Nat. Hazards Earth Syst. Sci., 8, 795–803, 2008
www.nat-hazards-earth-syst-sci.net/8/795/2008/

Natural Hazards and Earth System Sciences

Storm damage in the Black Forest caused by the winter storm "Lothar" – Part 1: Airborne damage assessment

J. Schmoeckel and C. Kottmeier

Institute for Meteorology and Climate Research, University of Karlsruhe (TH)/Research Center Karlsruhe, Germany

Received: 15 June 2007 – Revised: 9 October 2007 – Accepted: 20 December 2007 – Published: 1 August 2008

Abstract. An airborne survey of the Black Forest as affected by the winter storm "Lothar" in 1999 is performed by means of a color line scanner (CLS) with a CCD sensor, whose data in a visible and a near-infrared channel provide the Normalized Difference Vegetation Index (NDVI) as a measure of the damage in previously intact forest areas. The camera data, height data from a digital evelation model (DEM), land use information, and soil data are georeferenced and processed in a geographic information system (GIS) to derive relationship of the damage pattern to the characteristics of the local orography and soil types. The data cover an area of 4900 km^2, 2767 km^2 of which were forested. The 363 detected storm damage areas with a minimum detection size of 1.5 ha amount to 0.8% of the total forest area. Visual inspections at certain sites prove that none of the larger damage areas are missed, but areas smaller than 1.5 ha cause the total damage area to be up to twice our result, i.e. ≈1.6% of the forest area. More than 50% of the detected damaged areas are smaller than 5 ha and most of them have a size ranging from 1.5 to 3.5 ha. Forests on slopes with an inclination angle between 10 and 15 degrees show the highest fraction of damaged forest, doubling those on plains and below 5 degrees inclination angle. Forests on northwestern slopes are more affected than those on southwestern and western slopes, which faced the wind during highest wind speed occurrence. In contrast to other studies, this paper shows, that in steep areas, lee slopes are more damaged than the luv slopes. As expected, wet to moist soils represent an unstable location for the trees. But also medium-dry to dry locations that were considered to be relatively stable exhibited a highly damaged forest fraction. This can be attributed to mostly saturated soil from previous rain.

Correspondence to: J. Schmoeckel
(julia.schmoeckel@imk.uka.de)

1 Introduction

On 26 December 1999, many forest areas in France, Germany, Switzerland, Belgium and Austria were strongly damaged by the winter storm "Lothar". A total of 110 people lost their lives. The economic damage amounted to ≈11.5 billion EUR . Above all, roofs, claddings, scaffoldings, cranes, forests, and aerial lines were damaged. In France, more than 4 million households were without electricity up to several weeks in certain regions. Public passenger transport and telephone networks were out of order for similarly long time.

In Germany, the damage concentrated on Southern Germany and in particular on Baden-Württemberg. The winter storm produced 30 million solid cubic meters of waste wood (Odenthal-Kahabka, 2003). This exceeds the average annual use by more than 200%. Hence, damage in the forestry sector was more than twice as high as during the 1990 winter storm Wiebke that had been considered the most severe storm catastrophe in Germany until then. The meteorological causes of the winter storm, its predictability, and the storm development were analyzed in several papers (Kurz, 2000; Ulbrich et al., 2001; Wernli et al., 2002). This study focusses on the variety of factors influencing the damage and the damage patterns caused by "Lothar" in the Black Forest.

2 Forest damage in relation to orography, soil and tree properties

The risks of forests of being damaged by storms were studied in a number of papers. E.g. Mayer and Schindler (2002) give an overview about forest meteorological basics that cause windthrow in woods. A clear relationship between the storm damage of forests and the topographic properties, such as relief, exposure, and altitude above sea level, was found by Hütte (1964) already. Accordingly, all convex areas and in particular upper slopes and mountain ridges are endangered by high wind speeds with little turbulence. Moreover there

Published by Copernicus Publications on behalf of the European Geosciences Union.

are zones in which the speed and turbulence are increased simultaneously by the relief of the terrain. Examples of such endangered zones are the lower slopes of mountain flanks or medium and upper slopes of valleys hit by the air flow after it has crossed the valley.

The relevance of topographic parameters influencing the storm risk in forests was also emphasized by Rottmann (1986). These parameters are the shape of the terrain, especially the inclination of the slope, exposure, slope location, and altitude. These factors may reinforce or compensate each other. The shape of the terrain has the strongest influence, as it may increase or decrease the wind speed and turbulence by deflecting and channeling the wind. Consequently, forests at mid-latitudes on windward slopes or on the complete windward slope with convex bends are in particular danger as well as trees immediately in front of and behind the ridge line and sometimes on adjacent lee-side slope plains. Forests on steep mountain ridges and high plateaus are more endangered than forests on lower slopes, in deep valleys or behind bars on lee slopes.

After the storm "Vivian" in 1990 and "Lothar" several studies were made in Switzerland with attention to the influence of orography to the storm damage pattern in the forests. Bosshard (1967) and Schütz et al. (2006) emphasize e.g. the increasing damage on windward slopes with moderate inclination. Schüepp et al. (1994) and Schmidtke and Scherrer (1997) showed, that damage mainly occur on windward slopes at high elevations (1200 to 1600 m MSL).

In a manual on windbreaks in forests, Stathers et al. (1994) describe the influence of topography on flow and the resulting danger for the forests. The manual is based on observations, experience, and physical laws underlying windbreak. Accordingly, forests are susceptible to windbreaks at locations having the following properties:

- Rounded-off hills: Locations on flanks, especially sloped terraces, lower and medium altitudes of windward slopes, and lower lee slopes are susceptible to increased wind speed and turbulence. In general, the lee of a rounded hill is exposed to increased wind speeds, in particular when the terrain rises again behind the hill.

