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Original article

Forest storm damage is more frequent on acidic soils

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Abstract – We assessed the effect of chemical soil properties and acidifying depositions (sulphur and nitrogen) on the occurrence of storm damage during the storms "Lothar" and "Martin" (December 1999). Data from 969 sites in France, southern Germany and Switzerland was analysed with multiple logistic regression models. Variables found to be significantly related to storm damage, which was mainly scattered damage in our study, were "country", "soil pH", "proportion of coniferous trees", "slope", "humus type", "stand height", and "altitude". Wind speed was not significantly related to storm damage in the global model, but only in the model for France. Soil pH was one of the most significant factors with a lower pH on damaged plots. Atmospheric deposition rates were significantly associated with soil pH, but not directly with storm damage. Even though the mechanisms involved in the relationship between soil acidity and storm damage are still poorly understood, soil acidity should be considered a significant risk factor. Moreover, this large-scale study confirms that increasing the proportion of deciduous trees would reduce the susceptibility of forests to storm damage.

deposition / logistic regression / soil pH / wind damage / wind speed

Résumé – Les forêts au sol acide sont plus souvent endommagées par les tempêtes. Nous avons étudié l'effet des propriétés chimiques des sols et des dépôts acidifiants (soufre et azote) sur les dommages dus aux tempêtes durant les passages de « Lothar » et de « Martin » en décembre 1999. Les données de 969 sites en France, au sud de l'Allemagne et en Suisse ont été analysées à l'aide de modèles de régression logistique multiple. Les variables liées de manière significative aux dommages dus aux tempêtes étaient les suivantes : le pays, le pH du sol, la proportion de conifères, la déclivité du terrain, le type d'humus, la hauteur des arbres et l'altitude. Dans la plupart des sites, les dommages n'étaient que partiels. La vitesse du vent n'était pas liée de manière significative aux dommages dans le modèle global, mais dans un modèle utilisant uniquement les données de France. Le pH du sol, qui s'avère être l'un des principaux facteurs, était plus bas dans les forêts endommagées. Les taux de dépôts atmosphériques étaient étroitement liés à l'acidité des sols, mais pas directement aux dommages dus à la tempête. Même si les mécanismes provoquant l'interdépendance de l'acidité du sol et des dommages dus aux tempêtes ne sont pas clairement élucidés, l'acidité du sol devrait être considérée comme un facteur risque de grande importance. En outre, cette étude réalisée à large échelle confirme qu'une plus grande proportion d'arbres à feuilles caduques réduirait la sensibilité des forêts aux dommages dus aux tempêtes.

dépôts atmosphériques / régression logistique / pH du sol / dommages dus aux tempêtes / vitesse du vent

1. INTRODUCTION

Factors related to the occurrence of storm damage in forests can be grouped into four categories: meteorological conditions, topographic position, soil conditions, and stand characteristics. The relative importance of factors from these four categories has been considered in many studies using multivariate approaches (e.g. [10, 26, 34, 39]). However, chemical soil properties have not usually been included as exact soil information is mostly not recorded. One exception is the study by Braun et al. [7], in which greater storm damage in *Fagus sylvatica* L. and *Picea abies* (Karst.) L. stands was found on sites with low base saturation (< 40%). However, their study was restricted to a small sample of 62 storm-damaged sites in Switzerland.

Soil texture and soil chemical properties determine the nutrient supply available and the root anchorage of trees and are thus potentially related to storm damage. But soil conditions may have changed during the previous decades (e.g. [4, 14, 46]) due, for example, to atmospheric deposition. Atmospheric sulphur and nitrogen inputs have been shown to result in a decrease in soil pH [22]. A low soil pH could indirectly reduce a tree's resistance to storm damage by reducing the amount of soil volume exploited by its root system. The release of toxic aluminium species in the soil chemical solution may play a role in this since it has been shown to reduce fine-root growth in the subsoil [16, 32], which can lead to more superficial coarse root systems [25]. These effects have so far been demonstrated only for *Picea abies*. Additionally, increased nitrogen depositions

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Table I. Inventories used for the study (dbh = diameter at breast height).

