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Original article

Relation between ecological conditions and fir decline in a sandstone region of the Vosges mountains (northeastern France)

Anne-Laure Thomas[a], Jean-Claude Gégout[b,*], Guy Landmann[c], Étienne Dambrine[d] and Dominique King[a]

[a] Unité Science du Sol, SESCPF, INRA, 45160 Ardon, France
[b] Unité Écosystèmes Forestiers et Dynamique du Paysage, ENGREF, 14 rue Girardet CS 4216, 54042 Nancy Cedex, France
[c] DERF, Département de la Santé des Forêts, Ministère de l'Agriculture et de la Pêche, 19 avenue du Maine, 75732 Paris Cedex 15, France
[d] Centre de Recherches Forestières, INRA, Champenoux, 54280 Nancy, France

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Abstract – The present study re-examines the influence of ecological conditions on the health of silver fir (*Abies alba*) measured in 1989, during the so-called forest decline crisis, in the sandstone portion of the Vosges mountains, on the basis of an assessment of almost 3000 forest management units (10–20 ha each). Relationships between defoliation and needle yellowing (related to Mg deficiency) and environmental factors were analysed with contingency tables and modelled using discriminant functions. The results confirmed the predominant influence of altitude and stand age; these two factors explain 70% of the spatial variability of defoliation and 64% of that of yellowing. In addition, a database composed of 178 soil analytical profiles was analysed in relation to the geographic database. The commonly used variable "altitude" appeared to combine the influence of several related variables which are crucial for the biological functioning of the tree: especially the plant available water holding capacity and chemical characteristics were negatively correlated with elevation in the study area. This ecological feature is likely to be common to a number of mid-elevation mountain range in Europe and was often neglected in the earlier studies on forest decline.

forest decline / *Abies alba* / GIS / spatial analysis / discriminant analysis / Vosges mountains

Résumé – Relations entre les conditions écologiques et le dépérissement du sapin dans les Vosges gréseuses (France). Ce travail réexamine l'influence des conditions écologiques sur le dépérissement du sapin, mesuré lors de la crise du dépérissement forestier dans les Vosges, sur la base d'une notation exhaustive de 3 000 parcelles forestières (10–20 ha) gérées par l'Office National des Forêts dans les Vosges gréseuses. Les relations entre défoliation et jaunissement des aiguilles (généralement dû à une carence en Mg) et les conditions environnementales moyennes de chaque parcelle ont été étudiées par des tableaux de contingence, et modélisées en utilisant une analyse discriminante. L'altitude et l'âge des peuplements expliquent respectivement 70 % de la défoliation et 64 % du jaunissement. Le paramètre « altitude » combine de nombreux facteurs influençant le fonctionnement physiologique de l'arbre. En utilisant une base de données de 178 profils pédologiques, nous montrons que l'altitude est négativement corrélée à la réserve utile des sols et au taux de saturation, indépendamment du type de grès. Ce type de distribution est probablement assez banale dans un certain nombre de moyennes montagnes européennes, et forme un biais souvent négligé dans les études de dépérissement.

dépérissement forestier / *Abies alba* / SIG / analyse spatiale / analyse discriminante / Vosges

* Correspondence and reprints
Tel. +383 39 68 64; Fax. +383 39 68 78; e-mail: gegout@engref.fr

1. INTRODUCTION

At the beginning of the 1980s, a decreased vitality of silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* Karst.) was observed in several mid-elevation mountains of Central Europe. Visible symptoms were defoliation and yellowing of the foliage [15, 16]. In France, defoliation was most pronounced in the Vosges mountains in the North-East and needle yellowing due to a magnesium deficiency was especially widespread in the Vosges and the Ardennes [15].

Scientific studies carried out in the framework of the DEFORPA programme (French acronym for Forest Decline and Atmospheric Pollution) revealed that several factors interacted [14]:

– the climatic conditions, especially repeated droughts [1, 2];
– the site (topography, parent material, soil, etc.) and stand (age, density, etc.) characteristics [4, 15];
– the atmospheric deposition of acidic compounds on soils originally highly depleted, which causes losses of cations, primarily at the expense of the exchange complex, thereby increasing the nutritional difficulties of the forest trees [9].

These results were obtained primarily by field surveys and intensive studies using a relatively small number (typically in the range of 5–100) of sites.

