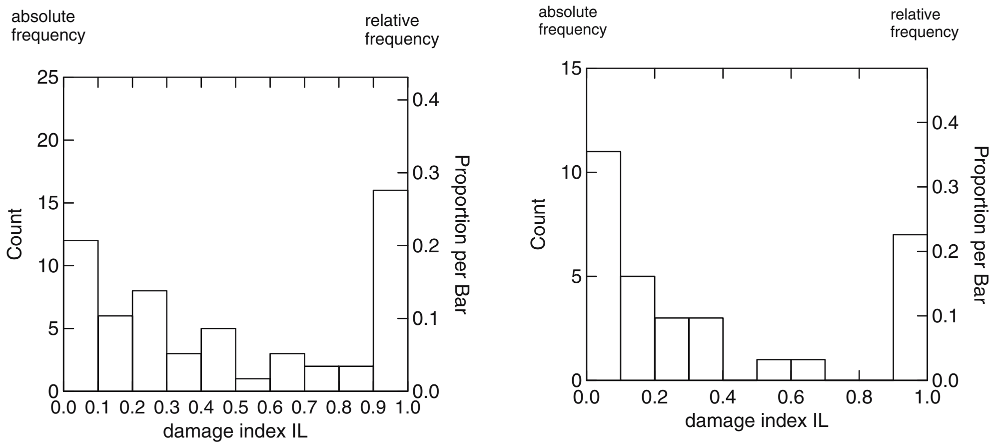


Fig. 3 Distribution of the damage index (IL) in relation to top height (Ho) for pure spruce stands (*left*) and beech stands (*right*). The *line* indicates the fitted linear regression

Fig. 4 Distribution of the damage index frequencies for pure spruce (*left*) and beech stands (*right*). Untouched stands have been excluded. In the case of even distribution, every class would reach a proportion of 0.1



distribution, with a clear decrease in recorded damage as canopy opening increases, followed by a peak for totally disrupted stands. This supports the hypothesis that the probability of stand collapse increases above a threshold of stand closure loosening (presumably about a closure of 0.4–0.5) because inner coherency is lost.

When considering stability, the main question which arises is: at what threshold (in terms of canopy opening or gap size) does destabilisation begin? From the point of view of airflow physics and tree behaviour, wind tunnel experiments showed that the creation of gap openings is more likely to generate turbulence which leads to stand destabilisation, than uniform opening of the shelter would (Gardiner 1994; Stacey et al. 1994; Gardiner et al. 1997). It seems that the risk of destabilisation starts once a gap with a diameter of one tree height appeared (0.1–0.2 ha size for our site conditions). Otherwise, practical silvicultural experience would lead to the conclusion that the destabilisation threshold of regular canopy openings occurs at around 0.4–0.5 of fully stocked stands (Mitscherlich 1974).

We can assume that the first trees to be eliminated in dispersed damage cases are the instable ones (because of their poor anchorage, i.e. after fungi infections or because of their extreme slenderness). The pertinent questions then are: how does the disturbance chain proceed in regular distribution of individual damage or by creating gaps? In the first case, where regular (systematic) loosening occurs, to what point of liability does this continue? Or are gaps created, and if so, of what size? According to footage from three films, it seems that initially (i.e. after the first heavy gusts), individual trees fell down in spruce stands, without showing a domino effect. Other individual damage was caused by subsequent gusts. Only after some dissipation of the main networking framework, from so-called "skeleton-trees" (the most stable ones), were gaps created, followed by total dissolution if wind gusts continued.

Damage assessment threshold

Figure 5 examines the changes in damage proportions (in terms of damaged stand numbers) for the pure spruce and beech stands at different damages thresholds, for two damage indicators: (a) the size of the widest gap and (b) the resulting canopy closure opening (IS).

The number of threatened stands decreases as the threshold increases. If we assume a gap width of 0.2 ha to be the determinant limit, 35.3% of the pure spruce stands have been damaged versus 11.2% for beech (giving a spruce/beech ratio of 3.1). At a threshold of 0.5 ha, the proportions are 26.5% for spruce and 9.8% for beech (a 2.7 ratio). At a canopy opening >0.5, 24.7% of pure spruce stands are badly affected versus 8.9% for beech (a 2.8 ratio). About 18.6% of spruce stands and 4.9% of beech (a 3.8 ratio) are completely destroyed. From this we can deduce that pure spruce is 2.7 to (over) 3 times more vulnerable than beech.