Inventory description	France	Baden Württemberg	Bavaria	Switzerland
Name and year of the inventory on stand structure and storm damage, year of the inventory	Réseau européen de suivi des dommages forestiers, 2000	Terrestrische Waldschadens inventur, 2000	Waldzustands erhebung, 2000	Landesforst inventar, 1993–1995, storm damage inventory 2000
Plot shape and size, criteria for tree selection	No fixed dimension, with 20 trees per plot located close to the plot centre, only dominant and co-dominant trees are selected	4 subplots along the main compass directions at a distance of 25 m from the grid point, 6 trees selected closest to each subplot centre, 24 trees per plot, only dominant and co-dominant trees are selected		Fixed-radius circular plots of 200 and 500 m^2. In the small circle all trees with dbh > 12 cm are selected, in the large circle all trees with dbh > 36 cm
Name and year of the inventory on soil conditions	Inventaire écologique, 1993–1994	Bodenzustands erhebung, 1990–1991	Waldboden inventur, 1987	Waldzustands inventur, 1993
Grid width of inventory plots (both inventories)	16 km × 16 km	16 km × 16 km	8 km × 8 km	8 km × 8 km
Total number of plots	494	136	241	98
Number of plots with storm damage	104	47	18	12
References (see also [23])	[2]	[8, 13]	[18]	[6, 10, 48]

can result in a reduced root/shoot ratio [12, 19, 29] and a lower wood density (Körner, personal communication). Such a change in the physical wood properties of a tree could make it more susceptible to stem breakage.

If one or several of these mechanisms act not only in an isolated situation, but at least on a regional scale, then storm damage can be expected to occur more often on acidic soils. We therefore hypothesised that storm damage would be more frequent on sites with (1) acidic soils and (2) high deposition rates of sulphur or nitrogen.

These hypotheses have not yet been tested on a large geographical scale because measuring chemical soil properties and deposition rates is laborious and costly. However, international large-scale monitoring programs such as ICP Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) and spatially modelled deposition rates can help to overcome these problems. Using a data set of 969 sites in France, southern Germany and Switzerland, we investigated the effect of soil properties and deposition rates on forest storm damage, and controlled the effects of other variables by including them in a multiple regression model.

2. METHODS

The study considered damage by the storms "Lothar" on December 26th, 1999, and "Martin" the following day. Lothar affected northern France, southern Germany (the counties of Baden-Württemberg and Bavaria) and northern Switzerland, while Martin affected central France and south-western Switzerland [52]. The two storm events originated from the same general weather situation [52] and therefore data from both storms was used in this study. The total investigated forest area amounts to about 19 000 km^2, with *Abies alba* Mill., *Fagus sylvatica*, *Picea abies*, *Pinus* spp., and *Quercus* spp. as the most frequent tree species. The data for storm damage, stand structure, and site conditions in the region investigated originate from several forest and soil inventories (Tab. I), which are part of the forest monitoring program ICP Forests (Level I).

We investigated the effects of various factors on storm damage on a site level, i.e. not a single-tree level, with a multiple regression approach. The logistic regression model is a non-linear transformation of the linear regression [21]. The response variable in standard logistic regression is binary. In our case the variable had the two values "storm damage occurred on the site" and "no storm damage occurred on the site". In addition, an ordinal logistic regression model was calculated and its results were compared with the binary regression model. The response classes in the ordinal model were calculated for each site from the proportion of the basal area of damaged trees in relation to the basal area of all trees. Models with binary responses were preferred because of methodological differences between countries in the recording of storm damage, the relatively small number of sampled trees per plot (Tab. I), and a skewed distribution with many plots with little damage and few plots with heavy damage.

A global model was calculated using all data, as well as separate models for France only and for Baden-Württemberg only. Calculating submodels was not possible for Switzerland because of the small number of plots in total, and for Bavaria because of the small number of damaged plots.

Predictor variables were classified as nominal, ranked, or continuous [45] (Tabs. II and III). Most nominal variables had different classes in the countries investigated. This necessitated standardisation to allow a combined analysis of all data. Therefore, the classes used in each country were aggregated into new classes, on the lowest common level of information. For example, topographic position is described with 11 categories in France, but with only 5 in Switzerland. We therefore assigned each French category to a Swiss category and used the latter for the classification (an extensive list describing this

Table II. Continuous and ranked explanatory variables included in the analysis.