The aims of this study were to: (1) analyse the relationships between the distribution of ecological conditions and the condition of silver fir trees in the sandstone Vosges with the help of a large statistical data base and (2) provide indicators to establish a map of zones at risk of decline.

2. MATERIALS AND METHODS

2.1. Study site

The study site covers a surface of 265 000 hectares (ha) in the western part of the Vosges. The climate is oceanic with a continental influence (mean temperature: 9 ^{o}C at 400 m of altitude; mean yearly precipitation: 1 000 mm). Altitude is moderate, ranging between 300 and 1 000 m.

The substrate is composed of different types of sandstones and conglomerate from the Permian and Lower Trias. Depending on their composition [18] the following substrates can be distinguished (*table I*):

– the Vosgian sandstone and conglomerate, very rich in Si (93%) and highly depleted in alkaline and alkaline earth (Mg, Ca, Na, K) cations;
– the intermediate sandstone, slightly richer in K but which Si content remains high (88%);
– the Permian, Senones and Voltzia sandstones which are characterised by a lower Si content (less than 80%) and above all by higher K and Mg contents.

The health of fir trees was assessed in 2 977 management units in 1989 by field foresters of the French National Forestry Board (ONF) [20]). The method consisted in rating the defoliation (*figure 1*) and foliage yellowing (*figure 2*) of the trees of each basic management unit (typically 10–20 ha in the Vosgian forests). Damage was expressed in three classes (*table II*). Training courses were organised for all foresters involved. No quality control was made, however, and it must be assumed that the assessment is rather crude (differences between assessors, difficulty to assess the “average” health of a large area).

Table I. Chemical composition of the different sandstone layers in the Vosges Mts [18].

	SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
Permian	73.95	13.19	1.72	0.25	0.02	0.73	0.56	0.40	7.30	0.23	0.09
Senones	81.46	8.45	1.46	0.11	0.06	0.33	0.47	0.25	5.30	0.16	0.05
Vosgian	92.70	3.18	0.46	0.36	none	none	0.37	0.10	1.55	0.14	0.08
Conglomerate	91.19	3.75	0.69	0.53	0.02	0.66	none	0.20	1.30	0.16	0.02
Intermediate	88.31	5.38	0.97	0.31	0.11	0.32	0.19	0.20	2.85	0.23	0.06
Voltzia	78.61	10.77	1.27	0.73	0.01	0.90	traces	0.20	4.80	0.49	0.16