- Mountain ridges: In case of air flow parallel to the ridge, the danger is highest for the lower slopes. In case of oblique flow (at an angle of 20 to 50 degrees), flow becomes turbulent on the middle slope and frequently changes its direction. The speed maximum is reached at the summit. Directly behind it, the speed decreases again. Lee waves may be generated. Their rotors near the ground may cause strong turbulence. Behind steep lee slopes, inclined terraces, plains or windward slopes of the next hill tend to be endangered most.

- Valley bottoms: If flow moves along a rising valley, the flow lines converge and, as a result, the flow speed increases. Narrow valleys cause stronger acceleration than wide valleys, in particular when the valleys narrow down and the valley bottom rises. In valleys cutting a plain, very high wind speeds may occur if the valleys are parallel to the flow direction.

- Terraces: Upper windward slopes, summits, and lee slopes are exposed to the highest wind speed and strongest turbulence.

- Saddles: They act like narrow valleys. The flow lines converge and flow is accelerated. Valley bottoms at high-altitude passes preferably cause windbreak. Lee slopes of steep ridges also are exposed to a higher danger. Frequently, the risk of windbreak is higher on moderately steep to steep slopes than on plains and flat slopes.

The following factors affect the stability of trees in case of storms:

- Forest density and distance of the trees to each other: Free trees tend to be more stable than protected trees, as they are adapted to frequently changing loads. Moreover, smaller groups of trees and forest edges in principle have a higher stability (Burschel, 1990; Sinn, 2000).

- Forest characteristics: Apart from the type, setup, and age of the forests, the tree species composition of forest stands, their h/d ratio (h/d=ratio of the height of the trunks to their diameter), and the type and state of the forest edge play an important role (Mattheck et al., 2001; Agster and Ruck, 2003). Extensive crowns offer large areas for the wind to attack. High trees experience higher wind speeds than smaller ones.

- Tree types: Even when they are leaved, deciduous trees are more resistant to storms than coniferous trees. In winter, when the deciduous trees are bald, their advantage becomes even more obvious (Dobbertin, 2002; König, 1995; Mayer et al., 2005). According to Aldinger et al. (1996), the stability of the most frequent types of trees increases from spruce to fir to pine to beech/oak.

- Pre-damage of the trees: Diseases or insect attacks influence the stability. It was demonstrated by tests of Steyrer (2000) that healthy trees resist to tension that is higher by 65% than trees damaged by e.g. rotten roots.

- Rooting of the trees: The deeper the roots of the tree are and the heavier the root system is in relation to the tree height and crown volume, the stronger it is held in the ground (Rottmann, 1986).

- Water budget of the ground: Locations with a higher water saturation offer less foot-hold to the trees. The tree roots are flatter and the ground is softer. Trees adapted to moist grounds form board roots and, thus, increase their stability (Bosshard, 1967).

– Types of soil: Trees on skeleton-depleted grounds with fine types of soil (such as silt or clay) lose stability after strong, long-term precipitation. Skeleton-rich or rocky, but jointed locations offer the best anchoring possibilities to roots and the highest stability to trees (Moore, 2000; Sinn, 2000).

Extensive studies related to the types of failure of trees were carried out by Mattheck (1997). These studies show how the trees adapt to external conditions, such as slope locations, rocks in the ground or wind-exposed locations.

Simulations in wind channels allow to investigate flow development near certain trees or forest edges (Ruck and Adams, 1991; Agster and Ruck, 2003). The atmospheric boundary layer is modeled with respect to the wind profile and turbulence. It is found that turbulent shear stresses at the crown level and, hence, the highest wind load of the trees depend on the type and permeability of the forest edge. This makes forest edges the starting areas of storm damage. Forests with permeable and moderately inclined forest edges are less affected by high wind loads than forests with dense, steep edges.

A quantitative approach to establishing a relationship between topographic conditions and wind protection is presented by Quine and White (1998). Using this method (TOPEX – TOPographic EXposure), the angles from any pixel to the points at a given distance (e.g. 7 km) are calculated in all eight main directions with a digital elevation model. If a maximum is found within this distance, this height is used for the calculation of the angles. The sum of the angles serves as a measure of wind protection of the respective pixel by the surrounding mountains. Low values indicate an exposed terrain (=low surrounding mountains), high levels stand for a wind-protected area. However, channeling effects of valleys, increased speeds by flow over or around mountains or lee-side downwinds by the formation of waves due to the stratification of the atmosphere are not taken into account. Moreover, prevailing wind directions are not considered when evaluating the degree of protectiveness of an area.

Hanewinkel et al. (2004) give an overview of different methods of storm damage risk assessment in forests. There are expert systems mainly based on local experience (e.g. Rottmann, 1986). Risk assessment was improved by windspeed or airflow modelling (e.g. König, 1995). While even statistical models like logistic regression model are limited in ability to predict damages to forest stands Hanewinkel et al. (2004) examined the artificial neural network technique to model wind damgage to forests. They show that this improves classification of forests susceptible to wind damage compared to a logistic regression model.