Variable	Type	Description
Altitude	Continuous	Meters above sea level
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
Cation exchange capacity	Continuous	Mean cation exchange capacity in cmol kg^{-1} for upper 40 cm of the soil
Deposition of N (NO_x + NH_x), SO_x (all countries)	Continuous	Modelled bulk deposition, 50 × 50 km^2 grid
Deposition of N (NO_x + NH_x), SO_x (France)	Continuous	Bulk deposition modelled with a geostatistical approach, converted with factor [15] into wet deposition
Deposition of N (NO_x + NH_x), SO_x (Baden-Württemberg, Bavaria, Switzerland)	Continuous	Modelled wet deposition, 1 × 1 km^2 grid
Proportion of coniferous species	Continuous	% coniferous trees of total stand basal area
Slope	Continuous	Slope in percent
Soil depth	Continuous	Lower limit of soil profile in cm (no data available for Bavaria)
Soil pH	Continuous	Mean pH ($CaCl_2$) (in the case of Baden-Württemberg mean pH (KCl)) for upper 40 cm of the soil
Stand height	Ranked	Average tree height in steps of 5 m (for Baden-Württemberg, tree height was estimated using stand age and yield tables)
Wind speed instantaneous (model with all countries)	Continuous	Modelled wind speed, 10 m above surface
Wind speed maximum (model with all countries)	Continuous	Maximum modelled wind speed within the last hour, 10 m above surface
Wind speed (model for France)	Ranked	8 classes with a width of 20 km/h for the classes above 80 km/h

reclassification procedure for all nominal variables is available from the authors).

Modelled wind speed data were provided by MeteoSwiss. Data were based on a high-resolution version (grid mesh 14 km) of the European model developed by the German Meteorological Service [30]. Modelled wind speeds were calculated as instantaneous values. From these values, maximum speeds on December 26th and 27th 1999 were calculated. For the regression model with only French data, a different wind model was used. In this model the maximum instantaneous wind speed per plot is based on an interpolation by MeteoFrance using 507 plots located below 500 m in altitude [28].

Atmospheric deposition rates of sulphur (SO_x) and nitrogen (the sum of NO_x and NH_x) were compiled from models with different resolutions: (1) The EMEP model, developed in the "Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe", with a resolution of 50 km [3] for the whole study area; (2) models with finer resolutions for France [9], Germany [15] and Switzerland [27].

We started our analysis with an extensive set of predictor variables (Tabs. II and III, see [33]). To detect multi-collinearity, i.e. strong correlations between predictor variables, two strategies were used: (1) Pearson correlation coefficients (r) were calculated between continuous predictor variables. Of those pairs of variables with $r > 0.45$, only one variable was included in the model. (2) The variance inflation factor (VIF) of the predictor variables included in the model was compared with a critical value of 10 [1]. The VIF is calculated as $1/(1-R^2)$, with R^2 obtained in a regression of the predictor variable against all other predictor variables. For continuous predictor variables, VIF was calculated with linear regression, and for nominal variables with logistic regression (in the latter case D^2 instead of R^2 was used).

Variables were ordered in the multiple models beginning with the variable with the lowest p-value in a univariate logistic regression (response storm damage yes/no) and ending with the one with the highest p-value. The goodness-of-fit was estimated using the formula: D^2 = (null deviance – residual deviance) / null deviance [17]. The logistic regression was performed in S-PLUS 6.1 for Windows Professional Edition with a logit link function, a maximum number of 50 iterations and a convergence tolerance of 0.0001.

Table III. Nominal explanatory variables included in the analysis.

Variable	Categories
Aspect	(1) north-west, west, south-west, (2) other
Bedrock acidity	(1) acidic, (2) intermediate, (3) alkaline
Humus type	(1) mull, (2) moder, (3) mor, (4) other
Soil moisture	(1) moist, (2) dry
Soil texture	(1) fine, (2) medium, (3) coarse
Soil type	(1) arenosols, (2) cambisols, (3) fluvisols, (4) gleysols, (5) histosols, (6) leptosols, (7) luvisols, (8) planosols, (9) podsols, (10) regosols, (11) vertisols
Stoniness	Stone content of the soil: (1) low, (2) medium, (3) high
Topography	(1) plain, plateau, (2) ridge, hilltop, (3) mid-slope, (4) foot of hill, gully, (5) other

3. RESULTS

The proportion of damaged plots was 19% in the data set with all countries. Proportions ranged from 35% in Baden-Württemberg, 21% in France, 12% in Switzerland to 7% in Bavaria.

Table IV. Continuous explanatory variables excluded from the multiple regression because of strong correlations with other explanatory variables. When the correlation coefficient exceeded 0.45, one variable was excluded.