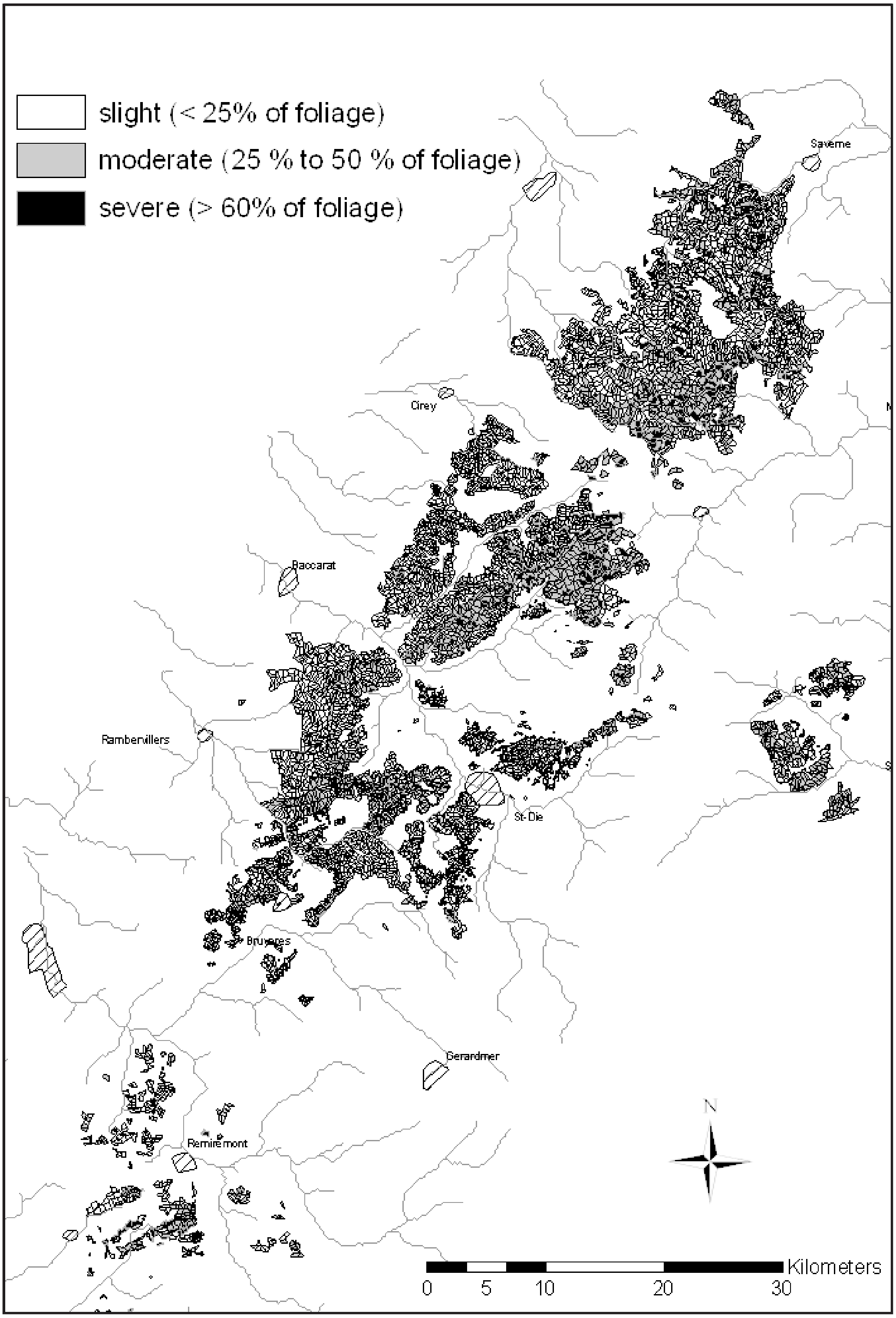

Figure 1. Map of Silver fir defoliation on sandstone in the Vosges Mts, evaluated on a forest management unit basis, in 1989.