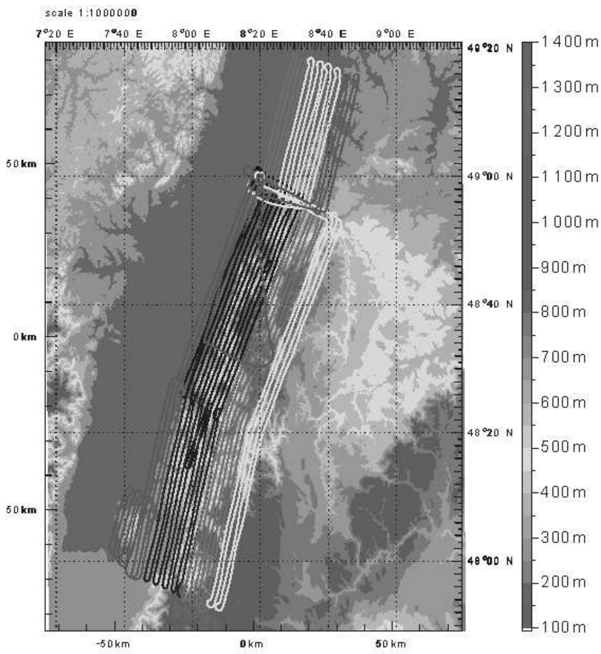

Fig. 1. Flight pattern with a Dornier 128 aircraft in May/June 2000 carrying an airborne scanner in the Northern part of the Black Forest.

3 Airborne survey for storm damage assessment

In May and June 2000, the Northern part of the Black Forest was surveyed by us in detail with an aircraft carrying a CCD line camera (Bochert et al., 2000) to determine the damage in the vegetation period after the "Lothar" storm (Fig. 1).

The survey was aimed at mapping the damage of the forests with a high spatial resolution in order to study the orography-caused enhancement of the wind. By means of a CCD sensor, the color line scanner (CLS) measured the intensities of the radiation reflected by the ground in three color channels: In the green (500–570 nm), red (580–680 nm), and the near infrared ranges (720–830 nm). In the near infrared between 750 nm and 1300 nm, reflection by leaves as compared to bald ground and dead vegetation is very high (Fig. 2 top). The steep increase of reflection between 690 and 740 nm is a typical characteristic of vegetation. The higher the chlorophyll content of the plants is, the further the steep increase is shifted towards higher wavelengths. From the intensities of the reflected radiation in the wavelength ranges of red and infrared radiation, the Normalized Difference Vegetation Index (NDVI) is determined. Figure 2 (middle) shows the relative sensitivity of the CCD sensor used in the CLS in the red wavelength range and in the near infrared. This CCD sensor has less steep cut-off frequencies (Fig. 2, bottom) than sensors used in various satellites for the determination of the

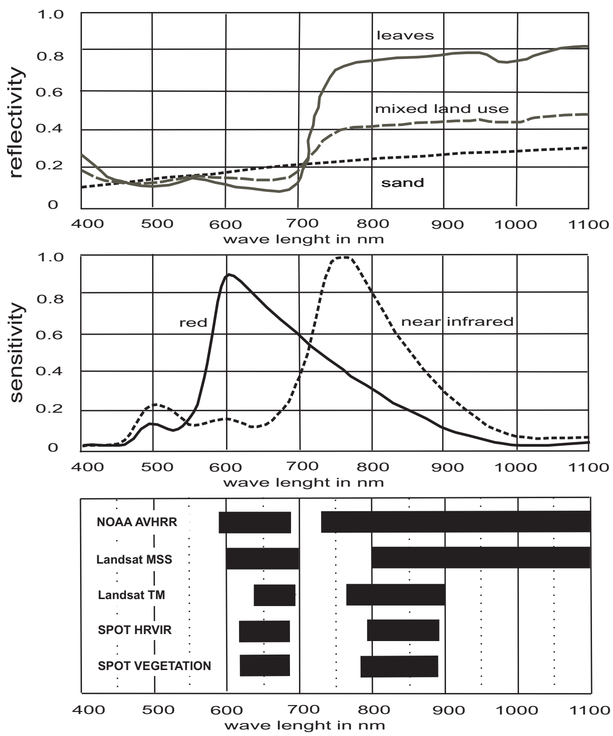

Fig. 2. Spectral reflectivity of leaves, for mixed land use, and of sand (top), spectral sensitivity of the CLS in the red and near infrared (middle), and spectral bands of various satellite sensors for the identification of vegetation (bottom) (Bochert et al., 2000).

NDVI. This is very useful (Bochert et al., 2000), as the sensitivities of the red channel and the channel for the near infrared overlap.

The NDVI is determined from the intensity of the radiation reflected by the surface in the near infrared (I_{nir}) and in the red wavelength range (I_{red}):

$$\mathrm{NDVI}=\frac{I_{\mathrm{nir}}-I_{\mathrm{red}}}{I_{\mathrm{nir}}+I_{\mathrm{red}}} \quad . \tag{1}$$

The NDVI varies between -1 (no vegetation) and 1. In the individual spectral ranges, brightnesses of the flight stripes vary. Shadows of trees or clouds, below which the flight was carried out, are visible. The NDVI compensates both brightness differences between the flight stripes and shadow effects quite well.

To correctly allocate the data to the ground surface, they have to be georeferenced first. For this purpose, the flight data also are recorded. These data include the absolute position and height of the aircraft (by differential GPS) as well as the inclination angles about the three axes at 50 Hz (1,2 m) resolution. In addition, the position of the camera relative to the axes of the aircraft has to be determined. This is done on the basis of calibration flights over ground reference points. To project the data correctly to the ground surface, the height is taken from a digital elevation model (DEM). The DEM used has a horizontal resolution of 50 m and a vertical resolution of 1 m. It is available for the complete measurement area.

To map the storm damage, it is important to distinguish between forest areas and non-forest areas. In principle, storm damage is reflected by a very low vegetation index (NDVI). However also settled areas, roads, waters, and areas used by agriculture have a very low vegetation index. On the other hand, fields covered by vegetation or pastures may have a very high vegetation index similar to that of intact forest. For this reason, land use data are considered. They show how the areas are used or whether they are settled. These data are available for the entire measurement area at a horizontal resolution of 30 m. Now, a mask of the forest areas can be determined from these land use data.