Excluded variable	Maintained variable	Correlation coefficient between excluded and maintained variable
Base saturation	Soil pH	0.823
Cation exchange capacity	Soil pH	0.725
Base cation/aluminium ratio	Soil pH	0.527
Wind speed instantaneous (model with all countries)	Wind speed maximum (model with all countries)	0.457

3.1. Relative importance of the predictor variables for storm damage

To avoid multi-collinearity, four predictor variables were excluded from the regression models: “base saturation”, “base cation/aluminium ratio”, “cation exchange capacity”, and “instantaneous wind speed” (Tab. IV). In the global model with data from all countries, several variables were significantly related to the occurrence of storm damage. In order of increasing *p*-values and thus decreasing relevance, they included “country” (more frequent damage in Baden-Württemberg and France than in Switzerland and Bavaria), “soil pH” (lower pH on damaged sites), “proportion of coniferous species” (higher proportion on damaged sites), “slope” (less slope on damaged sites), “humus type” (sites with humus type “mor” were more frequently damaged), “stand height” (stands with high trees were more frequently damaged) and “altitude” (sites at lower altitudes were more frequently damaged) (Tab. V).

Stand height was not significantly related to storm damage in a model that included only sites with a minimum stand height of 20 m (data from all countries). Thus an increase in the risk of storm damage with increasing stand height seems to be relevant only in stands with a relatively low height. Tall stands have a high risk but this risk does not increase with further increases in stand height. This relationship is reflected in the proportion of damaged plots for the different height classes (Tab. VI). Only one plot had a stand height below 2.5 m, and only three plots above 37.5 m.

When we replaced “soil pH” with “base saturation”, “base saturation” was significantly related to storm damage. It showed the highest explanatory power after “country” (data from all countries, model not presented). In this model the other significant variables were identical to those mentioned above.

“Maximum wind speed” was not significantly related to storm damage in the model for all countries, but it was in the model for France (Tab. V). This may be due to differences in the wind models, which probably provided more realistic wind estimates for France. Another variable significant in the model for France but not in the model for all countries was “soil texture”, with stands on coarse (sandy) soils being more frequently damaged. Variables significant in both the model for all countries and the model for France, and with the same direction of the effect, were “proportion of coniferous species”, “soil pH”, “stand height” and “slope”.

In the model for Baden-Württemberg only two variables were significantly related to storm damage: “aspect” (sites exposed to the west more frequently damaged) and “proportion of coniferous species” (higher proportion on damaged sites, Tab. V).

Table V. Results of the logistic regression analyses. The response variable was storm damage “yes/no”. The figures show Pr(Chi). Significant p-values ($p < 0.05$) are marked with an asterisk. The variables were fed into the regression model from lowest to highest Pr(Chi) in univariate regression with the response variable storm damage yes/no. In the model for France, specific wind speed data provided by [27] and bulk deposition data provided by [9] were used. In the model for Baden-Württemberg, total deposition data provided by [14] was used.

Variables	All countries	France	Baden-Württemberg
Altitude	0.012*	0.073	0.444
Aspect	0.063	0.757	0.000*
Bedrock	0.213	0.895	0.895
Country	0.000*	–	–
Deposition N	0.387	0.603	0.335
Deposition S	0.493	0.106	0.970
Humus type	0.007*	0.385	0.389
Proportion of conifers	0.001*	0.000*	0.003*
Slope	0.006*	0.042*	0.815
Soil moisture	0.286	0.796	0.166
Soil pH	0.000*	0.001*	0.124
Soil texture	0.121	0.001*	0.556
Soil type	0.196	0.063	0.807
Stand height	0.012*	0.015*	0.667
Topography	0.435	0.126	0.235
Wind speed maximum	0.343	0.000*	0.629
Number of plots	969	494	241
D^2 (null deviance – residual deviance) / null deviance	0.21	0.35	0.29

Estimated deposition rates were not significantly related to storm damage in any of the three models (Tab. V). In univariate comparisons, mean deposition rates were not higher on damaged sites. Thus, no simple relationship between estimated deposition rates and storm damage was found.

The variance inflation factors (VIF) in the global model were largest for “soil pH” (VIF = 2.94), “country” (2.56) and

Table VI. Stand height and percent of sites with storm damage. Differences in the occurrence of storm damage between classes of stand height were significant (chi-square test, $p = 0.0285$).