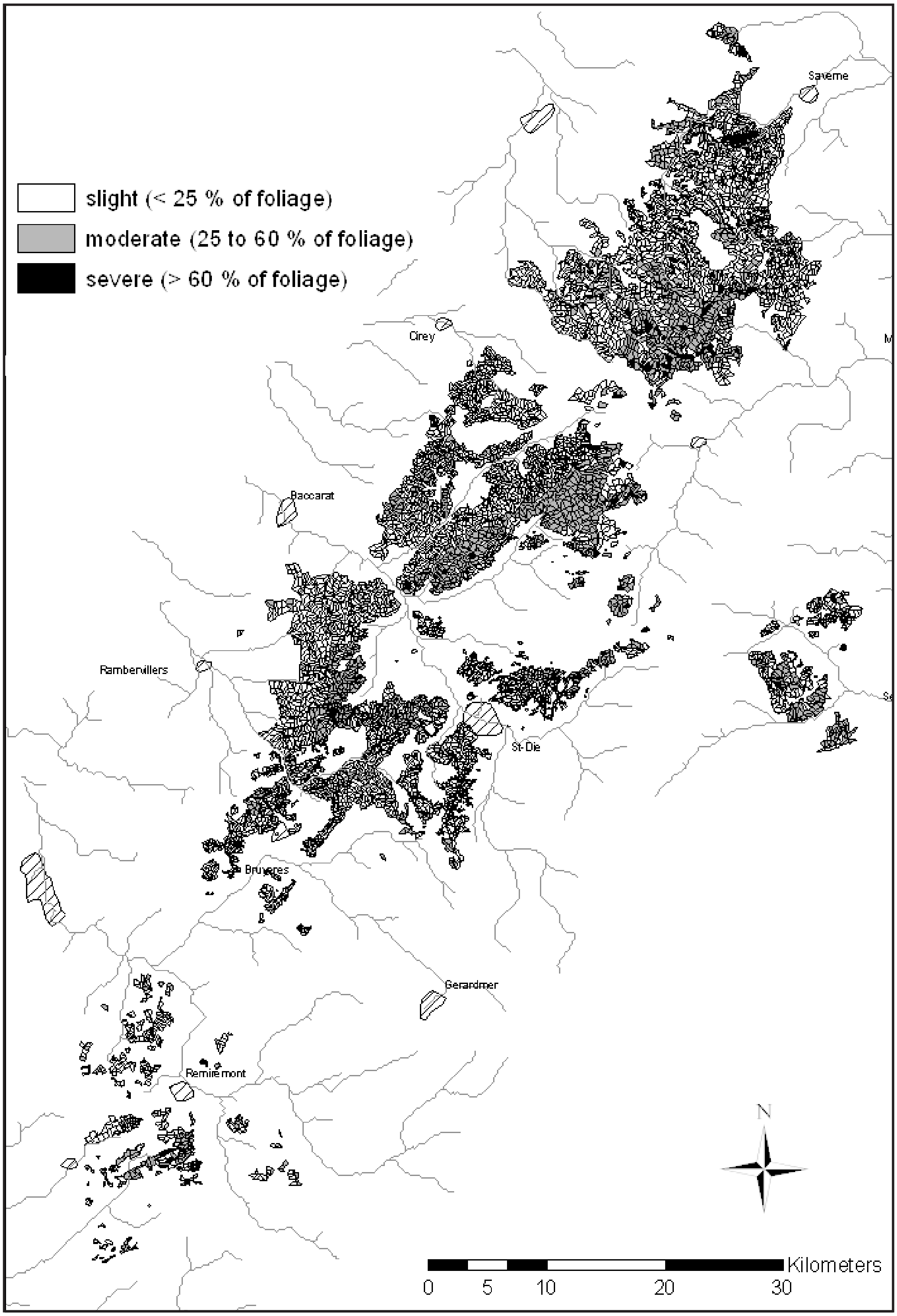

Figure 2. Map of Silver fir yellowing on sandstone in the Vosges Mts, evaluated on a forest management unit basis, in 1989.

Table II. Definition of damage classes.

Class	Loss or decoloration of foliage	Loss
1	< 25%	slight
2	25 to 60%	moderate
3	> 60%	severe

Geological data (maps at 1:50 000 scale) were obtained from the French Geological Survey (BRGM). Topographic data were obtained from a Digital Elevation Model (DEM) at a 50 m step taken from the IGN (National Geography Institute) database. Several parameters were derived from this database: (1) altitude, (2) slope, (3) slope orientation and (4) surface convexity in the direction of slope. Finally, climatic data at the 1 km step (annual precipitation and mean temperature) were obtained from Météo-France.

All data gathered were rendered consistent and georeferenced in the same projection system and thus constitute a geographic database of the sandstone part of the Vosges.

In order to circumvent the lack of soil data (only a map of soil types covering a part of study area was available), we built a second database of 178 plots describing the ecological conditions of sites (plant cover, topography, parental rock, pedogenetic types of soils) [10]. Physical (depth, texture, stoniness and structure) and chemical (pH-H_2O, pH-KCl, NH_4Cl-exchangeable Ca, Mg, K, base saturation at soil pH) characteristics of upper pedological horizons were available. The plant available water holding capacity (field capacity minus wilting point) down to 60 cm depth holding capacity down to 60 cm depth was estimated for 42 of these soils as a function of texture, stoniness and thickness of the horizons according to [13].

2.2. Analysis of the relationships between forest damage and ecological conditions

In order to study the effect of each ecological variable on fir decline, (1) all data were divided into classes, (2) the information layers were geographically combined, and (3) contingency tables were constructed with paired variables in order to obtain the area of each damage class for each class of ecological variable studied [6]:

– Altitude and slope were divided into classes of equal amplitudes; slope orientation was divided into 8 directions (N, NE, E, SE, S, SW, W, NW); topography was divided into convexity or concavity. Climatic variables (precipitation and temperature) were also transformed into classes of equal amplitudes.

– A Geographic Information System was used to geographically combine the different maps taken two by two (an ecological variable and defoliation or yellowing variable). After each cross, a unique layer was obtained composed of basic polygons containing all the data from the two combined layers.

– Using the resulting layers, contingency tables were established. Each class of damage (1, 2 or 3) was combined with classes of substrate (Permian, Senones, Vosgian, intermediate sandstone or conglomerate), topography classes (classes of altitude, slope, orientation, convexity), as well as precipitation and temperature classes. The values of the contingency tables were the areas measured in hectares.

The chi-square test ($\chi 2$) applied to the contingency tables was used to assess the relationships between damage classes and ecological factors and the contingency coefficients (C) to measure the intensity of the relationships.

