2.3.

Influence of stand characteristics and landscape structure on wind damage

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Introduction: Key factors influencing vulnerability to wind damage

The risk of wind damage to forest stands is mostly a combination of wind climate (e.g. average and gust wind speed and wind direction: see Chapter 2.1), tree and stand characteristics as controlled by silvicultural management, site characteristics and factors increasing stand exposure (see Chapter 2.2).

Two widely acknowledged predisposing factors for storm damage are tree species and tree or stand height. Other important characteristics influencing wind damage risk to individual trees or forest stands are the relation between the tree diameter and tree height (referred to as h/d-ratio), crown length, root rot, stand density and structure. Other site related characteristics of importance include exposure (e.g. topography, upwind clear cuts), aspect, slope, water regime and soil texture. Tree and stand characteristics appear to have more impact on tree and stand vulnerability than site characteristics.

Tree species

Tree species can have a noticeable effect on vulnerability towards storm damage. Comparisons with respect to tree species are limited since no approach is currently available that covers the entire variety of species groups. However, statistical analyses of damage suggest that conifers are more susceptible to damage than broadleaves because of the higher drag of the evergreen coniferous forests during winter storms when broadleaved species are leafless. From an analysis of damage caused by the storm "Lothar" there was found to be a decreasing probability of storm damage to single trees from Norway spruce, which was the most vulnerable, to Silver fir/Douglas fir to European pine/larch, beech/oak and other broadleaves, which were the least vulnerable (see Figure 14). In Scandinavia the probability of damage was found to decrease from Norway spruce to Scots pine to birch. A similar ranking of species has been found by a number of researchers including following analysis of the severe storms in December 1999 in France (see Table 1 in Chapter 4.2). These analyses suggest that in general poplar and spruces appear to be amongst the most vulnerable and Silver fir, European pine, beech and oak amongst the least vulnerable species. However, very recent studies suggested Douglas fir is as vulnerable as Norway spruce, so it is important to realise that species

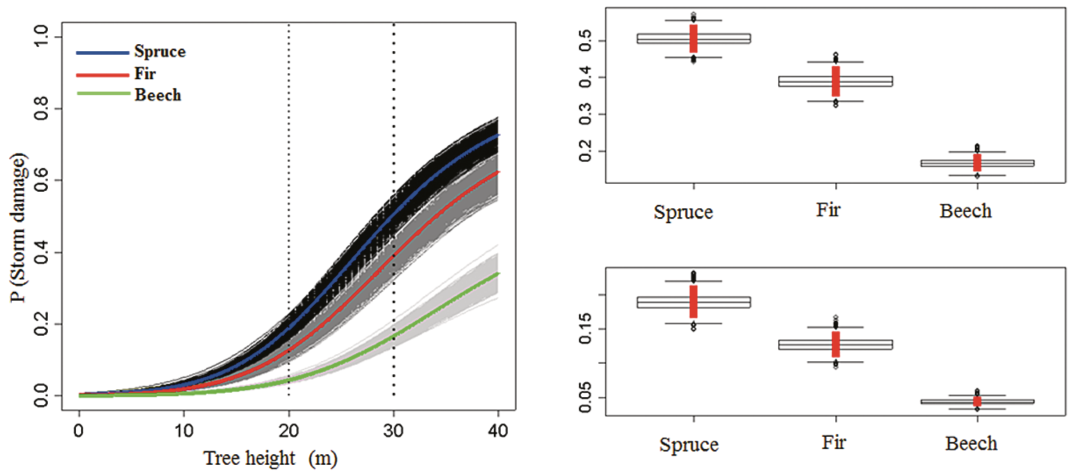

Figure 14. Damage probability for different tree species from analysis of damage in storm Lothar.

differences are not yet fully quantified and the exact order of species vulnerability is not certain and probably depends on location and soil. As always planting species adapted to the soil and climate of a location should be a priority.

Species differences

Spruces and poplar appear to be among the most vulnerable to storm damage and Silver fir, European pine, beech and oak among the least vulnerable.

Tree height and related parameters

Many statistical and mechanistic model approaches predict an increase in damage probability with increasing tree height although the impact varies with species. In many mechanistic models stem taper (height/diameter ratio or h/d ratio) is also identified as being important in controlling storm damage vulnerability (see Chapter 2.2). Other factors such as stem volume, mean diameter, volume indices and stand age have also been found to be good predictors of the probability of damage in post storm damage empirical analyses. However, height (in particular dominant height) has an advantage over other factors as a measure of vulnerability because it is relatively independent of silvicultural treatment and, even though height is generally more difficult to measure than stem diameter, recent advances in airborne LiDAR[1] allow measurement of the height of every tree in a forest at a relatively low cost.