Stand height (m)	Number of sites	Occurrence of storm damage (%)
< 2.5	1	0.0
2.5–7.5	49	10.2
7.5–12.5	68	7.4
12.5–17.5	171	13.5
17.5–22.5	244	21.3
22.5–27.5	207	22.2
27.5–32.5	146	23.3
32.5–37.5	61	21.3
37.5–42.5	3	0.0

"bedrock acidity" (2.00). As the VIF did not exceed the critical value of 10 [1], and as models with a reduced set of predictor variables did not show new results, all variables were retained in the model.

When we replaced the binary response variable with the percentage of storm damage in 5 equal classes (width 20%), i.e. in an ordinal regression approach, with data from all countries, the results were similar, but not identical to the model with binary response as described above. In contrast to the binary model the variable "soil type" was significantly related to storm damage. There were two variables, "humus type" and "altitude", that were not significant in the ordinal regression model but were in the binary model.

3.2. Soil pH as a predictor variable

Soil pH was one of the most significant factors in the model for all countries and the model for France (Tab. V). On damaged sites, the median soil pH was 0.3 pH units lower in the data set for all countries (Fig. 1). Medians of soil pH of undamaged and damaged sites were 4.5 and 4.2 for France, 5.6 and 4.9 for Switzerland, 3.5 and 3.5 for Baden-Württemberg, and 3.8 and 4.0 for Bavaria. In Bavaria, however, the only country where the median soil pH was higher on damaged sites, the number of sites with damage was very small (18 out of 241).

The fact that some non-soil variables correlate with both soil-pH and storm damage could help to explain some potentially misleading correlations that are responsible for the observed lower pH on damaged sites (see the discussion for possible misleading correlations). "Altitude", "deposition rates", "proportion of coniferous species" and "maximum wind speed" were only weakly related to "soil pH", but the relationships were significant in a linear regression (Tab. VII).

"Soil pH" and "soil depth" were more strongly correlated, with a higher pH on shallow soils (Tab. VII). Moreover, sites with high soil pH (pH > 6.5) were associated with alkaline bedrock, high stone content and fine soil texture (Tab. VIII). Sites with low soil pH (< 4.5), which were more susceptible to storm damage, were associated with acidic bedrock, low stone content, and coarse soil texture (sandy soils).

Table VII. Pearson correlations of "soil pH" with continuous variables (one by one). For the variable "soil depth", analyses were calculated for a reduced data set since data were unavailable for Bavaria.

	Correlation coefficient with soil pH	p-value, linear regression with soil pH as response
Altitude	0.08	0.000
Deposition N	–0.24	0.000
Deposition S	–0.25	0.000
Proportion of conifers	–0.24	0.000
Soil depth	–0.47	0.000
Maximum wind speed	–0.22	0.000

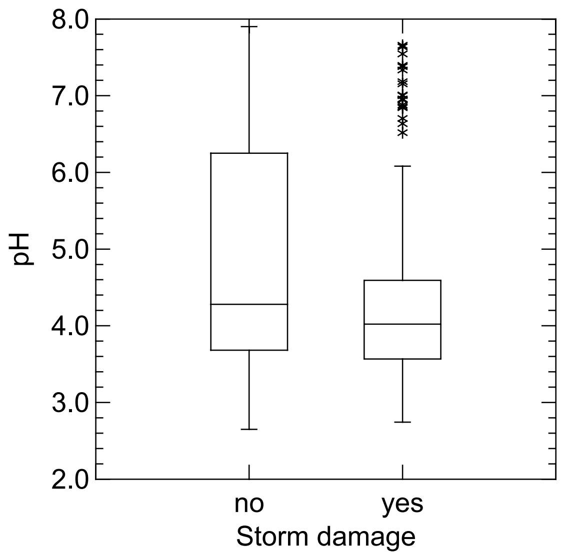

Figure 1. Soil pH on sites without ($N = 788$) and with storm damage ($N = 181$). The horizontal lines in the middle of the boxes are medians. The horizontal lines marking the box ends are the upper and lower quartiles. Asterisks (*) indicate values that are below the 1st quartile or above the 3rd quartile by at least 150% of the interquartile range (3rd–1st quartile). The relationship is significant in univariate logistic regression (response: storm damage yes/no, predictor: soil pH) with $p = 0.000$.

