

Monitoring Forest Condition in Europe: Impacts of Nitrogen and Sulfur Depositions on Forest Ecosystems

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Abstract—Forest condition in Europe has been monitored over 19 years jointly by the United Nations Economic Commission for Europe (UNECE) and the European Union (EU). Large-scale variations of forest condition over space and time in relation to natural and anthropogenic factors are assessed on about 6,000 plots systematically spread across Europe. This large-scale monitoring intensity is referred to as “Level I.” Causal relationships are studied in detail on about 860 intensive monitoring plots covering the most important forest ecosystems in Europe. This intensive monitoring is referred to as “Level II.” Crown condition shows a very high spatial and temporal variation which is explainable mainly by tree age, weather extremes, biotic factors, and air pollution. At open field stations close to Level II plots, results of wet deposition measurements indicate that sulfate and nitrate concentrations decreased from 1996 to 2001, whereas ammonium concentrations fluctuated during the same measuring period.

Introduction

Forest condition in Europe received increasing attention in the early 1980s as a response to growing concern that defoliation in parts of the forests in Europe could be caused by air pollution (Ulrich 1981, Schütt 1982). Since then forest condition has been a subject of scientific, political, and public debate, today being discussed within the wider context of sustainable forest management. The European-wide monitoring of forest condition was started 19 years ago by the International Cooperative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) under the Convention on Long-range Transboundary Air Pollution (CLRTAP) under the United Nations Economic Commission for Europe (UNECE) in close cooperation with the European Union (EU). Today, 38 European countries as well as Canada and the United States of America are participating, rendering the monitoring program one of the greatest of its kind worldwide. Canada and the United States of America do not use the same monitoring methods as the countries in Europe. However, they contribute national reports and are increasingly involved in the further development and joint application of monitoring methods in some fields of the program. The main objectives of the program are:

- to provide knowledge of the spatial and temporal variation in forest condition on the European scale and their relationships to environmental factors

- to contribute to a better understanding of the relationships between the condition of forest ecosystems and both natural and anthropogenic stress factors (in particular, air pollution) throughout Europe using a network of sample plots

The infrastructure, data base, and results created by ICP Forests and EU permit increasingly contributes to forest policy at national, pan-European, and global level on the effects of climate changes on forests, sustainable forest management, and biodiversity in forests.

The Monitoring System

The above mentioned two objectives are implemented by means of a systematic large-scale monitoring network and an intensive forest monitoring program. The large-scale monitoring (Level I) aims to assess the spatial and temporal variation of forest condition across Europe. It is therefore pursued on a large number of monitoring plots. Given the large number of plots, only a limited set of parameters can be assessed and hence little evidence of cause-effect relationships can be expected at Level I. Cause-effect relationships are the target of the intensive monitoring program (Level II) with its much larger set of monitoring parameters. The labor and cost intensive monitoring restricts the number of Level II plots. The numbers and the locations of the Level II plots were chosen by each country according to international guidelines

Table 1.

Surveys conducted	Level I	Level II
Crown condition	Annually (5,942 plots)	Annually (866 plots)
Foliar condition	Once (1,497 plots)	Every 2 years (855 plots)
Soil chemistry	Once (5,289 plots)	Every 10 years (865 plots)
Soil solution chemistry	-	Continuously (243 plots)
Tree growth	-	Every 5 years (859 plots)
Ground vegetation	-	Every 5 years (730 plots)
Atmospheric deposition	-	Continuously (499 plots)
Ambient air quality	-	Continuously (133 plots)
Meteorological condition	-	Continuously (202 plots)
Phenology (optional)	-	According to phenophases (59 plots)
Remote sensing (optional)	-	(157 plots)

and national priorities. The intensive monitoring aims at the ecosystem scale rather than at the European-wide scale.