1 LiDAR: Light Detection and Ranging: Remote sensing method allowing detailed examination of the surface of the Earth

Stem taper (h/d-ratio)

The effect of an increasing damage probability with decreasing taper or increasing height/diameter at breast height ratio is described in many investigations The impact of taper on the probability of stem breakage or uprooting is usually not possible to include within statistical models due to a lack of a reliable and comprehensive enough database. However, the effects of taper on stem breakage and uprooting probabilities can be evaluated using mechanistic models. It should be noted in this context that stem taper is influenced by thinning and thus often used as an indicator for stand stability and individual tree stability prior to a thinning (used to select the most vulnerable trees for removal).

Another source of evolution of taper over time is a tree's natural growth pattern with fast height growth in the early stage and decreased height growth with maturity. Thus, older trees naturally have lower h/d ratios. It is important to consider tree or dominant stand height as an indicator of wind loading first and then, in a second step, to analyse the impact of taper on stability. Considering only the effect of taper on storm risk without considering the effect of height may lead to false conclusions on the stability of stands.

Lower h/d ratios, which have been found to indicate lower risk of snow breakage and therefore indicate better individual stem stability are not necessarily a sign for higher stability in general. Lower h/d ratios coincide with larger crowns and thus increase the windload or drag of trees. Therefore, the h/d ratio may affect storm risk in opposing directions. The evidence from different studies is that h/d ratio is not always a good indicator of stand storm resistance although it is probably a good indicator of individual tree relative stability within a stand.

Management operations

Silvicultural interventions can influence storm risk in many ways. In the long term, the choice of tree species (see above) and rotation age or target diameter determine the principal risk predisposition of forest stands. Second, the effect of rotation age or target diameter on storm risk is the result of the associated increase in tree or stand heights, which are also correlated to age. In addition, thinning also influences storm risk. When performed at an early stand age, thinning has the effect of increasing the stability of individual trees. This has been ascribed to increased growing space for individual trees promoted through thinning that improves development of structural roots and stems. In taller stands, however, thinning tends to temporarily destabilize stands, mostly by disrupting the canopy and increasing its aerodynamic roughness. Since the canopy recloses again usually between 2 and 8 years after a thinning, this temporary destabilization affects the risk of damage to stands in the short term. While thinning has been recognized as a risk factor, it remains uncertain how important the effect of this silvicultural intervention is when compared to other known factors influencing storm risk such as tree species, tree height, height to diameter ratio and site conditions. There is evidence that late moderate to heavy thinning can increase vulnerability, while pre-commercial and light thinning at regular intervals can improve storm resistance.

Timber removals are often found to destabilize stands if they remove dominant trees. This observation is plausible since dominant trees usually have a better developed structural rooting system than co-dominant, intermediate or suppressed trees and may therefore form a stable ''skeleton'' or ''scaffolding'' for the stand. Removing these firmly rooted trees leaves the less stable individuals in the stand. In addition, these less stable trees are also then exposed to higher wind loads, since removing the taller dominant trees increases the wind speed in the canopy of the sub-dominant trees, because the sheltering effect of the dominants is removed.

There is evidence of augmented storm risk with increasing volumes of removed timber probably due to a temporary disruption of the canopy surface, which increases turbulence and tree swaying. Other studies also quantified that thinnings in general have a damage increasing effect, but could not state whether this impact was directly related to the amounts of timber removed. However, all these findings indicate that thinning operations temporarily reduce the collective stability. Seed-tree cutting (felling) and special cutting (tree felling for ditches, roads or power lines, or sanitation cutting after damage) may also increase the probability to storm damage because of the gaps they open in the canopy (see Chapter 2.2).

Important Stand and Management Factors

Tree height is the single most important factor indicating stand stability with trees increasing in vulnerability (lowered critical wind speed) with height.

Height to diameter ratio is not always a reliable indicator of stand stability but can be a good indicator of the relative stability of individual trees within a stand.

Heavy thinnings, especially late in a rotation, will increase the risk of wind damage

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Soil characteristics

Soil properties are known to affect the level of impact of storm damage. This is true for spruce, particularly for those rooting in soils where oxygen availability is severely restricted by temporary waterlogging (see Figure 28). It has been suggested that the occurrence of waterlogged soils is one possible factor responsible for the increase of storm damage in Europe. Soil water balance is thus used as a significant predictor in storm damage modelling. Very wet (peaty) humus forms were found to have equally significant effects on storm damage as waterlogged soils.

It was also found that storm damage increased with a growing deterioration of the humus form, which usually leads to higher soil acidity. Although the mechanisms behind the relation between storm damage and soil acidity are not completely understood, soil acidity is considered a significant risk factor for storm damage.

Terrain characteristics

Investigations of damage caused by the 1999 storm Lothar in the Northern Black Forest showed the highest levels of damage in passes between mountains, west to east running valleys and westerly parts of the first mountain range. This matched a statistical analysis of the same storm which showed a higher frequency of damage on westerly exposed sites.

