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The relative importance of soil acidification and nitrogen deposition for storm damage in forests – methodological considerations and presentation of a broad scale study

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Abstract

After the storm damage in Central European forests in the 1990's the question of measures to reduce future damage arose. For the development of such preventive measures an understanding of the factors influencing storm damage in forests is necessary. We try to elucidate in this study the relative importance of various factors for storm damage by the gales/hurricanes 'Lothar' and 'Martin', with a focus on potential effects of sulphur and nitrogen deposition. Elevated depositions of sulphur and nitrogen may reduce root biomass and thus potentially lower tree resistance to storms. Data from several hundred sites will be analysed with robust regression techniques, and enable us to assess and quantify the role of different factors for forest storm damage.

Introduction

The forest damage caused by storm events in the 1990`s in Central Europe arose the question, which measures could help to reduce future damage (WSL & BUWAL 2001). A prerequisite to the development of such measures is a profound understanding of the factors influencing forest storm damage. Factors related to storm damage can be classified in four groups (König 1995): meteorological conditions, site conditions, forest management activities, and stand characteristics. In the following paragraph we give a short overview (see Webb 1999 for an extensive review).

(1) Meteorological conditions: Storm damage obviously depends on wind speed. This effect was proven by various studies (König 1995, Renaud 2002). Precipitation before the storm event increases soil water content which reduces tree resistance (Braun et al. 2003). (2) Site conditions: A higher susceptibility to storm damage was found on soils (i) with higher moisture (Dobbertin 2002), (ii) with lower stone content (Dobbertin 2002), (iii) with high clay content (König 1995) and (iv) with greater depth (König 1995, Dobbertin 2002, compare to Rottmann 1986, Peterson 2000). Slope, relief, aspect and altitude were found to affect storm damage, too. Dobbertin (2002) found higher damage on hilltops and in even terrain. Aspect and altitude are related to wind speed, which was already mentioned as an important factor for storm damage. (3) Forest management activities: Thinning and timber harvest before the storm event increase the risk of storm damage (König 1995). Increased storm damage seems to occur especially after heavy thinning in formerly dense stands (Röhrig & Gussone 1990). (4) Stand characteristics: Stands dominated by coniferous trees are more susceptible to storm damage than those with deciduous trees (Rottmann 1986, Dobbertin 2002).

According to several studies, stand height is strongly positively correlated to storm damage (Wölfle 1936, König 1995, Dobbertin 2002).

Braun et al. (2003) found significantly higher damage on sites with low base saturation (in their case <40% in the upper soil). However, their study uses data from only 62 stands. They explain this result with reduced root bracing because of soil acidification. Fine roots grow slower and are damaged in acidic soils because of the release of toxic forms of aluminium (Marschner 1995). Soil acidification caused by SOx deposition is a well known process (e.g. Ulrich 1989). Therefore, high deposition rates of SOx may be correlated with storm damage.

Nitrogen deposition has, in the case of NHx, also an acidifying effect. Besides, nitrogen is essential for plant nutrition and promotes shoot growth (Marschner 1995). Experiments revealed a reduced root/shoot ratio with increased nitrogen availability (Levin et al. 1989). This may increase tree susceptibility to storm damage.

Whereas the principal mechanisms of storm damage are reasonably well understood, an in depth understanding of the relative importance of the different factors is still lacking. This statement holds especially true for effects of soil acidification and nitrogen deposition. Therefore, we conducted a study to assess the relative importance of soil acidification and nitrogen deposition and tested the following hypotheses:

- Storm damage is higher on sites with low base saturation.
- Both nitrogen and sulphur deposition enhance storm damage.

Effects on forest damage by the 1999 hurricanes 'Lothar' and 'Martin' in France, Germany and Switzerland were analysed with multiple regression techniques on an extensive data base with several hundred sites. To assess the relative importance of sulphur and nitrogen deposition, modelled deposition rates were included in the analysis. In this paper, we present the data and discuss the methodological approach.