These are key considerations when estimating how likely storm damage is to reoccur at the stand level, assuming complete randomness. For our data set we have a damage proportion of 35% (for the creation of gaps over 0.2 ha in spruce stands (Fig. 5). Because our data set comprises solely early mature to mature stands (aged between 60 and 120 years), this damage proportion should be related to the whole stand life span

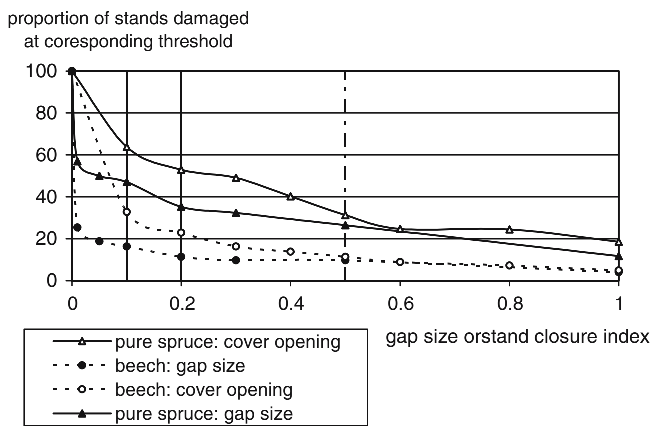


Fig. 5 Cumulative proportion of the number of stands damaged at different thresholds of relative stand closure (index IS), or the presence of different sized gaps (in hectares) for pure spruce stands and beech stands

(120 years). For the whole life span this makes a proportion of 0.35/2 or 17.5%. Therefore, the probability of return time at stand level is (1/0.175)×15 = 86 years. Using a different threshold value (gaps of 0.5 ha), the result would be 113 years (1/26.5)/2)×15. For beech, the development stage I (DO 30–40, upper age limit 75) shows no damage (statistically significant from development stage classes II and III). The risk of damage begins at development stage II (DO 40 cm). This corresponds to a life span proportion of 37.5%. Using a damage threshold of 0.2 ha gaps, the calculated risk of storm recurrence at stand level gives 1/(0.375×0.112)×15 = 357 years (for a gap threshold of 0.5 = 408 years). These results are consistent with recurrence risk calculations for Scotland by Quine and Gardiner (1998), which fall between 70 years for exposed positions and 300 years for less exposed sites.

Gap distribution

The distribution of gaps after storm disturbances is well known in forest literature, and has been the key argument for the different regeneration theories of pristine natural conifer forests (i.e. Sernander 1936; Runkle 1982; Liu and Hytteborn 1991; Foster and Boose 1992; Quine 2003), where gaps are considered to be randomly distributed. After a storm event, the pattern of gap size distribution follows a sharply decreasing exponential function; i.e. in terms of gap numbers, there are more small gaps and fewer large ones. The distribution of gap numbers in our case (Fig. 6, cumulative representation) corresponds well to observed damage in conifer plantations, for instance in Scotland after Quine and Bell (1998). About 80% of the gaps are smaller than 1 ha.

One key issue is the comparison of gap size and wind characteristics (Fig. 7). For spruce stands (where the proportion of spruce is > 80%) there was no clear correlation between gap width and maximal wind speed,

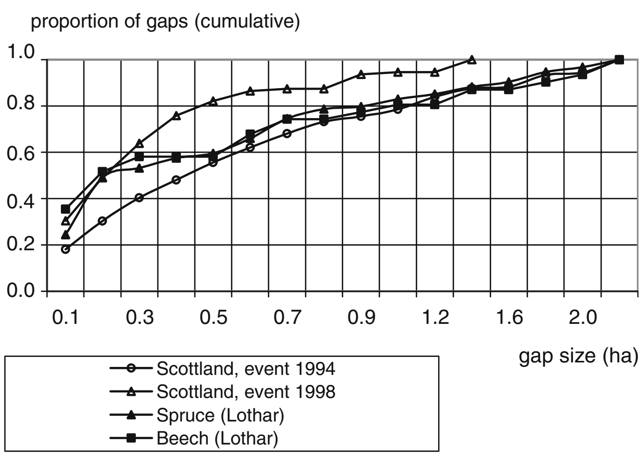


Fig. 6 Gap size frequency (cumulative). Comparison between spruce and beech with two storm events in Scotland (after Quine and Bell 1998)

which corroborates the statistical independency between these variables. The same can be said for wind gusts (variable BOE45; results not presented). For beech, on the contrary, there is a clear borderline significant difference between class 1 and 5.