2.3. Statistical modelling of the influence of ecological factors on fir decline

After bivariate analyses, multivariate analyses were carried out in order to find the combined effects of ecological variables. They were conducted at the level of the individual management unit. Therefore topography was characterised by a mean value of altitude, slope, convexity and orientation (after transforming the angle given by the orientation value into sine and cosine in order to render the variable linear) for each management unit. Similarly, mean precipitation and temperature values were calculated. Lithology was characterised by the relative surface covered by each type of substrate. We also sought to establish a statistical model that could predict damage using the variables available in the geographic database.

A step by step discriminant analysis was used to determine the ecological variables that best correlated with damage [19, 23]. It provided a linear model expressing the intensity of damage (class 1 or classes 2 and 3) as a function of parameters related to vegetation, topography, lithology and climate. The mathematical distance used was the Mahalanobis distance. A probability or erroneous classification measures the risk of assigning a management unit to a damage class to which it does not belong [6]. This probability of erroneous classification was calculated from the function:

$$P = 1 - \Phi\left(\sqrt{D^2}/2\right)$$

where

P is the probability of an erroneous classification,

Φ is the distribution function of the reduced normal distribution,

D^2 is the Mahalanobis distance.

The extent of validity of the discriminant analysis was also measured with the method of crossed validation [19]. The population of all the plots was divided into two randomly chosen samples. Discriminant analysis was conducted on 75% of the observations (basic sample) and was used to establish classification rules. These classification rules were then applied to the remaining 25% (test sample) and the error rate was determined.

3. RESULTS

3.1. Description of damage in the study area

Among a total of 2 977 units (35 591 ha) observed, 43% of fir plots were moderately or severely defoliated (36% in class 2 and 7% in class 3) (*figure 1*) and 36% exhibited yellowing of the foliage (34% in class 2 and 1% in class 3) (*figure 2*). The two damage symptoms were strongly linked, since defoliation and yellowing scores were identical on 72% of the study area.

3.2. Relationships between ecological factors and damage intensity

The analysis of contingence tables (*table III*) showed that altitude was the variable best correlated with the intensity of both defoliation and yellowing (C = 0.36 and 0.30). The proportion of damaged fir which was relatively low between 200 and 600 m increased between 600 and 1000 m. Stand age was the second factor statistically linked to defoliation (C = 0.29). The proportion of severely defoliated trees was much higher in stands more than 100 years old. Yellowing was less correlated with age than defoliation (C = 0.18). Stand age was found to increase with altitude (C = 0.18).

Slope orientation was the third factor to explain defoliation (C = 0.13) and yellowing (C = 0.12). Fir damage was more pronounced in south/south-east orientations. Slope intensity was also correlated with defoliation (C = 0.12) and to a lesser extent with yellowing (C = 0.08). Fir trees in general seemed to be more defoliated on steep slopes (more than 20%). Parent material was weakly linked to damage (C = 0.09 for defoliation and 0.10 for yellowing).

3.3. Statistical modelling

A step by step discriminant analysis was carried out by introducing the ecological variables one by one and

Table III. Contingency coefficients derived from contingency tables measuring the relationship between environmental variables and damage classes. N1 = defoliation class; N2 = yellowing class; Ag = age of the population; G = geology; Al = altitude; β = slope; ϕ = orientation; Cx = convexity; P = precipitation; T = temperature.

	N1	**N2**	**Ag**	**G**	**Al**	β	ϕ	**Cx**	**P**	**T**
N1	1.00									
N2	0.54	1.00								
Ag	0.29	0.18	1.00							
G	0.09	0.10	0.13	1.00						
Al	0.36	0.30	0.18	0.24	1.00					
β	0.12	0.08	0.08	0.34	0.29	1.00				
ϕ	0.13	0.12	0.13	0.17	0.14	0.17	1.00			
Cx	0.09	0.06	0.04	0.23	0.29	0.06	0.11	1.00		
P	0.29	0.28	0.12	0.29	0.51	0.19	0.18	0.04	1.00	
T	0.20	0.20	0.13	0.31	0.44	0.28	0.13	0.02	0.34	1.00

selecting only those having a significant influence on the distribution of forest damage. Because defoliation class 3 represented a small area, damage classes 2 (moderate) and 3 (severe) were grouped (920 management units) and compared with damaged class 1 (1 312 management units). The same was done for yellowing: classes 2 and 3 (792 management units) were grouped and compared with class 1 (1 440 units).