Methods

Inventories included

The study was restricted to storm damage by 'Lothar' on December 26th in 1999 and 'Martin' the following day. Lothar affected northern France, southern Germany (the counties of Baden-Württemberg and Bavaria) and northern Switzerland. Martin affected central France and south-western Switzerland (WSL & BUWAL 2001). The data for storm damage, stand structure, and site conditions in the region investigated come from several forest and soil inventories (Table 1). These inventories are part of the forest monitoring program ICP Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests).

Variable description

Response variables were chosen to describe storm damage (Table 2). The predictor variables (Table 2) were selected to reflect the factors potentially affecting storm damage presented in the introduction. Variables were classified in nominal, ranked, discontinuous and continuous (Sokal & Rohlf 1981). Some variables had different classes in the countries investigated, which necessitated merging classes to allow a combined analysis of all data.

The new classes were established on the lowest common level of information in the investigated countries.

Table 1: Inventories included in the study.

Inventory	**France**	**Baden-Württemberg**	**Bavaria**	**Switzerland**
Inventory on forest stand structure and storm damage, year of the inventory	Réseau européen de suivi des domages forestiers, 2000	Terrestrische Waldschadens-inventur, 2000	Waldzustands-erhebung, 2000	Sanasilva, 2000
Inventory on soil conditions, year of the inventory	Inventaire écologique, 1993-1994	Bodenzustands-erhebung, 1990-1991	Waldboden-inventur, 1987	Bodeninventur auf Sanasilva – Netz,1993
Grid width of inventory plots	16 km x 16 km	16 km x 16 km	8 km x 8 km	8 km x 8 km
Plot number	503	136	285	98

Modelled wind speed data was provided by MeteoSwiss with the Swiss Model. The Swiss Model is a high-resolution version (grid mesh 14 km) of the European model developed by the German Meteorological Service (Majewski 1991). Of the modelled wind speeds (calculated at each timestep) the maximums on December 26th and 27th 1999 were included in the analysis. Modelled deposition rates of oxidised sulphur (SOx), oxidised nitrogen (NOx) and reduced nitrogen (NHx) were compiled from models with different resolutions: (1) The EMEP model, developed in the Co-operative Programme for Monitoring of the Long-Range Transmission of Air Pollutants in Europe, with a resolution of 50 km (Barrett & Berge 1996, Metcalfe et al. 1999) for the total study area. (2) Models with finer resolution for France (Croisé et al. 2002), Germany (Gauger et al. 2000) and Switzerland (Kurz et al. 1998).

Table 2: Variables included in the analysis. The variable 'storm damage' (continuous and nominal) is the response variable (1), the other variables are predictor variables (2 meteorological conditions, 3 site conditions, 4 stand characteristics). Variables marked with an asterisk have different classes in the countries investigated and were standardized for inclusion in a single analysis.

variable	**type**	**description**
1. storm damage	continuous	% of total stand basal area before the storm of trees broken or uprooted by the storm
storm damage	nominal	classes: yes/no
2. wind speed	continuous	maximum of modelled wind speed 10 m above surface
3. deposition of NOx, NHx, SOx	continuous	modelled bulk deposition
altitude	continuous	meters above sea level
aspect	nominal	classes: 1 north-west, west, south-west 2 other
slope	continuous	slope in percent

Table 2 continued

topography*	nominal	classes: 1 plain, plateau 2 ridge, hilltop 3 mid-slope 4 foot of hill, gully 5 other
bedrock acidity*	ranked	classes 1 acidic 2 intermediate 3 alkaline
soil type*	nominal	classes according to World Reference Base for Soil Resources
humus type*	nominal	classes 1 mull 2 moder 3 mor 4 other
soil texture*	nominal	classes: 1 fine 2 medium 3 coarse
stoniness*	ranked	classes 1 no stones 2 stony 3 very stony
soil depth	continuous	measured soil depth in cm
soil moisture*	nominal	classes 1 moist 2 dry
soil pH	continuous	mean pH ($CaCl_2$) (in the case of Baden-Württemberg mean pH (KCl)) for upper 40 cm of the soil
cation exchange capacity	continuous	mean cation exchange capacity in cmol+ kg^{-1} for upper 40 cm of the soil
base saturation	continuous	mean base saturation in % for upper 40 cm of the soil
base cation/aluminium ratio	continuous	minimum base cation/aluminium ratio measured in the soil profile
4. stand height	discontinuous	average tree height in steps of 5 m
stand structure*	nominal	classes 1 single-storey 2 multi-storey 3 irregular
canopy cover*	ranked	classes 1 dense 2 intermediate 3 open
proportion of coniferous species	continuous	% coniferous of total stand basal area