For mapping the storm damage, the NDVI is calculated from all data obtained and orthoprojected at a resolution of $2\times2\,\mathrm{m}^2$. Representation is accomplished by the geo-information system (GIS) Geomatica by PCI Geomatics. In a GIS, the NDVI, terrain elevation, land use or location properties may be superposed as georeferenced data. Also inside a completely intact forest, there may be individual pixels or small areas with a low vegetation index, e.g. paths or small clearings. To prevent them from being identified as storm damage areas, the condition of storm damage areas having a minimum size of 1.5 ha is applied. Smaller areas originate from single or few thrown trees are not that relevant to the study anyway because the main focus is on orographical effects. As the resolution of the land use data of 30 m is much lower than that of the NDVI data, potential mis-allocations at forest edges are corrected separately.

The following list summarizes the processing steps and criteria for the automatic detection of storm damage areas from NDVI data:

– A forest mask derived from land use data hides non-forest areas.

– An NDVI limit distinguishes between a potential storm damage area (NDVI$\leq$0.7) and intact forest (NDVI$>$0.7).

– Storm damage areas $<$1.5 ha are not considered.

– Storm damage areas and clouds differ in the variance of the NDVI. Areas with a variance $>$500 within a 5×5 matrix are identified as storm damage areas as this threshold was determined by visual assessment.

– Individual pixels of NDVI$>$0.7 within damage areas are added to the latter.

This method allows for a realistic classification of storm damage areas based on CLS data.

4 Storm damage assessment

The storm damage caused by "Lothar" has to be attributed to very high wind speeds. It is known that forests are more or less susceptible to strong winds depending on their site conditions. Among others, the soil properties are of importance. To consider this influence, soil data were made available by the Forest Research Institute of Baden-Württemberg (FVA) in Freiburg. Based on experience, the FVA has distinguished three stability classes (stable – neutral – unstable) depending on the type of soil. This was done for the main types of trees typical of the Black Forest, namely, spruce and beech. For example, trees growing on moist soils or soils with a varying moisture content are considered to be highly unstable. This also holds for stony and blocky grounds. The site data are available for state forests only. As storm damage areas with a minimum size of 1.5 ha are considered only, the lower resolution can be tolerated. The site data can be projected to other resolutions only with a small loss of information, as they are available in a vectorial form. For the reasons given above, a resolution of 30 m was selected. Hence, a pixel corresponds to an area of 900 m^2 (0.09 ha).

In total, the flights in June 2000 recorded data on an area of 4907.9 km^2. Of these, 2767.3 km^2 have been classified as areas covered by forests based on the land use data. This corresponds to 56.4% of all data (3 074 800 pixels of 30×30 m^2 each). The damage areas detected with the method described cover 22.2 km^2 (2220 ha) or 0.8% of the forest area surveyed (24 667 pixels). In total, 363 storm damage areas were found. More than 50% of the damaged areas are smaller than 5 ha. Most have a size ranging from 1.5 to 3.5 ha. Some areas are larger than 40 ha. Figure 3 shows the distribution of the size classes of the storm damage areas. The class width is 1 ha. As the smallest damage area is 1.5 ha in size, the 1-ha class is empty.

For a subset of data ($\approx$145 ha) a comparison from the proportion of storm damage areas as derived from the CLS data (by automatic detection method) with storm damage maps of the FVA (gained by personal inspection) is made. It shows that our technique detects about half of the damage areas (2.4% damaged forest versus 4.7% on the damage maps). Some of these damaged areas cannot be distinguished from intact forest in the close surroundings when visually inspecting the high resolution (2×2 m^2) NDVI data. Especially small damage areas or areas interspersed with intact trees or vital underwoods are not detected. Also, the damage areas classified by personal inspection are often larger than derived from the CLS data. These peripheral areas probably are partly damaged. What is important, the developed method ensures, that no false detections occur at all.

Based on this partial area, it can be estimated that about 50% of the damaged areas and therefrom most of those above 1.5 ha can be detected by CLS flights using the method above. For the comparison with wind data from a numerical

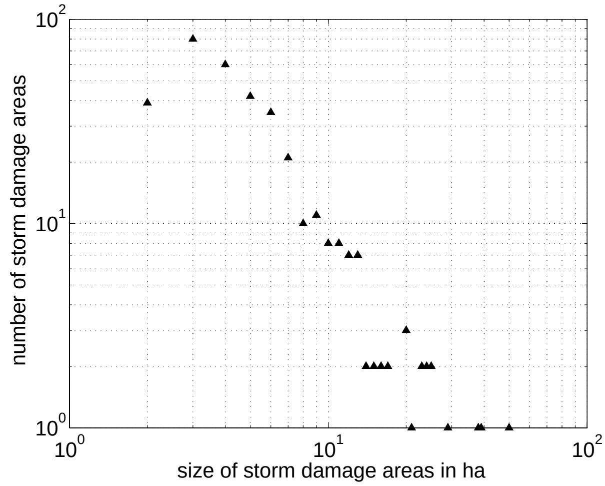

Fig. 3. Distribution of the sizes of the storm damage areas for the whole study area.

flow model (Schmoeckel and Kottmeier, 2008[1]), the damage areas are a suitable reference in terms of intensity and spatial assignment, since the model resolution is 1 km^2.

The distribution of the storm damage areas (Fig. 3) follows in general a typical log-log relation as described by Schmidtke (1993). Based on this relation and reinforced by the comparison with damage maps described above we may presume that there is a border problem at the lower limit and there are about twice as much damage areas in the 2-ha class as detected, as well as a lot smaller areas that are not detectet at all with the described technique. Schmidtke (1993), too, describes the underestimation of small damage areas by remote sensing technincs for the storm damage of "Vivian" 1990 in Switzerland.