At Level I, approximately 6,000 permanent plots are systematically arranged in a 16 x 16 km transnational grid. In a small number of countries the plots are arranged randomly instead of systematically, but the plot density corresponds to that of the 16 x 16 km grid. In parts of Scandinavia even the density of the plots is smaller, which results in an under-representation of this part of Europe in the total Level I plot sample. On all Level I plots, annual crown condition assessments are carried out. Also, soil surveys were conducted on 5,289 plots, most of them in the years 1993 to 1995. A repetition of the soil survey is planned for 2006. Moreover, foliage surveys were conducted on 1,497 plots, most of them in the years 1992 to 1997.

For the intensive monitoring more than 860 Level II plots were selected in the most important forest ecosystems of the participating countries. The intensive monitoring aims at crown condition, soil condition, soil solution chemistry, foliage chemistry, tree growth, tree phenology, ground vegetation, meteorological condition, ambient air quality, and deposition. Not all of the respective monitoring activities are conducted on all Level II plots (table 1). The crown condition surveys on the Level II plots and on about half of the Level I plots include the assessment of several identifiable damage types such as insects, fungi, game, fire and abiotic agents. For Level II also the assessment of litterfall is foreseen and the respective method has been developed. All surveys within the program are based on harmonized methods documented in a regularly updated manual (Anonymous 2001). Since the establishment of the program, a comprehensive data bank on a wealth of monitoring parameters has been built up. In each participating country, the responsibility for the surveys lies with the national forest services. All countries are represented in the Task Force of ICP Forests, which is chaired by Germany. For the coordination of parts of the monitoring, data management, evaluation, and

reporting, Germany hosts the Programme Coordinating Centre (PCC) at the Federal Research Centre for Forestry and Forest Products (BFH) in Hamburg, Germany.

Crown Condition

Approach

Crown condition is a fast reacting indicator for numerous environmental factors affecting tree vitality. It is assessed by means of visual assessments of defoliation and discoloration. This is an inexpensive method permitting about 135,000 sample trees to be assessed annually on the approximately 6,000 plots at Level I. The drawback of this approach is that the assessment results are influenced by the subjectivity of different observers. Several data quality assurance measures were therefore introduced. At the national level, observer bias is estimated by analyzing training and test results as well as results of control assessments (Schadauer 1991, Köhl 1991 and 1992). A high standard of training of the assessors can reduce observer bias. For individual species, the possibility to reach reliable results of the defoliation assessments at the national level has been shown (Eichhorn and Ackerbauer 1987, Dobbartin and others 1997). At the international level, the assessment results show systematic inconsistencies between different countries (Innes and others 1993). Several efforts are undertaken to identify and reduce such systematic inconsistencies by means of cross-calibration and inter-comparison courses as well as by means of photographic techniques.

Spatial and Temporal Variation

Trees of the six most frequent species having been assessed continuously at Level I between 1989 and 2002 reveal in general increasing defoliation; however, with great differences between individual species (fig. 1). The increase is very obvious for maritime pine (*Pinus pinaster*), as well as for holm oak (*Quercus ilex* and *Quercus*