The following model was derived for defoliation:

$$Y1 = 5.266 - 0.007\text{alt} - 0.018\text{age}$$

where

$Y1$ is the discriminant function associated with defoliation,
alt is the mean altitude of the plot,
age is the maximal age of the population on the plot.

The probability of erroneous classification was 31% with the model set and 30% using cross validation.

For yellowing, the first two variables were also altitude and stand age:

$$Y2 = 3.640 - 0.006\text{alt} - 0.006\text{age}$$

where

$Y2$ is the discriminant function associated with defoliation,
alt is the mean altitude of the plot,
age is the maximal age of the population on the plot.

The probability of erroneous classification was 36% with the model set and 33% using cross validation.

The results show that 70% of the variability of defoliation and 65% of that of yellowing can be explained by altitude and stand age. Defoliation and yellowing were not related to the parent rock. Altitude was strongly linked to the other topographic variables: high altitudes are characterised by steep convex slopes, while at low altitudes the slopes are weak and concave. This was why adding altitude to the effects of the other topographic variables provided redundant data that did not significantly increase the probabilities of erroneous classification associated with the discriminant analyses.

4. DISCUSSION

Defoliation and foliage yellowing were found closely related while some of the earlier studies carried out in the Vosges highlighted some differences in the distributions the two symptoms [15]. However, in this study yellowing was less distinctly correlated to some site (e.g. slope) and stand (especially stand age) factors, which was consistent with former studies. Moreover, a possible methodological bias may have reinforced the similarity between the two symptoms: foliage yellowing is generally difficult to detect and becomes more easy to detect in defoliated trees (the observation of the upper side of dense crowns is problematic), especially under the observation conditions considered here, i.e. foresters walking through the forest and not concentrating on a few trees as commonly practised in permanent plots.

Stand age and altitude appeared as the two predominant “causal” variables when considering fir decline in the sandstone area, while the parent rock had no apparent effect. Tree age has been identified by a number of authors as being correlated with defoliation. This has been verified in almost every region and for every single species although with some differences between species [7, 15]. Silver fir is among the species for which age is most determining. Altitude, on the other hand, is commonly presented as a causal factor in connection with forest decline. It cannot, however, be seen as a factor acting directly on the condition of forest trees [12]. Instead, it appears necessary to examine the factors “hidden” behind altitude.

4.1. Climatic factors

Dendroecological studies have shown that severe water stress (during consecutive dry years) was an important cause of damage, especially crown deterioration, in silver fir [2, 3]. Annual precipitation is positively correlated with altitude (*table III*) which should be a favourable factor for the well being of the trees. The quantity of water available to trees, however, depends not only on rainfall, but also on the storage capacity of the soil. Plant available water holding capacity was found to decrease linearly with increasing altitude ($p < 0.01$, $r = -0.43$), from 73 mm at 350 m to 36 mm at 700 m. This sharp trend reflects the fact that high elevation soils are generally more superficial, whereas colluvial soils located at the bottom of the slope are deeper and contain a higher proportion of clay which increases the water reserve. Senones and Voltzia sandstones which are located at low altitude (generally less than 500 m) provide a higher percentage of clay than the Vosgian sandstone, which is located at higher altitude (generally more than 550 m). Other studies carried out in the Vosges and the Jura [5] [7, 17] found a significant relationship between silver fir decline and the plant available water holding capacity of the soil.

4.2. Nutrient supply

Generally, the soil base saturation depends partially on the mineral content of the parent rock. This relationship was, however, not found for the soil database used in this study (*figure 3*), even though there was considerable variation in soil types as a function of the parent rock. This could be partly due to the existence, in the study area, of superficial (periglacial, loessic or weathering) formations that are not mentioned on geological maps, but the main explanation is probably that the general mineralogical context of soil arising from the different sandstones is rather homogeneous.

Altitude was negatively and significantly correlated with exchangeable Ca (r = –0.30), Mg (r = –0.27) and K (r = –0.40) in the first soil horizon. It is well established, experimentally and in the field, that there is a clearcut relationship between the intensity of foliage yellowing of forest trees and the Ca and Mg content of the soil [8, 14]. It should be noted, however, that the relationship between nutrient content and altitude is not a general one; in the southern Vosges, for example, nutrient rich substrates can be found at high elevation, so that the overall relationship between soil status and elevation is less clear for the whole Vosges Mts than for the study area.