5 Results of influence parameters analysis

The height of the terrain, slope inclination, orientation of the slopes, and curvature of the terrain are referred to as topographic parameters and calculated from the digital elevation data. Information on the soil types and the water budget of the soils was made available by the FVA for this work in the form of so-called site data. They exist in digital form and cover a large part of the area studied. Other parameters mentioned in Sect. 2 like type and tree species composition of the forests and the age of the trees for public inventories or municipal forests are available at the forest offices. For some years now, the information gathered on the forests by

[1]Schmoeckel, J. and Kottmeier, C.: Storm damage in the Black Forest caused by the winter storm "Lothar" – Part 2: Damage in relation to simulated flow over complex orography, Nat. Hazards Earth Syst. Sci, in review, 2008.

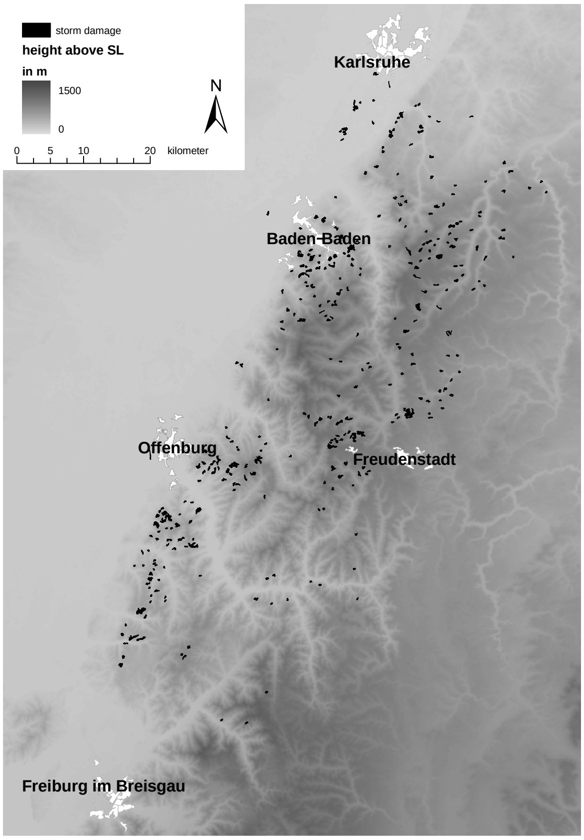

Fig. 4. Automatically detected storm damage areas (in black) in the area studied.

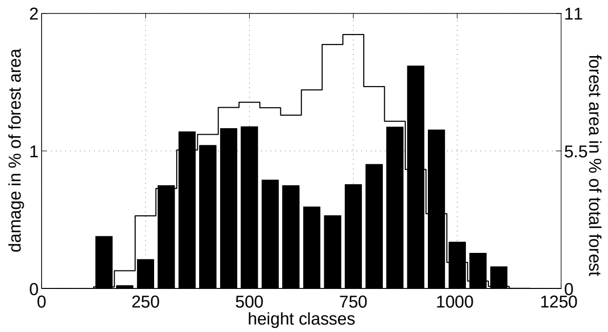

Fig. 5. Percentage of damaged forest and total forest area of height classes (bars). The stairs curve represents the ratio of the forest area of each class compared to the overall forest area.

inspections has increasingly been put into geographical information systems (GIS). But these data still cover only part of the area studied and cannot be used for automatic process in the present work.

Figure 4 shows the distribution of the damage in the Black Forest. A case study exemplary made in the surroundings of the city of Baden-Baden (Fig. 4) indicates a clear relationship between the topography and the location of the storm damage (Schmoeckel, 2006).

Damage is more frequent on slopes of Northwestern orientation, saddles, and exposed ridges. To quantitatively evaluate the relationships for the complete area studied, a classification is made for each topographic parameter. As regards the elevation data, the classes cover 50 elevation meters each, the inclination classes cover 5 degrees each. Eight orientation classes exist over azimuth sectors of 45 degrees each. The main directions (N, NE, E, ...) are located in the middle of the class. The curvature of the terrain is divided into four classes: Concave, convex, saddle areas, and terrain without any curvature. For a small part of the total area surveyed (1.42%, 0.25% of the forest area), no elevation data are available.

The bar charts in the following figures show the damage area of each class, normalized to the forest area of the respective class. This means that the total forest area of a class corresponds to 100%. The damaged fraction is the normalized damage area per class in %. Hence, the fractions of the damaged areas of the individual classes can be compared. In addition, the figures indicate the distribution of the entire forest over the classes represented on the abcsissa in the form of a stepped line. The forest fractions over the classes total 100%.

The distribution of storm damage with elevation (Fig. 5) is characterized by hardly any forest areas existing at low elevations up to 150 m above sea level and high locations above 1100 m. Here, only occasional damage was detected.

Most of the storm damage occurs in the elevation class of 900 to 950 m (1.16%). More than 1% damage occurred between 350 m and 550 m and from 850 to 950 m. Between 700 and 750 m (0.53%), less damage appeared. Probably, this effect is caused by the special profile of the black forest. Exposed ridges in case of Western flows are found at altitudes between 400 and 600 m and above 800 m. In the moderate elevation range between 600 and 800 m, there are only few exposed ridges.

Forests on slopes with an inclination between 10 and 15 degrees show the highest storm damage (1.01%) (Fig. 6). This is comparable with the results found by Dobbertin (2002) for the storms "Vivian" and "Lothar" in Switzerland or Mayer et al. (2005) in France. Forests on plains and flat slopes of up to 5 degrees inclination show the smallest damage (0.53%). Storm damage is also smaller on very steep slopes, though the decrease of damage with increasing slopes was not as high as found by Schütz et al. (2006).

Slopes oriented towards the Northwest, North, and Southeast have higher damage than others (Fig. 7). Northwestern slopes are most affected (1.04%). Forests on Southwestern slopes (0.53%) are less affected. This is interesting, as the highest speeds during the storm occurred with Southwesterly and Westerly wind directions. Western slopes also are less affected.