The same kind of analysis has been carried out for the extended perimeter (where damage types have been assessed on the basis of aerial photos, and include both dispersed damage areas and severely damaged areas or gaps). The number of considered entities (Number of gaps, $n = 1{,}784$) gives a larger sample for statistical evidence and provides more differentiation possibilities. These results differ from the main study in that stand composition or structure is not considered. A small tendency towards increasing gap width and wind speed is detectable (Fig. 8) but none of the results are statistically significant except between class 1 and 6 (dispersed damages vs. gaps over 2 ha).

Damage types

Both breakages and uprooting occurred during the same damage event. In our study, breakage amounts between 40 and 60% on average for spruce, with great variation from one case to another. It is not yet clear whether breakage or uprooting occurs first, i.e. in the starting phase of stand breakdown. When material response is considered, the rupture strains which lead to both types of damage are more or less the same (Dunham and Cameron 2000). It seems that small differences and material failure can bring about one type more than the other. Our results for pure spruce stands show that the proportion of breakage decreased slightly with the damage index, but more evidently with canopy closure before LOTHAR(Fig. 9), which suggests that the swaying regime has had an influence.

Tree species and mixture

Figure 10 presents the results of the variance analysis for mixture effects. An admixture of 10–20% of broad-leaved tree species significantly improves stability (by a factor of 3.4). This is in keeping with the well-known positive effect of a spruce/beech mixture on stability (Flury 1930; Burger 1941; Kennel 1965; Otto 2000), i.e. because spruce can develop better crowns while assimilation linger during winter time, when mixed broad leaved trees lose their leaves (Schütz 1989). The improved stability of spruce in the mixture is largely recognised, except for where spruce dominates the canopy (Lüpke and Spellmann 1997, 1999). The effect of Douglas fir on increasing stability is interesting. It lies in the same order of magnitude as broad-leaved trees (a 3.5-fold effect). Because of the small sample number (18 stands) these results can only be confirmed at a level of $P = 0.10$. They may be attributed to high timber quality (module of elasticity for Douglas fir is 37% better than spruce), a better stem form and anchorage.

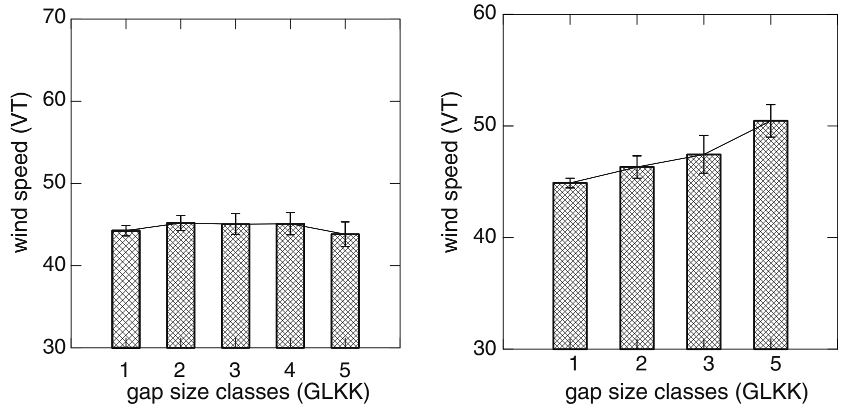


Fig. 7 Analysis of variance of dependence between gap size classes and wind speed in spruce(*left*) and beech (*right*). Gap size class GLKK: *1* no gap, *2* size 0.01–0.3 ha, *3* 0.3–0.99 ha, *4* 1.0–2.5 ha and *5* ≥2.5 ha