In addition, several studies have shown in the Vosges mountains and elsewhere that atmospheric acid deposition was positively related to rainfall amount, which in turn is related to altitude [11]. This means that the original differences between high and low altitude sites, as regards the nutrient content of the soil, probably were exacerbated over the last decades.

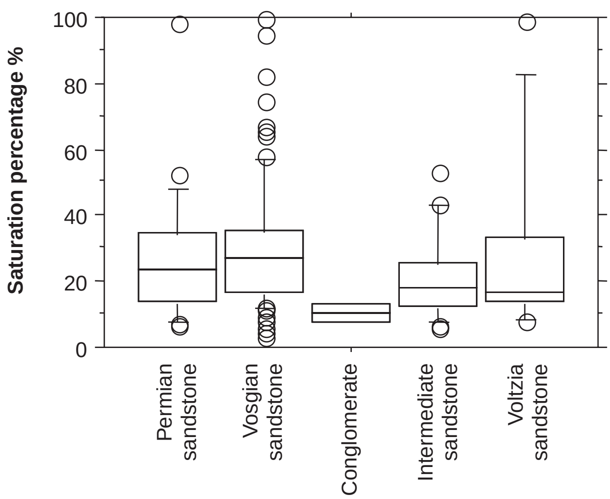

Figure 3. Soil base saturation in the first pedological horizon per type of sandstone, established from a database of 136 soil profiles.

5. CONCLUSION

Results obtained for a large area (265 000 ha), using information on a large number (2 977) of management units have confirmed the conclusions of earlier studies (relying on more limited data sets) as to the positive relationship between mean altitude, stand age and fir decline.

The variable “altitude” synthesises the influence of a set of variables which are determinant to tree physiology and health and all more or less correlated to elevation. These variables include the temperature and the precipitation, the nutrient content and the water holding capacity of the soil. The soil characteristics depend on the distribution of parent rock and soil types along the slopes, but not in an unequivocal way, which means that maps of parent material and soil types can not serve as surrogates for the more relevant (deterministic) criteria such as soil characteristics. This is an important limitation for GIS approaches using only the classically available data on land morphology, geology and soil types [22].

In this respect, the use of a soil chemistry [GL1]database in combination with a geographic database established with a GIS proved highly valuable in this study. The rather loose relationship between the distribution of damage and the nature of parent rock and soil type could otherwise been have interpreted as a lack of effect of the soil characteristics on the condition of fir. The conclusions of some earlier studies on forest decline as to the absence of clear influence of site conditions on forest health must therefore be taken with caution as already stated earlier [15]. A spatial approach relying on a “classical” geographic database remains nevertheless very interesting; it helps testing and upscaling the results from a few research sites and allows defining critical thresholds and mapping zones at risk [20, 21, 22].

In order to limit future damages, silviculture should aim in these high elevation areas at avoiding over-ageing of silver fir, and, probably, more importantly, at decreasing the competition for water by appropriate thinnings and that for mineral nutrients by avoiding the exportation of nutrient rich part of trees and/or restoring these barren soils by liming. Although the situation of silver has improved since the early 1990s (although less distinctly at higher elevation), it is likely that the triggering conditions for a new phase of fir decline may show up in the future, especially under changing climatic conditions and considering the slow recovery of soil fertility following the decrease of atmospheric acidic load.

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REFERENCES

[1] Becker M., The role of climate on present and past vitality of silver fir forests in the Vosges mountains of northeastern France, Can. J. For. Res. 19 (1989) 1110–1117.

[2] Becker M., Bert G.D., Landmann G., Lévy G., Rameau J.C., Ulrich E., Growth and decline symptoms of silver fir and Norway spruce in northeastern France: relation to climate, nutrition and silviculture, in: Landmann G., Bonneau M. (Eds.), Forest decline and atmospheric deposition effects in the French Mountains, Springer, Berlin, Heidelberg, New York, 1995, pp. 143–156.

[3] Bert G.D., Impact of ecological factors, climatic stresses and pollution on growth and health of silver fir (*Abies alba* Mill.) in the Jura Mts: an ecological and dendroecological study, Acta Oecol. 14 (1993) 229–246.

[4] Bonneau M., Le « nouveau dépérissement » des forêts. Symptômes, causes possibles, importance éventuelle de la nature des sols, Sci. Sol 4 (1985) 239–251.