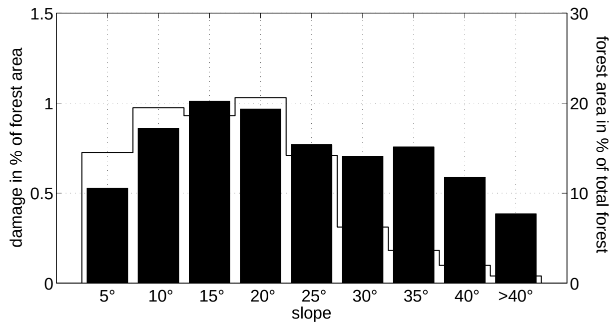

Fig. 6. Percentage of damaged forest and total forest area of slope classes (bars). The stairs curve represents the ratio of the forest area of each class compared to the overall forest area.

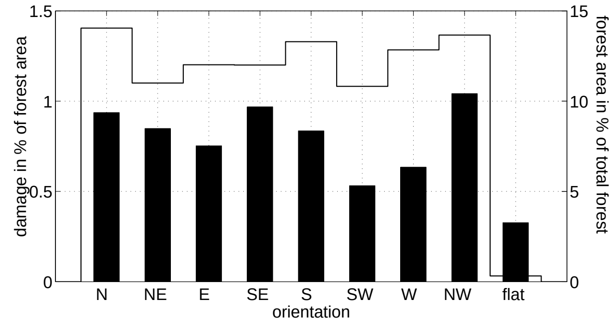

Fig. 7. Percentage of damaged forest and total forest area of orientation classes (bars). The stairs curve represents the ratio of the forest area of each class compared to the overall forest area.

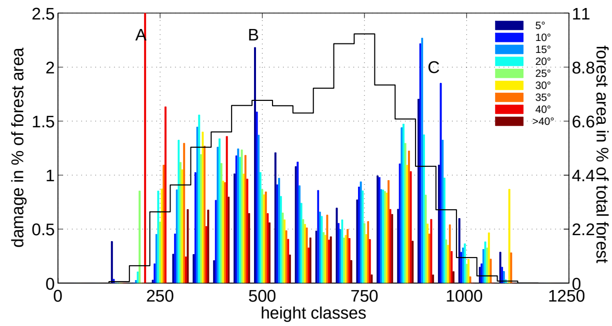

Fig. 8. Percentage of damaged forest and total forest area of height classes (bars), colour codes giving the terrain slopes. The stairs curve represents the ratio of the forest area of each height class compared to the overall forest area.

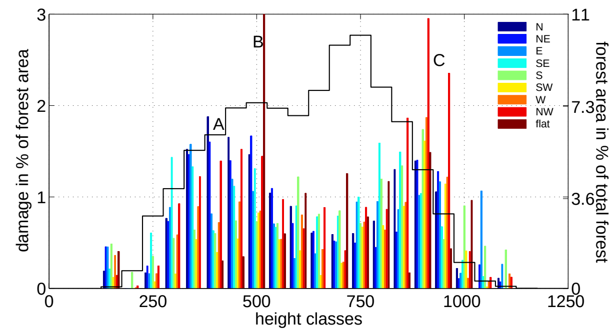

Fig. 9. Percentage of damaged forest and total forest area of height classes (bars), colour codes giving the terrain orientation. The stairs curve represents the ratio of the forest area of each height class compared to the overall forest area.

Analysis of the storm damage as a function of the different parameter combinations leads to more classes containing reduced numbers of data only. For two influencing parameters, most of the combinations formed have still far above 10 000 forest pixels. However, at lower and higher elevations no conclusions can be made due to low sample size.

It is noticeable that damage is very high on flat slopes of up to 5 degrees inclination at altitudes between 500 and 550 m (Fig. 8 B). At higher elevations from 900 to 1000 m, damage occurs more often on slopes inclined by 5 to 15 degrees (Fig. 8 C). Only few damage pixels cause the high values for steep slopes at 250 to 300 m height (Fig. 8a – 2 from 42 forest pixels damaged =4.76%).

At lower locations between 300 and 500 m, Northern and Northeastern slopes were damaged most frequently (Fig. 9a). Northwestern slopes exhibit more damage than slopes of other orientations at higher locations between 800 and 950 m (Fig. 9c). Smallest damage occurred at an altitude from 250 to 300 m and from 650 to 750 m on Southwestern and Western slopes. Only few damage pixels cause the high values on flat areas at 450 to 500 m (Fig. 9b) – 11 from 232 forest pixels damaged =4.74%).

Slopes with inclinations between 10 and 20 degrees exhibit highest damage when oriented in western to northern directions (Fig. 10a). Also Schütz et al. (2006) pointed out this relation for Switzerland after the storm “Lothar”. Similarly high damage was found on steeper slopes in case of southeastern orientation (Fig. 10b). This differs to the results of Schütz et al. (2006) which found less damage on steeper slopes for all orientations. Lee vortices behind hill tops may cause damage on this steep leeward slopes (also observed by (Bosshard, 1967) on leeward slopes).

In total, saddle locations exhibit little more storm damage than locations with other curvatures but a clear relation of curvature of the terrain and altitude or slope orientation is not found (not shown).

This is also true for the combination of curvature and slope orientation. Exceptions are the accumulation of damage at saddle locations with Southeasterly orientation (Fig. 11a) and on concave locations of Northern orientation (Fig. 11b).