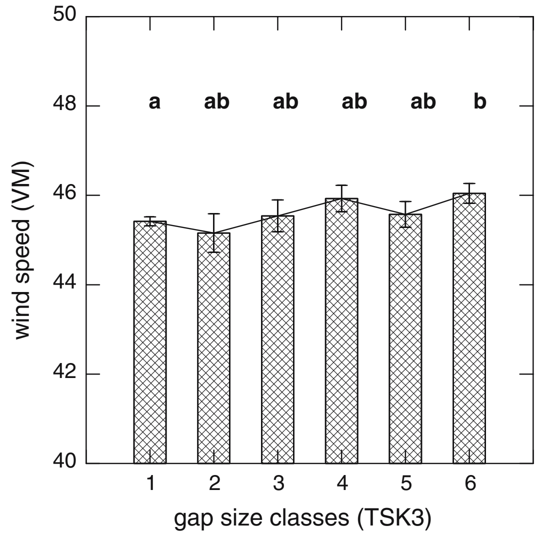


Fig. 8 Analysis of variance between gap size and wind speed for the larger perimeter (forest area 65,000 ha, 1,842 contiguous forest entities). Classes: *1* dispersed damages, *2* gap size 0.2–0.6 ha, *3* 0.61–1.0 ha, *4* 1.01–1.4 ha, *5* 1.41–2.0 ha and *6* >2.01 ha. Differences significant between classes 1 and 6 ($P = 0.006$)

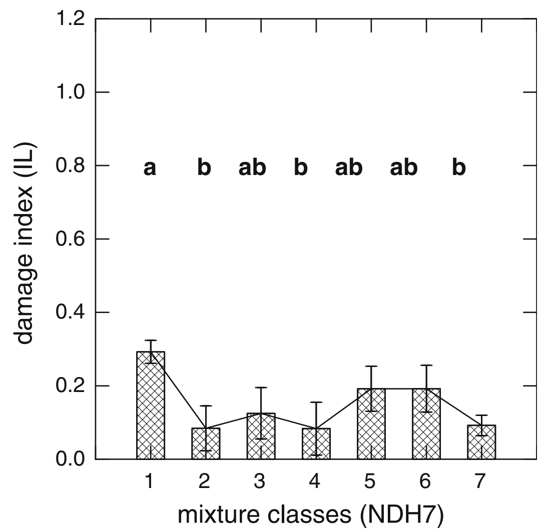


Fig. 10 Effect of tree mixtures on damage index: ANOVA with different mixed species and proportions. Mixtures classes with different letters were significantly different at $P = 0.10$. *1* Pure spruce/fir (≥ 90%) *2* rich spruce/fir (80–89%), *3* dominant spruce/fir (70–79%), *4* admixture douglas fir (≥5%), *5* admixture larch (≥5%), *6* admixture pine (>10%) and *7* broad leaved (≥80%)

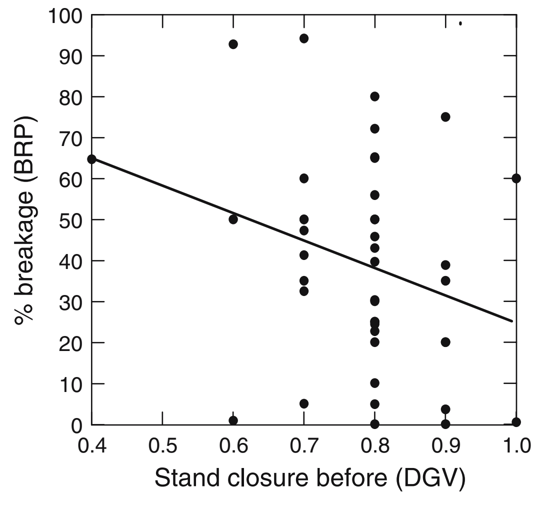


Fig. 9 Breakage ratio for pure spruce stands in relation to stand closure before LOTHAR.Regression coefficient significant at $P = 0.058$; $R^2 = 0.084$

Practitioners recognised that Douglas fir trees generally withstood storms (Drouineau et al. 2000; Bosshard 1967) particularly on enough permeable soil conditions suitable for Douglas fir anchorage. This was evident in our interviews with the rangers. Larch or pine did not prove to be of statistical significant influence.

This result is of paramount importance for silvicultural practice. It shows that stability can be improved efficiently by using mixture regulation during the first development stage.