Other studies have given contrasting importance to wind speed and topographic shelter variation in explaining storm damage locations, with some studies finding highest damage where the wind was least gusty and the shelter highest. This may be as the result of tree acclimation, with trees growing in the most exposed locations being more stable than trees which are normally well sheltered from the wind and which can be badly exposed under very strong storm conditions.

Important Site and Terrain Factors

Anything that reduces rooting depth can increase the risk of wind damage

Waterlogging of soils increases the vulnerability of stands

Trees on acidic soils appear to have an increased vulnerability to wind damage

Passes between mountains are found to have increased damage

Valleys running from west to east have higher damage levels in storms (for storms with strong westerly winds)

The first westerly slopes on mountain ranges are susceptible to increased levels of damage (for storms with strong westerly winds)

Stand structure

Stand structure is probably one of the most difficult parameters to assess and include in storm risk predictions. Wind tunnel and airflow modelling studies have shown that the structure of the stand affects the shape of the wind profile with implications for the wind loading of individual trees under different forest configurations.

Empirical modelling studies suggest that on sites of moderate exposure, an irregular stand of spruce is more wind stable than a conventionally thinned regular stand, although the advantage disappears with increasing exposure. Hence, irregular stands may provide structures with more stable characteristics, but these cannot be considered in isolation from the prevailing wind climate and the local site type.

As the current versions of mechanistic models predict the risk for the mean tree within a stand or at its newly created edge, it should be noted that this approach only works well for regular, single species stands. In heterogeneous stands different trees will not necessarily have equal risk. Furthermore, these models do not capture the process of wind damage in real stands. In reality, the failure of one tree alters the wind regime for its neighbours and may make it more liable to damage and recent model developments now incorporate this process.

Wind risk models
Models support the calculation of the wind risk in forests. Empirical models are based on statistical evaluation of damage in stands after a storm whereas mechanistic models use engineering principles to calculate the risk. Empirical models are more accurate for forests in the area where they were developed (e.g. the empirical model "Lothar" is applicable in Central Europe). Mechanistic models are more adaptable to different forest conditions and allow incorporation of the impacts of a changing climate. They are available (e.g. "ForestGALES", "Hwind", "FOREOLE") for the major conifer species growing in Europe but not currently for broadleaf species.

Surrounding forest

Several studies strongly advocate a significant influence of edge structure and upwind forest gaps on damage probability. Upwind gap size, distance from upwind stand edge and the length of the forest edge have been shown to be important factors in predicting levels of damage (see also Chapters 2.1 and 2.2). The structure of the forest edge might also be important but this is often difficult to assess or such information is rarely available (see discussion in Chapter 2.1). For more than one century the optimization of the so-called "spatial order" (the spatial position of different forest stands to each other according to their age and height) in order to minimize storm damage was a crucial goal of forest management planning in parts of Central Europe. From recent storm damage the success of aiming to always locate the oldest stands in downwind positions by means of long-term "intelligent" cutting regimes appears to be very limited.

Importance of different variables

Overall forest stand characteristics were found by statistical analysis after several storm events to be more important for predicting long-term storm damage than soil, site, topography or wind speeds during a storm. Tree species and average tree or stand dimensions, especially height, have been found to be the most important factors controlling storm damage in the forests typical of central Europe with small-scale harvesting interventions (typically single tree selection) or managed with "close-to-nature" systems and with long rotation periods.

In contrast, in short-rotation clear-cut systems more typical of northern Europe there is less variation in tree height within stands and these systems are also usually monocultures with clear-fell replanting regimes. In these circumstances variations in individual tree shape as indicated by taper are likely to be more important and the impact of upwind clear fell areas has been found to be extremely important.

Potential management activities to reduce storm damage

These are discussed in detail in Chapter 4.2 but some general rules that can be determined from observations of actual wind damage in forests are summarized in the highlight box below.

Important Factors Affecting Risk of Wind Damage

General Observations

- Conifers appear to be generally more vulnerable than hardwood species.
- Spruce and poplar are among the most vulnerable species
- Silver fir, European pine, oak and beech are amongst the least vulnerable
- Waterlogged soils or soils with restricted rooting increase the vulnerability of trees
- Trees on acidic soils are more at risk

In long rotation systems (high final tree height and high target diameters)

- Early thinning to reach target diameters quickly and at lower heights reduces wind damage risk
- Slopes and valleys exposed to the prevailing wind are particularly susceptible to wind damage
- Thinning in the late stages of a rotation increase the risk of wind damage

In short rotation systems using clearfell/replanting

- New edges on the upwind side of stands can produce a large increase in wind damage risk
- Trees with higher taper appear to be the most wind firm within a stand
- Thinning on exposed sites can lead to increased wind damage

Recommended reading

Albrecht, A., Hanewinkel, M., Bauhus, J. and Kohnle, U. 2012. How does silviculture affect storm damage in forests of south-western Germany? Results from empirical modeling based on long-term observations. European Journal of Forest Research 131: 229–247.

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