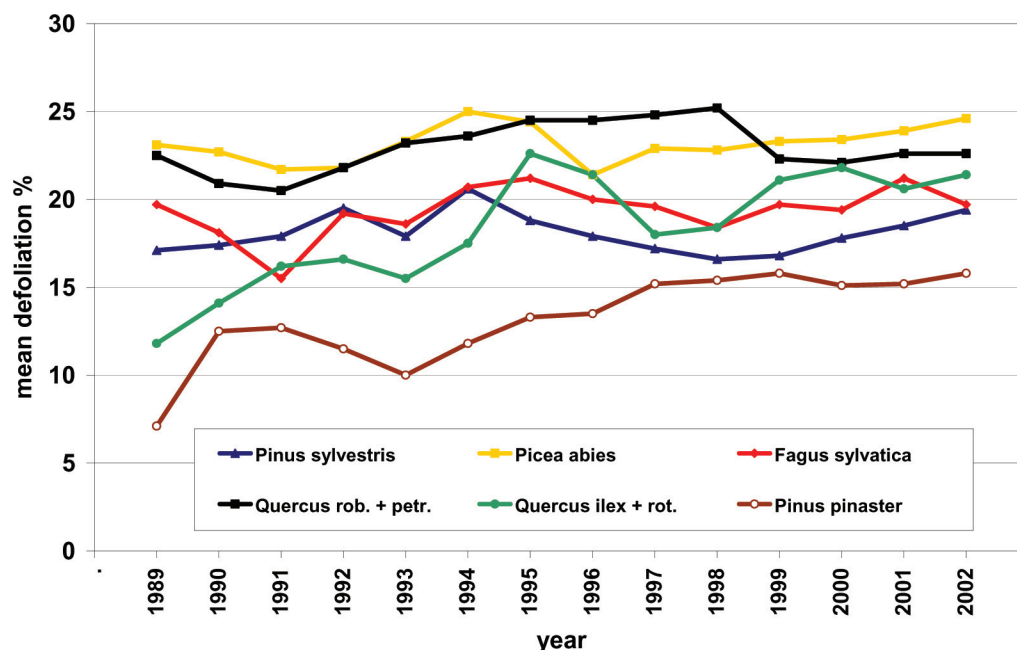


Figure 1. Development of mean defoliation of the six most frequent species. Number of trees: Scots pine (*Pinus sylvestris*), 2521; Norway spruce (*Picea abies*), 2988; pedunculate oak (*Quercus robur*) and sessile oak (*Q. petraea*), 1237; common beech (*Fagus sylvatica*), 2620; maritime pine (*Pinus pinaster*), 1360; and holm oak (*Quercus ilex* and *Q. rotundifolia*), 2243.

rotundifolia). Defoliation of Scots pine (*Pinus sylvestris*) and Norway spruce (*Piceas abies*) was higher in 2002 than in 1989; however, showed large annual fluctuations over the period of observation. Scots pine recovered markedly from its high defoliation in 1994; however, its defoliation has been increasing again after 1998. No trend at all is revealed for the defoliation of common beech (*Fagus sylvatica*), as well as for pedunculate oak (*Quercus robur*) and sessile oak (*Quercus petraea*). The latter two species reveal an obvious recovery from a high of defoliation in 1998 (Lorenz and others 2003). The mean development of defoliation across Europe (fig. 1) does not reflect the high spatial variation of defoliation and its development, or any causes related to it.

In recent multivariate and geostatistical studies (Lorenz and others 2002), both the temporal and the spatial trends in mean plot defoliation of Scots pine (1,313 plots) and common beech (399 plots) were evaluated in relation to:

- the presence of biotic agents (insects and fungi) according to crown condition assessments
- the amount of precipitation from January to June provided by the Global Precipitation Climatology Centre (GPCC)
- the deposition of S, NO_x, and NH_y as modeled by the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP)

The only significant – but weak ($r^2 = 0.44$) – statistical relationship found is the positive correlation between defoliation of Scots pine and sulfur deposition. This is explained by the high number of Scots pine plots in areas of previously high defoliation and sulfur

depositions particularly in parts of Poland, the Czech Republic, Slovak Republic, and Baltic States. Figure 2 shows the decrease in defoliation of Scots pine in these areas from 1994 to 1999. Comparatively small areas of increasing defoliation in Bulgaria and Norway were explained by weather extremes and *Gremmeniella abietina* attacks, respectively, by the national forest services. The temporal trends in the defoliation of common beech show a more heterogeneous spatial pattern with several spots of improvement and deterioration scattered across Europe. Frequently reported stressors influencing the condition of common beech are drought and frost. The spatial variation of defoliation of both Scots pine and common beech was largely explained by stand age and by the variable “country.” The correlation with the latter variable reflects partly the above mentioned systematic methodological differences or differences in forest history between countries. The correlation between defoliation and stand age has been recognized since the first crown condition surveys. It seems plausible that this reflects at least partly the natural thinning of the crown with increasing tree age.