Deposition rates correlated more strongly with "soil pH" if only subsets with a limited pH range and not all the data were included in the analysis. For sites with pH below 4.5, the Pearson correlation coefficient of nitrate deposition with soil pH was $r = –0.45$ (linear regression: $p = 0.000$), and of sulphate deposition $r = –0.41$ (linear regression: $p = 0.000$). Correlations of soil pH with ammonia deposition were very weak for this subset ($r = –0.01$, linear regression: $p = 0.826$), but significant in a subset of sites with pH > 6.5 ($r = –0.33$, linear regression: $p = 0.000$).

Table VIII. Cell frequencies of nominal soil variables in different classes of soil pH. For the variable "stoniness" analyses were calculated for a reduced data set excluding plots in Bavaria.

Variable	Classes	Number of plots	% of plots with			p (chi-square test)
			pH < 4.5	pH 4.5–6.5	pH > 6.5	
Bedrock	Acid	223	34.9	10.0	0.5	0.000
	intermediate	426	50.7	37.2	29.6	
	alkaline	320	14.4	52.8	69.8	
Stoniness	Low	379	60.5	52.3	31.7	0.000
	intermediate	172	26.0	18.7	23.0	
	high	173	13.5	29.0	45.3	
Soil texture	Fine	97	2.3	18.8	22.7	0.000
	medium	617	63.7	62.9	66.7	
	coarse	253	34.0	18.3	10.6	

4. DISCUSSION

4.1. Merits and drawbacks of our statistical approach

Storm damage is the result of complex interactions between many factors [49]. In this study, we used regression models with a large number of variables to analyse data from a region covering several countries in Central Europe. This approach has advantages and disadvantages. The advantages are: (1) It is quite powerful since, with 969 sites, many observations are included. (2) It was possible to test the effects of many variables on storm damage simultaneously. This does not mean that a mechanistic explanation of the observed relationships is possible because only correlative relationships could be found. However, with our extensive set of explanatory variables, plausibility checks and the identification of misleading correlations were possible. Correlations between predictor variables (multicollinearity) were a potential problem, which had to be addressed. (3) Many factors in our data varied greatly because the geographic region investigated was large. Therefore the potential effects of factors were easier to detect, and the results have a more general validity. However, this is not only an advantage because global patterns may not apply on a finer local scale.

The disadvantages are: (1) It was not always easy to compare the values for some variables between countries as a result of methodological differences (see Tabs. I and II). (2) Some variables were rough estimates based on models (e.g. wind speed). This may, in some cases, explain why they were not significantly related to storm damage.

The chosen approach with a binary, instead of a ordinal, response has both an advantage and a disadvantage. The advantage is that the results are very stable even though the number of cases in the two classes differed considerably (81% of the cases in the class "no storm damage", 19% in the class "storm damage"). The disadvantage is that the results do not allow the prediction of the extent of storm damage, but only its occurrence. However, the majority of plots in our data-set had little damage and our results can help to explain the occurrence of this kind of damage. According to a Swiss study carried out after "Lothar", more than half of the damage, in terms of tree canopy cover affected, was scattered damage with less than 30% of the canopy disturbed [11].

4.2. Relative importance of predictor variables

Significant variables in the logistic regression model with all data were "country", "soil pH", "proportion of coniferous species", "slope", "humus type", "stand height", and "altitude". The high explanatory power for storm damage of the variable "country" is surprising because, in principle, this variable should be ecologically irrelevant. The large differences between countries in the proportion of damaged sites should be captured by other explanatory variables. The observed high explanatory power of "country" for storm damage could be due to (1) methodological differences (e.g. the smaller number of sampled trees on the Swiss plots could have resulted in a smaller number of plots where at least one tree was damaged), (2) differences in factors related to storm damage between countries and, at the same time, no or only poor representation of these factors in any explanatory variables other than "country" (e.g. differences in storm characteristics such as duration of strong winds or gusts), or (3) country-specific differences in interactions between explanatory variables.

4.3. Soil pH as a predictor variable

"Soil pH" had the second highest explanatory power for storm damage, which was unexpected. The significantly lower soil pH on damaged sites (Fig. 1) may have been the result of misleading correlations with non-soil variables. The cause of the detected pH effect would then be not soil pH, but a third variable which is related both to storm damage and soil pH. Two misleading correlations seem possible: (1) Coniferous tree species were found to cause soil acidification [38] and these species are more susceptible to storm damage ([10, 40], this study). Thus it is possible that storm damage is not related directly to low soil pH, but is only more frequent in stands with a high proportion of coniferous species. A significant correlation (Tab. VII) seems to support this point. However, the pH values on damaged sites were lower than those on undamaged sites in both pure coniferous and pure deciduous stands (results not shown). Such an effect may thus play a certain role, but cannot explain the high explanatory power of "soil pH". (2) It is possible that the sites with low soil pH coincided with high wind speed. There was a weak but significant negative correlation between soil pH and wind speed estimates (Tab. VII).