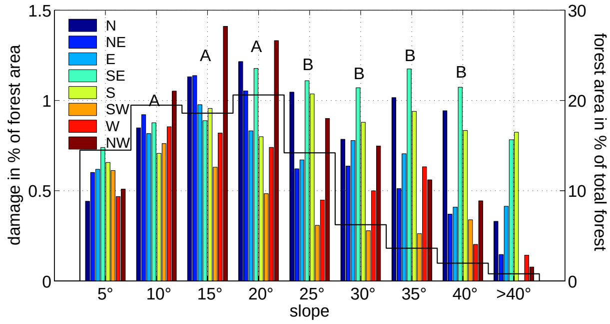

Fig. 10. Percentage of damaged forest and total forest area of slope classes (bars), colour codes giving the slope azimut. The stairs curve represents the ratio of the forest area of each height class compared to the overall forest area.

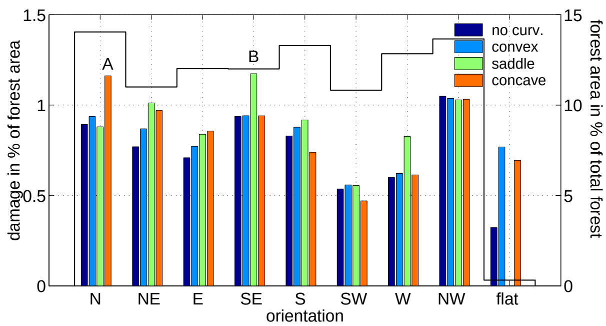

Fig. 11. Percentage of damaged forest and total forest area of orientation classes (bars), colour codes giving the terrain curvature. The stairs curve corresponds to Fig. 8.

Hence, the orographic influence on the storm damge atterns is clearly visible.

Analysis of storm damage in forests with respect to site data is based on a reduced data volume. Site data are available for 23.45% of the area surveyed and for 41.95% of the forest area. This forest area was damaged by 0.94%. The reference figures of the forest area were modified accordingly.

As expected, wet to moist soils represent more unstable locations for the trees (also shown in Table 1). This is comparable to studies of Dobbertin (2002) who found an increasing probability of damage in Switzerland during “Vivian” and “Lothar” on sites with less water permeability or water logging. Storm damage on this soil type covers a proportion of 1.54% of the forest area. In contrast to this, storm damage on soils that have been classified as having a variable moisture or being wetted easily is unexpectedly small with 0.75%, as these types of soils are also considered to be unstable. Medium-dry to dry locations that were considered to be relatively stable exhibit a large damaged forest fraction (1.20%). This might be due to the weather conditions of December 1999 (DWD, 1999). At the time of the storm, the soil probably was saturated with water. Hence, even medium-dry to dry locations offered less stability to the roots of the trees (Bosshard, 1967; Dobbertin, 2002). Also Schmidtke and Scherrer (1997) pointed out that longer rain periods before the storm (“Vivian” in Switzerland) level the differences in soil stability due to the water budget. No information is available on whether the damage was caused by disrooting or by the breaking of the tree trunks whereby more information about stability could be gained. Broken trees indicate stable locations, as the trees root stably in these areas, whereas the trunks yield at a sufficiently highly wind pressure. Disrooted trees indicate unstable locations.

Table 1. Forest damage with respect to site data.

soil type	damage of forest area
wet – moist	1.54%
variable moisture – easily wetted	0.75%
medium dry – dry	1.20%

6 Conclusions

The described method for automatic detetion of storm damage areas from airborne gained vegetation data (NDVI) is suitable for damage areas larger than 1.5 ha. With the given resolution of the land use date needed for the study, areas smaller than 1.5 ha are not detected. The number of areas smaller than 2 ha is underestimated. The resulting pattern of storm damage caused by the winter storm “Lothar” in the Black Forest region reflect a variety of influences. In addition to the wind field, which is reconstructed from numerical models and observed wind data in a parallel paper (Schmoeckel and Kottmeier, 2007), these are properties of the forest stand (tree types, heights, separations), of the soil (type, moisture), and the orographic exposition (saddles, crests, valleys), the latter also taking effect on wind flow over mountains. Despite the extended study area of about 4900 km^2, the large number of influencing factors limits the reliability of empirical relationships based on multiple-parameter combinations.

Strong dependencies are found in relation to terrain height, slope orientation with respect to the wind, and soil moisture content. The bimodal frequency distribution of damage related to terrain height (with damage maxima in 350 to 550 m and in 850 to 950 m) can be explained by the wind direction from the West and Southwest and the mountain configuration with a first chain of luv-side mountains, which tend to shelter major parts of the mountain range in front of the higher mountains, which themselves are more affected again. Although this profile in damage distribution dominates the influence of other parameters, it is clearly shown, that moderate slopes are more often damaged in higher elevations. Northern to southeastern orientated slopes are damaged more frequently in moderate hights up to 550 m.

Slopes up to an inclination of 20 degrees were more affected than steeper slopes or flat terrain. This reinforces studies in Switerland. Although the main wind direction during the storm had westerly components, most damage was found on northern and northwestern slopes. Unexpectedly a large number of damage areas appeared on southeastern i.e. leeside slopes. What is more, these slopes are mainly steep with inclinations above 25 degrees. This was not found in other studies.

The damage patterns identified are clearly related to characteristics of atmospheric flow over the complex orography.

Edited by: U. Ulbrich
Reviewed by: Two anonymous referees

References

Agster, W. and Ruck, B.: The Influence of Aerodynamic Properties of Forest Edges and Stands on the Pressure Pattern within a Forest, in: Proceedings of the International Conference Wind Effects on Trees, edited by Ruck, B., Kottmeier, C., Mattheck, C., Quine, C., and Wilhelm, G., 25–32, 2003.

Aldinger, E., Seemann, D., and Konnert, V.: Wurzeluntersuchungen auf Sturmwurfflächen 1990 in Baden-Württemberg, Mitt. Ver. Forstl. Standortskde. u. Forstpflanzenzüchtg., 38, 11–25, 1996.