Nitrogen and Sulfur Depositions

Approach

In accordance with its political mandate under CLRTAP, ICP Forests is paying particular attention to the effects of air pollution on forests, among the multitude of other factors affecting forest condition. Indirect effects of

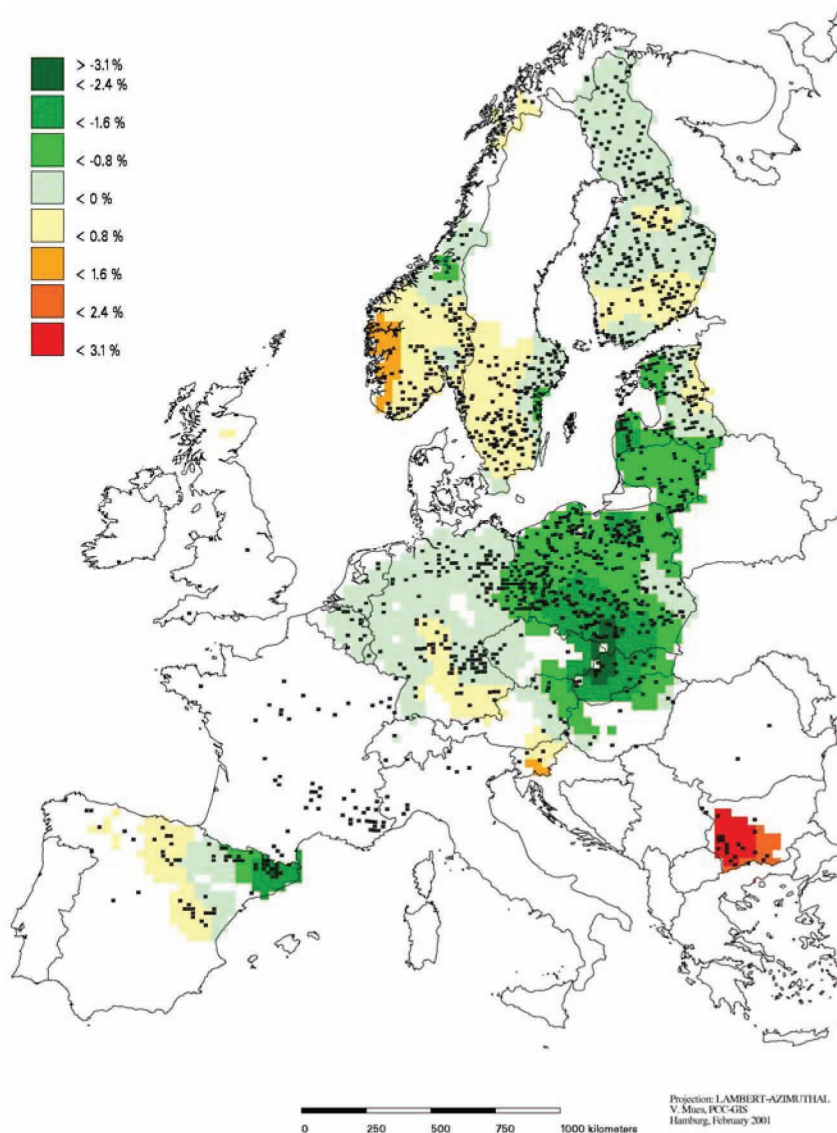


Figure 2. Kriged temporal trends of defoliation (changes in defoliation in percent points) of Scots pine (*Pinus sylvestris*) from 1994 to 1999 (from Lorenz and others, 2002).

nitrogen and sulfur depositions via the forest soils have been described both by forest damage research (Ulrich 1981) and by forest condition monitoring (De Vries and others 2001). On Level II plots, total atmospheric deposition under canopy is derived by adding throughfall and (for common beech because of its smooth bark) stemflow, while correcting for the effects of element interactions with the canopy (uptake and leaching) using bulk deposition. Bulk deposition is measured in the open field close to the Level II forest plots. It reflects the local air pollution situation and provides a reference for the measurements under canopy. The methods and results of a study of the temporal development and the spatial variability of nitrate (N-NO_3), ammonium (N-NH_4), and sulfate (S-SO_4) are described, based on the Level II bulk-deposition data expressed in terms of annual mean concentration. Results of an estimation of critical loads for nitrogen and acidity follow.