Multifactor analysis

An analysis of interdependence between different vulnerability factors using stepwise linear regression models provides: (a) very weak correlative overall effects (measured with R^2) and (b) the elimination of nearly all variables with no significant effect. So, for pure spruce

Table 1 Results of stepwise multiple linear regression for pure spruce stands

Dependent variable: LIL, n: 93, multiple R: 0.3119 $R^2=0.0972$, adjusted squared multiple R: 0.0668, standard error of estimate: 2.84

Rank	*Effect*	*Coefficient*	*Standard error*	*t*	*P (Two tail)*
	Constant	−10.0925	3.894	−2.59	0.011
1	EXKL aspect classes	−0.4034	0.192	−2.09	0.039
2	HO top height	0.1319	0.067	1.94	0.054
3	DGV cover before Lothar	4.737	2.980	1.59	0.115 n.s.

Dependent variable: LIL (log transformated damage index). Other nonsignificant variables, in decreasing rank of factor influence: TURB ($P=0.30$), B40D (HD slenderness, $P>0.50$), KPR crown proportions ($P>0.50$), MUM elevation asl ($P>0.50$); with $P>0.80$: BOE45, EGV thinning intensity, NG slope, VT wind speed ($P=0.99$) Regression technique: stepwise backward

stands (Table 1), only aspect and top height were clear indicators (although the latter was just not significant). Stand density before LOTHAR also had some indicative power. Neither wind characteristics nor h:d (ratio of slenderness) proved to be significant. The overall explanatory strength of the model explains only 7% of the variance. Such results are compliant with other comparable studies (Lohmander and Helles 1987; Schmid-Haas and Bachofen 1991; König 1995; Valinger and Fridman 1997; Redde 2002). They support our statement of high stochasticity of the stand failure phenomenon and suggest a complex interaction between predisposition and trigger effects.

The fact that the h:d factor is of negligible influence is worth mentioning. This is consistent with the results of similar studies carried out recently (Schmid-Haas and Bachofen 1991; Redde 2002). These authors like others agree that the h:d factor is not a valid indicator for stability against storm damage (Dunham and Cameron 2000). If anything, it can be used more to indicate vulnerability to snow damage rather than to wind.

Table 2 Results of stepwise multiple linear regression for beech stands

Dependent variable: LIL, *n*: 99, multiple *R*: 0.543 $R^2=0.295$, adjusted squared multiple *R*: 0.273, standard error of estimate: 2.17

Rank	*Effect*	*Coefficient*	*Standard error*	*t*	*P (Two tail)*
	Constant	−17.4701	2.871	−6.08	2.4×10^{-8}
1	V6 wind speed	0.5041	0.093	5.41	4.7×10^{-7}
2	EGK year after last thinning	−0.2506	0.116	−2.16	0.033
3	HD slenderness h:d	0.0440	0.023	1.87	0.064 n.s.

Dependent variable: LIL (log transformated damage index)

For beech stands (Table 2) the correlation effect is much higher, contributing 27% of the overall variance and emphasising the highly significant effect of wind speed and emergence of the variable years after the last thinning. Just nonsignificant arise the factor h:d.

The differences between spruce and beech can be interpreted as a different impact of the wind. In the first case (spruce), the chaotic and intricate reaction during short heavy gusts could be decisive, as it determines the factor of stand cohesion and so whether the stand fails or not. In the second case, the decisive factors could be the long-term strain of swaying and the resultant material fatigue or loosening of soil cohesion. Swaying or shaking experiments (White et al. 1976; Rodgers et al. 1995) showed that after a long time, the soil around swaying trees can lose its properties and the swaying behaviour of the trees changes.

Predisposition factors from relief

A stepwise linear regression analysis for our main study (i.e pure spruce and beech stands) shows that the explanatory value of the considered relief variables (aspect, slope, altitude) is weak if the variables are considered separately. For spruce, it explained only 2% of the variance. Aspect alone stands out as a significant variable. For beech, the explanatory power of the model