Statistical analysis

Among the large variety of statistical methods available, regression analysis is the appropriate method to assess the relative importance of different factors (predictor variables) on storm damage (response variable). Least-square linear regression requires normality of residuals and independence of predictor variables (Sokal & Rohlf 1981), requirements which are not fulfilled in our data. The data is characterized by non-normal, non-linear relationships, many zero cases, and multi-collinearity. In this section we give a short overview of robust methods which are appropriate for this kind of data, and point out those which we plan to use in this study.

Logistic regression analysis: The logistic regression model is a non-linear transformation of the linear regression (Hosmer & Lemeshow 2000). The response variable in standard logistic regression is binary; in our case the variable has the two values 'storm damage occurred' and 'no storm damage occurred'. Logistic regression has often been used to investigate the relative importance of different factors for storm damage in forests (e.g. Valinger & Fridman 1997, Jalkanen & Mattila 2000, Sinton et al. 2000, Mitchell et al. 2001). An extension of standard logistic regression, known as multinomial logistic regression, enables a response variable with not only two but with several categories to be investigated (Hosmer & Lemeshow 2000).

Classification and regression trees: The purpose of classification and regression trees is to determine a set of if-then logical conditions that permit accurate prediction or classification of cases (Breiman et al. 1984). These if-then conditions are displayed in 'trees' with one point at the top and a dichotomous separation in branches. Classification and regression trees are very robust because there are no assumptions on the distribution of residuals or on the relationship between predictor and response variables. Dobbertin (2002) used classification trees to study the influence of stand structure and site factors on storm damage in forests.

Categorical regression analysis and *generalized linear models* are two other methods which have so far not been applied to storm damage data to our knowledge. The statistical analysis in this study focuses on these methods. In categorical regression analysis (see Meulman et al. 1999) a regression of the response variable on the categorical predictor variables is calculated, a method also performed in canonical correlation analysis. The response variable has the form of ordered categories. The predictor variables, be they nominal, ordinal or numerical, are scaled in such a way that comparisons of regression coefficients between variables are possible.

Generalized linear models (GLM) are extensions of linear models that allow for non-linearity and non-constant variance structures in the data (see Guisan et al. 2002). They are based on an assumed relationship (called a link function) between the mean of the response variable and the linear combination of the predictor variables. Data may be from several families of probability distributions; thus GLMs are flexible and well suited for analysing ecological relationships.

Spatial effects, especially spatial auto-correlation, of the response variable have to be taken into consideration (Millard & Neerchal 2001) in our case. The amount of storm damage on one site could be affected by the amount on a site nearby. To discover spatial auto-correlation the coefficients Moran´s I and Geary´s c are appropriate measures (Legendre &

Legendre 1998, Fortin 1999). The exclusion of spatially auto-correlated plots from the regression analysis is one approach to deal with this problem.

Investigations with any regression analysis needs extra care in interpretation of the results because relationships between variables may be non-causal (Sokal & Rohlf 1981). However, experiments for a rigorous testing of hypotheses are hardly possible in the study of factors affecting forest storm damage.

Conclusions

This study differs in three major points from most former studies investigating effects on forest storm damage: (1) The explicit investigation of effects of sulphur and nitrogen deposition, (2) a large data set with several hundred sites scattered over the total area affected by the gales 'Lothar' and 'Martin', (3) the application of robust regression techniques with the response variable (storm damage) on both continuous and nominal scales. The results of this study are likely to contribute to a better understanding of storm damage in forests and may promote the development of policy directives and forest management guidelines to reduce storm damage in the long term.

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