However, it is likely that the modelled wind speed data we used did not adequately represent the real wind speed. The fact that we found no effect of wind speed on storm damage in the model for all countries supports this conclusion. The geographical distribution of soil pH seems to be more related to the underlying bedrock (Tab. VIII) than to prevailing wind patterns during "Lothar" and "Martin". In conclusion, we assume that such potentially misleading correlations had no relevant effect.

Many soil properties are related to soil pH [41]. We therefore assume that it is not just a single mechanism but several pH-related mechanisms that simultaneously affect the storm resistance of trees. With our correlative approach, however, we are unable to distinguish these different mechanisms. Nevertheless we do suggest some potential mechanisms.

On sites with low pH, root anchorage may be reduced because of toxic aluminium species and a shortage of calcium and magnesium availability. Toxic aluminium species are released below pH 5 and cause reduced fine root growth [31]. However, this mechanism cannot be fully responsible for the observed pH effect since a higher occurrence of damage on sites with lower pH was also observed on sites with pH > 5 where aluminium toxicity does not occur (models not shown). Moreover, on acidic sites, shortages of calcium and magnesium are more likely to occur. A shortage of calcium could be related to reduced tear strength of roots [31]. This means that roots potentially break easier and thus loose their capacity to anchor trees in the soil. A shortage of magnesium causes reduced root growth [31]. On sites with pH > 5 no aluminium toxicity occurs and usually the availability of calcium and magnesium is high. The effects mentioned above should result in a better root anchorage on sites with higher pH. In addition, high calcium content in the soil promotes a stable soil structure [41] which is first related to high sheer resistance and second allows water to percolate fast to the groundwater. During the period before the storm "Lothar" and "Martin", in some regions heavy rainfalls had occurred. Therefore, the percolation capacity may have influenced a stand's resistance to storm.

Sites with high pH, and little storm damage, were associated with fine soil texture, shallow soils, and high stone content (Tabs. VII and VIII). Fine soils (clays) have a high cohesive and adhesive strength and were found in tree pulling experiments to provide better root anchorage than coarse soils [35]. Trees on rocky and shallow soils are often well anchored because roots penetrate into rock crevices [37]. In Central Europe rocky and shallow soils often occur on calcareous bedrock with high pH, e.g. Rendzinas (a type of Leptosols). Therefore a possible reason for there being less damage on sites with high pH could be that the root anchorage on them is stronger. The effects of soil-water content on storm damage could be related to soil depth, too, because water tends to percolate well through shallow soils with high stone content (e.g. Leptosols). However, in contrast to our results, some other studies found storm damage was actually higher on shallow soils ([5, 36, 40, 51]), which the authors attributed to the reduced rooting depth. Moreover, the fact that many windthrow-affected areas on shallow soils coincide with topographically exposed landform positions [44], may make them more susceptible to damage.

In a study using Swiss data, storm damage was more severe on sites with low base saturation [7]. This agrees, to a certain extent, with our results for Central Europe: We found "base saturation" to have significant effects on storm damage in a logistic regression model with "base saturation" instead of "soil pH". Also, storm damage occurred more frequently on sites with low base saturation. However, our response variable was binary (storm damage yes/no) and we included all sites in our analysis, whereas [7] used a continuous response variable (proportion of damaged trees) and included only sites with at least one tree damaged.

As we found greater storm damage on sites with low soil pH, we need to consider the factors affecting soil pH. The decisive factor is bedrock, or more precisely, the carbonate content and buffer capacity of the bedrock (Tab. VIII). On sites with low buffer capacity, atmospheric depositions of sulphur and nitrogen reduce soil pH [47, 50]. On these sites acidic atmospheric depositions are likely to increase the risk of storm damage. In contrast, on sites with a high carbonate content and buffer capacity of the bedrock, acidic depositions are unlikely to affect storm damage. However, we would like to stress that, even though we found no significant effect of modelled deposition rates on storm damage, such an effect cannot be excluded for real deposition rates.