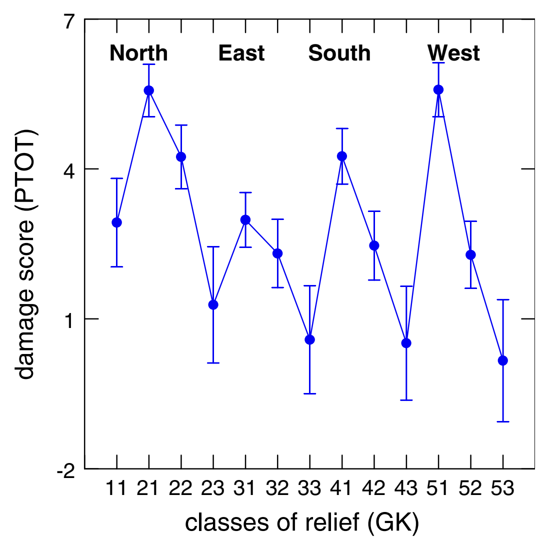


Fig. 11 Results of the analysis of variance between aspect classes of different gradients and damage score (percentage of gap and dispersed damage area) within the extended perimeter. Classes: *11* flat ($N=197$), *21* *N*-slope gentle (1–19% scant) ($N=561$), *22* *N*-slope steep (20–49% scant) ($N=379$), *23* *N*-slope very steep (>50%) ($N=114$), *31* *E*-slope gentle ($N=515$), *32* *E*-slope steep ($N=331$), *33* *E*-slope very steep ($N=132$), *41* *S*-slope gentle ($N=499$), *42* *S*-slope steep ($N=326$), *43* *S*-slope very steep ($N=119$), *51* W-slope gentle ($N=528$), *52* *W*-slope steep ($N=343$), and *53* *W* slope very steep ($N=103$). Significant differences at level $P=0.05$: classes 51 to 23–31–32–33–42–43–52–53, 21 to 23–31–32–33–42–43–52–53

was 14% of the variation and the significant variables were aspect ($P=0.001$), aspect×slope ($P=0.01$), and elevation ($P=0.02$).

As far as the influence of relief on storm sensitivity is concerned, previous studies suggest an interaction between slope and aspect. For instance, in the same region of the Swiss Midlands after Storm, Schmid-Haas and Bachofen (1991) showed a concentration of damage in relatively flat forests compared to steeper slopes, which were much less damaged. To address this issue, we analysed variance at the level of forest massifs entities (subdivided into 13 relief classes) on the basis of aerial photographic gap assessment within the extended perimeter. The larger unit numbers ($n=4{,}147$) allow for a statistically more differentiated response. However, these results do not distinguish between tree species or stand structure because data comes from large-scale photogrammetrical base. The response variable here is the damage score, measured as a percentage of threatened forest areas (gaps and dispersed damage), Fig. 11.

The results clearly confirm the reducing effect of steep slopes on vulnerability. There are clear differences in sensitivity for gentle, steep, or very steep slopes. For wind facing slopes (westerly), damage ratios were 6:3:1 for gentle, steep, and very steep slopes, respectively. Similar tendencies were found for other aspects, though they are not statistically significant in every case. Gently sloping wind exposed slopes display 2.2 times more damage than the average and 2 times more than gentle easterly slopes, which are protected from the wind. Southerly slopes show intermediate damage, and northerly slopes are similar to west exposed ones.

The considerable differences caused by gradient are also of interest. They can be interpreted in such a way that trees on steep sites are more exposed to wind forces. They adapt by developing larger roots. This phenomenon is well known as adaptive growth, (Coutts 1983; Stokes et al. 1995) or thigmomorphogenis (Jaffe 1973).

Triggering factors

Our study revealed some likely indications of how the presence of previous gaps (intentionally created or not), and borders with neighbouring stands affect damage susceptibility. Our very small sample means that we do not have definitive proof, though this factor seems to be one of the most credible triggering factors, according to previous studies (Bosshard 1967). Wind tunnel experiments have shown that the risk of destabilisation increases significantly with a gap width of one to two times the height of dominant trees (Gardiner 1994; Stacey et al.1994). Moreover, by studying gap formation and extension after storm events, Quine (2003) showed that a new storm creates new gaps as well as enlarging existing ones, even if enlargement occurs more often than new gap creation.

The distance to forest edge, recorded in both lee and luff directions, also fails to provide significant results. Our results showed a tendency towards increased damage at a distance of two to three tree lengths behind the forest edge (leeward). This is in keeping with experimental wind tunnel results (Stacey et al. 1994; Foudhil et al. 2003).