Bochert, A., Hacker, J. M., and Ohm, K.: Color Line Scanner as imaging NDVI Sensor, in: Second EARSeL Workshop on Imaging Spectroscopy, Enschede, 11–13 July 2000, 2000.

Bosshard, W.: Erhebungen über die Schäden der Winterstürme 1967, Schweizerische Zeitschrift fr Forstwesen, 118, 806–820, 1967.

Burschel, P.: Erfahrungen aus dem grossen Sturm in Südost-England im Oktober, Allg. Forst Z., 45, p. 942, 1990.

Dobbertin, M.: Influence of stand structure and site factors on wind damage comparing the storms Vivian and Lothar, For. Snow Landsc. Res., 77, 187–205, 2002.

DWD: Witterungsreport (Express), Deutscher Wetterdienst, ISSN 1436–6789, 1999.

Hanewinkel, M., Zhou, W., and Schill, C.: A neural network approach to identify forest stands susceptible to wind damage, Forest Ecol. Manage., 196, 227–243, 2004.

Hütte, P.: Untersuchungen über den Einfluss des Geländereliefs auf Richtung, Geschwindigkeit und Struktur des Sturmes im Hinblick auf die Gefährdung der Fichte, Ph.D. thesis, Georg-August-Universität zu Göttingen, 1964.

König, A.: Sturmgefährdung von Beständen im Altersklassenwald: ein Erklärungs- und Prognosemodell, Ph.D. thesis, Ludwig-Maximilians-Universität München, 1995.

Kurz, M.: Die Dezemberstürme 1999, Ber. des Deutschen Wetterdienstes, 220, 2000.

Mattheck, C.: Design in der Natur – Der Baum als Lehrmeister, Rombach Ökologie, Freiburg i. B., 1997.

Mattheck, C., Bethge, K., Tesari, I., and Kappel, R.: Ein neues Versagenskriterium für nicht fäulegeschädigte solitäre Bäume, Wiss. Berichte d. Forschungszentrums Karlsruhe, FZKA 6666, 2001.

Mayer, H. and Schindler, D.: Forstmeteorologische Grundlagen zur Auslösung von Sturmschäden im Wald in Zusammenhang mit dem Orkan Lothar, Allg. Forst- und Jagd-Z., 173, 200–208, 2002.

Mayer, P., Brang, P., Dobbertin, M., Hallenbarter, D., Renaud, J.-P., Walthert, L., and Zimmermann, S.: Forest storm damage is more frequent on acidic soils, Ann. For. Sci., 62, 303–311, 2005.

Moore, J. R.: Differences in maximum resistive bending moments of *Pinus radiata* trees grown on a range of soil types, Forest Ecol. Manage., 135, 63–71, 2000.

Odenthal-Kahabka, J.: Hurricane “Lothar” and the forests of Baden-Wrttemberg (Germany) – damages, impacts and effects, Forest Research Institute of Baden-Wrttemberg, Wonnhaldestr. 4, 79100 Freiburg,, http://www.cetreacer.qc.ca/publications/colloques/2003/Articles/Jutta%20english.pdf, 2003.

Quine, C. P. and White, I. M. S.: The Potential of Distance-Limited Topex in the Prediction of Site Windiness, Forestry, 71, 326–332, 1998.

Rottmann, M.: Wind- und Sturmschäden im Wald, J. D. Sauerländers Verlag, Frankfurt am Main, 1986.

Ruck, B. and Adams, E.: Fluid Mechanical Aspects of the Pollutant Transport to Coniferous Trees, Bound.-Lay. Meteorol., 56, 163–195, 1991.

Schmidtke, H.: Die fraktale Geometrie von Sturmschadenflächen im Wald, Allg. Forst Z., 48. Jg., 710–714, 1993.

Schmidtke, H. and Scherrer, H.-U.: Sturmschäden im Wald, Zürich: vdf, Hochsch.-Verl. an der ETH, 1997.

Schmoeckel, J.: Orographischer Einfluss auf die Strömung abgeleiet aus Sturmschäden im Schwarzwald während des Orkans “LOTHAR”, Ph.D. thesis, Universität Karlsruhe (TH), 2006.

Schüepp, M., h. Schiesser, H., Huntrieser, H., h. U. Scherrer, and Schmidtke, H.: The Winterstorm ”Vivian” of 27 February 1990: About the Meteorological Development, Wind Forces and Damage Situation in the Forests of Switzerland, Theor. Appl. Climatol., 49, 183–200, 1994.

Schütz, J.-P., Götz, M., Schmid, W., and Mandallaz, D.: Vulnerability of spruce (Picea abis) and beech (Fagus sylvatica) forest stands to storms and consquences for silviculture, Eur. J. Forest Res., 125, 291–302, 2006.

Sinn, T.: Biostatische Baumkontrolle, Stadt und Grün, 9, 4625–4633, 2000.

Stathers, R. J., Rollerson, T. P., and Mitchell, S. J.: Windthrow Handbook for British Columbia Forests, Tech. rep., B.C. Min. For., Victoria, B.C. Working Paper 9401, 1994.

Steyrer, G.: Bruch- und Wurfgefahr bei Wurzelfäule, Ergebnisse eines Umziehversuches an Fichten, available at: http://bfw.ac.at/400/1253.html, 2000.

Ulbrich, U., Fink, A. H., Klawa, M., and Pinto, J. G.: Three Extreme Storms over Europe in December 1999, Weather, 56, 70–80, 2001.

Wernli, H., Dirren, S., Liniger, M. A., and Zillig, M.: Dynamical Aspects of the Life Cycle of the Winter Storm Lothar, Q. J. Roy. Meteorol. Soc., 128, 405–429, 2002.