4.4. Other predictor variables

The other variables significantly related to storm damage are not as surprising as "soil pH" or "country", but confirm existing knowledge. Deciduous trees are less susceptible than coniferous trees to storm damage because they have a lower wind load during the leafless period, when strong winds usually occur in central Europe [10, 24, 26]. More frequent damage on sites with gentle slopes can be explained by the reduced run-off and therefore higher water logging on these sites in comparison with sites on steep slopes. More frequent damage on the humus type "mor" fits well with our observed pH effect because mor is usually found on acidic bedrock with a low soil pH. However, it is not clear what effect is responsible for the additional explanatory power of the variable humus type, independently of the variables pH and tree species (tree species affect the humus type with their litter).

Stands with taller trees have already been shown to be more susceptible to storm damage [10, 26, 39, 51]. The increase in area affected by storm damage in Europe has been explained with increased tree ages and thus taller trees [42]. However, our results suggest that above a certain limit, stand height is less important in explaining storm damage. Storm damage increases linearly with increasing stand height only at heights below approximately 20 m (Tab. VI). The high variation in stand height distribution, tree species composition and possibly also canopy roughness between sites may explain why our results differ from those found in previous studies. In *Fagus sylvatica* stands in north-eastern France, storm damage increased almost linearly with increasing stand height in stands taller than 20 m [5]. Stand height was also the most important variable explaining the occurrence of storm damage in a Swiss study [10]. In this study, the optimal cut-off point for damaged and non-damaged stands occurred in stands between 25 and 30 m in height.

Altitude was negatively related to storm damage in our study. This result is unexpected because wind speed usually increases with increasing altitude [20]. However, the hurricanes "Lothar" and "Martin" caused damage primarily in the lowlands and had lost much of their force by the time they reached the Alps.

We were surprised to find that wind speed was not significant in the model for all countries because the primary reason for storm damage is, of course, wind. Wind speed during "Lothar", however, varied on a small spatial scale [43] and the wind model used may well have been too rough as the grid size was 14 km^2. Similarly, radar estimates of wind speed 1000 m above ground with a resolution of > 250 m were unable to explain storm damage around Zurich in Switzerland [43]. The greater explanatory power of the French wind estimates could be the result of them being more reliable. Realistic wind speed estimates are probably easier to obtain in the less complex French terrain than in Baden-Württemberg, Bavaria, and Switzerland. In agreement with our results for France, wind speed was significantly related to storm damage in a study covering north-eastern France [5].

4.5. Differences between countries

The significant variables in the model for France were very similar to those in the model for all countries. This was probably due to the high proportion of French sites in the data set. As 494 out of 969 sites (51%) were located in France, the results in the model for all countries were clearly affected by the situation in France. Thus, our set of predictor variables is best suited for explaining storm damage in France.

The model for Baden-Württemberg had only two significant variables: "proportion of coniferous species" and "aspect". The small number of significant variables may be due to the relatively small number of sites (n = 136) compared to the number of predictor variables (n = 16). "Soil pH" was not significant in this model, probably because few of the sites in this country had a pH above 4. The pH effect, with a lower pH on damaged sites, was found in France and Switzerland only, where the medians of soil pH were relatively high in comparison with the two other countries.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FOREST MANAGEMENT

The observed lower pH values on sites with storm damage are based on a reliable database. No evidence for misleading correlations with non-soil variables was found. Thus, it is reasonable to expect the risk of storm damage to be higher on sites with low soil pH. We have not, however, been able to identify a single mechanism to explain this observed relationship. We assume that complex soil-root interactions must be the underlying cause.

The root-soil interactions of trees have not yet been conclusively investigated. Future studies should explore experimentally the relationships between soil pH and root growth, root dimensions, and root tear strength.

The effect of sulphur and nitrogen depositions on the soil-root system remains unclear. On one hand, in this study sulphur and nitrogen depositions were not significantly related to storm damage. On the other hand, stands on acidic soils were more severely damaged, and sulphur and nitrogen depositions are known to cause soil acidification on poorly buffered soils [50].

Even though the observed pH effect on storm damage is difficult to explain, these empirical results have important implications for forest managers who want to base silvicultural decisions on the best possible information about risks and benefits. Our study suggests that soil acidity should be taken into account in such decisions. From an economic perspective, we suggest investing less in trying to produce high quality timber on acidic sites because these sites carry a greater risk of storm damage. Although some conifers have a high resistance to storm damage, coniferous species are generally more susceptible than deciduous species. Therefore we recommend increasing the proportion of deciduous species in stands to reduce the risk of storm damage.

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