Influence of thinning

It is not easy to determine how silvicultural treatment influences storm susceptibility, because thinning brings with it both positive and negative effects. One positive effect of thinning is its preventive function over time: the thinning regime improves stem form and anchorage. On the other hand, it is widely recognised that stand stability can be reduced after heavy thinning. In fact, some studies have shown that the length of time after thinning is a relevant independent variable when considering damage (Persson 1975; Lohmander and Helles 1987; König 1995). Other studies negate that the most recent thinning has an effect on susceptibility (Schmid-Haas and Bachofen 1991; Redde 2002). These contradictions are not surprising, as results will vary depending on the kind of thinning regime used. Negative effects will prevail after an intervention in situations with late commencement of thinning operations, less frequent thinning from below. In countries such as Switzerland with intensive thinning regimes in terms of early commencement, frequent return and thinning from above, the destabilisation factor should be less significant. In our study, the most recent thinning operations did not appear to be significant for pure spruce stands, both in terms of thinning intensity and number of years after thinning.

Conclusions for silvicultural practice

Analysis of the spatial and temporal variability of the wind field, damage patterns and the overall explanatory power of different variables suggests that storms of this magnitude are highly chaotic and their effects are therefore largely unpredictable. The overall determinative power of independent variables was unexpectedly weak, especially in the case of pure spruce stands ($R^2<0.10$). This allows us to suggest that the high susceptibility of spruce (three times more than beech) depends on its sensitivity to destructive repeated gusts, in which occurrence is highly stochastic. Beech stands appear to be somewhat more predictable, possibly because not single gusts but long swaying time could be responsible for damages.

This leads to the conclusion that avoidance strategies based on reduced rotation time are not particularly realistic. A worst case scenario estimation (pure spruce stands) of the likelihood of a storm of similar magnitude to LOTHAR reoccurring on a stand level works out at a return time of between 75 and 115 years. This assumes full randomness, and variation depends on the damage threshold used. For other tree species or stand conditions, the return time lies well (several times) above the rotation. Even if the return time of such a storm is much shorter on other scales (i.e. forest enterprise), any strategy which aims to reduce the rotation seems somehow misplaced because of the relatively small threatened forest area (about 2.5% on average), and because age (respectively height), from a certain threshold on, does not have a significant causal influence on vulnerability. Whichever the assumptions, reducing rotation on the whole forest needs hardly unrealistic interventions in relation to a rather low diminution of the risks. Other strategies which aim to avoid sensitive species (spruce, fir) on sensitive sites (wind exposed gentle slopes), or which favour mixtures or stability (thinning) seem to be much more realistic.

The promotion of mixture seems to be a very effective and sound measure. Even a mixture of 10% of broadleaved trees or wind-firm conifers like Douglas fir (or possibly larch) greatly reduces storm vulnerability, conditional that the soil properties are convenient for their anchorage. Promoting mixture is not only a core decision for stand establishment but is also achievable at the level of tending operations.

The negative effect of thinning does not emerge clearly as an explanatory variable in regression models. Its long-term impact can be nevertheless considered as valuable. The very question of thinning must be differentiated because stability as a concept relies on different interactions: individual stability versus collective stability, enhanced by reducing tree swaying using neighbours in closed stands. The key to effective thinning is to enhance stability factors (stem form, crown) without loosening stand cohesion. Both thinning intensity and the method used to liberate the crown of concerned crop trees are important because they determine the overall canopy opening, at least in young stands. Because young stands under a certain height (corresponding to an age of 60 years for spruce and 75 for beech) are not threatened by storms, thinning in young stands does not have any negative effects, and so is fully effective. Nowadays, less traumatic thinning methods are also available, especially for young stands. These so called situative thinning (Schütz 2003) aim to liberate punctually and socially according to the intrinsic stability of the crop trees, and are therefore more efficient. The effect of thinning on stem or crown form is largely recognised (Nielsen 1990, 1991). This means that thinning, the more so as it is not begun too late, still appears to be an effective measure for improving stability.

The fact that irregular forest (i.e. spruce-fir mixed planter forests) turned out to be significantly more resistant to LOTHAR than regular forest (Dvořak et al. 2001) supports this finding. Belated thinning could bring about destabilisation and act as a trigger for stand failure. New insights into airflow over a forest (Gardiner 1994; Stacey et al.1994) show, however, that the presence of gaps (or edges) is more likely to induce destabilisation than regular opening of the canopy. Therefore, gaps or inner edges seem to trigger vulnerability more than regular canopy openings stand loosening. This raises the issue of how to lead regeneration. For sensitive species, such as spruce, gap opening does not seem to be an appropriate method for slow natural regeneration, but should be substituted by edge felling progression against or parallel to wind direction.

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