[5] Bruckert S., Relations du dépérissement avec l'écologie dans le Jura, in: Bonneau M., Landman G. (Éds.), Pollution atmosphérique et dépérissement des forêts dans les montagnes françaises, programme DEFORPA, rapport 1992, Institut National de la Recherche Agronomique, Nancy, 1993, pp. 129–130.

[6] Dagnélie P., Analyse statistique à plusieurs variables, Les Presses Agronomiques de Gembloux, 1975.

[7] Drapier J., Analyse du dépérissement dans les Vosges Alsaciennes par l'Inventaire Forestier National, in: Bonneau M., Landman G. (Éds.), Pollution atmosphérique et dépérissement des forêts dans les montagnes françaises, programme DEFORPA, rapport 1992, Institut National de la Recherche Agronomique, Nancy, 1993, pp. 115–120.

[8] Dreyer E., Fichter J., Bonneau M., Nutrient content and photosynthesis of young yellowing Norway spruce trees (*Picea abies* L. Karst.) following calcium and magnesium fertilisation, Plant Soil 160 (1994) 67–78.

[9] Dupouey J.L., Thimonier A., Lefevre Y., Le Tacon F., Bonneau M., Dambrine E., Poszwa A., Landmann G., Désaturation et enrichissement en azote des sols forestiers du Nord-Est de la France au cours des dernières décennies, Rev. For. Fr. L 5 (1998) 391–402.

[10] Gégout J.C., Étude des relations entre les ressources minérales du sol et la végétation forestière dans les Vosges, Thèse, Nancy I, ENGREF, 1995.

[11] Ignatova N., Dambrine E., Spruce canopy uptake of deposited N, Ann. For. Sci. 57 (2000) 113–120.

[12] Innes J.L., Forest health: its assessment and status, CAB International, Wallingford, UK, 1993, 677 p.

[13] Jamagne M., Betremieux R., Begon J.C., Mori A., Quelques données sur la variabilité dans le milieu naturel de la réserve en eau des sols, B.T.I. 324–325 (1977) 627–641.

[14] Landmann G., Forest decline and air pollution effects in the French mountains: a synthesis, in: Landmann G., Bonneau M. (Eds.), Forest decline and atmospheric deposition effects in the French mountains, Berlin, Heidelberg, New York, Springer Verlag, 1995, pp. 407–452.

[15] Landmann G., Bonneau M., Bouhot-Delduc L., Fromard F., Chéret V., Dagnac J., Souchier B., Crown damage in Norway Spruce and Silver Fir: relation to nutritional status and soil chemical characteristics in the French mountains, in: Landmann G., Bonneau M. (Eds.), Forest decline and atmospheric deposition effects in the French Mountains, Springer, Berlin Heidelberg, New York, 1995, pp. 41–81.

[16] Landmann G., Bert G.D., Pierrat J.C., Becker M., Bonneau M., Souchier B., Crown damage in Norway Spruce and Silver Fir: relation to site and stand factors in the French Mountains, in: Landmann G., Bonneau M. (Eds.), Forest decline and atmospheric deposition effects in the French Mountains, Springer, Berlin, Heidelberg, New York, 1995, pp. 82–119.

[17] Lévy G., Becker M., Le dépérissement du sapin dans les Vosges : rôle primordial de déficits d'alimentation en eau, Ann. Sci. For. 44/4 (1987) 403–416.

[18] Perriaux J., Contribution à la géologie des Vosges gréseuses, Mém. serv. Carte géol. Als. Lorr., 1961, 18.

[19] Saporta G., Probabilités, analyse des données et statistiques, Éditions Technip–Paris, 1990.

[20] Seveleder O., Cartographie des dommages forestiers dans le massif vosgien, Éd: Office National des Forêts, Epinal, 1998, 40 p.

[21] Thomas A.L., King D., Dambrine E., Party J.P., Probst A., A spatial study of the relationships between streamwater acidity and geology, soils and relief (Vosges Northeastern France), J. Hydrology 217 (1998) 35–45.

[22] Thomas A.L., King D., Dambrine E., Couturier A., Roque J., Modelling spatial variability of soils with parameters derived from relief and geological materials in a sandstone part of the Vosges (N-E France), Geoderma 90 (1998) 291–305.

[23] Webster R., Burrough P.A., Multiple discriminant analysis in soil survey, Journal of Soil Science 25 (1974) 121–134.