Concentrations of Sulfur and Nitrogen in Bulk Deposition

Bulk deposition expressed in terms of annual mean concentration in deposition samples was calculated as the volume weighted average in mg/l (Farmer and others 1987). For mapping concentrations across Europe, mean plot-wise ion concentrations over the years 1999 to 2001 were calculated. For tracing and mapping trends, a trade-off had to be made between the length of the time span on the one hand and the amount of data (number of countries having contributed to the data pool) on the other hand. Taking into account these two aspects, the time period 1996 to 2001 was rated as most suitable. For the quantification of temporal changes, linear regression was used. With the years of assessment as predictor and annual mean ion concentration as target variable for each plot, linear relationships were obtained. The slopes of the

linear equations were statistically tested and depicted in maps according to the following classification:

- negative slope, error probability 5% and less
- negative slope, error probability more than 5%
- positive slope, error probability 5% and less
- positive slope, error probability 5% and more

It must be stressed that conclusions about temporal changes in ion concentration based on such short time series can only be made with great reservations. Nevertheless, there is no doubt about temporal changes in annual concentration of nitrate, ammonium and sulfate in bulk precipitation. Likens and Bormann (1977) showed their evidence for watershed ecosystems in New England. Ulrich and Lanier (1999) developed a national indicator based on national volume-weighted mean concentrations, which was used by Ulrich (2003) for the French intensive monitoring network "RENECOFOR." They found linear trends in nitrogen, sulfur, calcium, and magnesium concentration between 1992 and 2002.

In central Europe, there is an obvious cluster of plots with high volume weighted nitrate (N-NO_3) concentrations ranging from > 0.5 to 0.65 mg/l . On about one-third of the plots in Poland and northern Germany, concentrations are > 0.65 to 2.6 mg/l . In the other parts of Europe, the concentrations are clearly lower, showing concentrations between 0.1 and 0.5 mg/l (fig. 3). The concentrations of ammonium (N-NH_4) and sulfate (S-SO_4) show similar spatial patterns as those of nitrate, for example, a cluster of high concentrations in central Europe, with particularly high concentrations in Poland.

The temporal development of nitrate concentrations reflects the statistical uncertainties inherent to the short time series. Most plots do not show statistically significant changes in concentrations between 1996 and 2001. However, the share of plots with no significant decrease (69.0%) and the share of plots with significant decrease (15.3%) in concentrations sum up to 84.3%. This may be cautiously interpreted as indicating an overall decrease in nitrate depositions. The temporal development of ammonium is affected by similar statistical uncertainties resulting from the short observation period (Fischer and others 2004). Compared to nitrate and ammonium, the temporal development of sulfate concentrations shows a much more pronounced decrease from 1996 to 2001 (fig. 4). Decreases in sulfate concentrations were found on 89.4% of the investigated plots. On 44.8% this decrease is statistically significant. These plots do not reveal a pronounced spatial pattern. However, those plots showing increasing sulfate concentrations are clustered in Poland. The obvious decrease in sulfate concentrations is also evident in the graph of the temporal development of mean plot concentrations on all plots for each year

from 1996 to 2001 (fig. 5). This reflects the successful reduction of sulfur emissions over more than two decades under CLRTAP of UNECE. Nitrate concentrations are also decreasing, but the decrease is less obvious than for sulfate. Linear regressions of the time series yield stable statistical parameters for both sulfate and nitrate. In contrast, this is not the case for ammonium concentrations. They show a fluctuating development over the period of observation.

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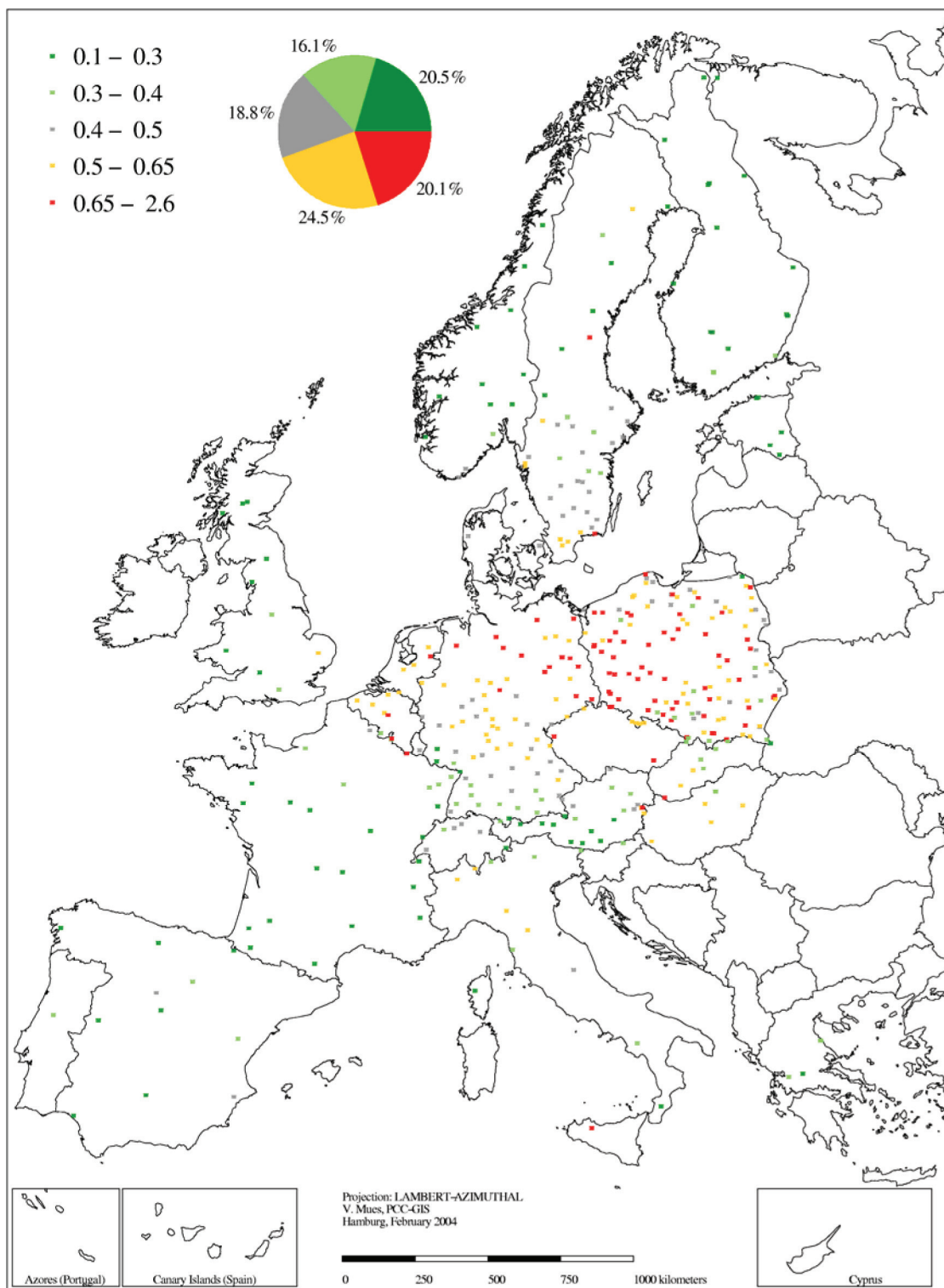


Figure 3. Geographic variation of the volume weighted mean N-NO₃ concentrations in mg/l between 1999 and 2001 on 409 Level II plots.

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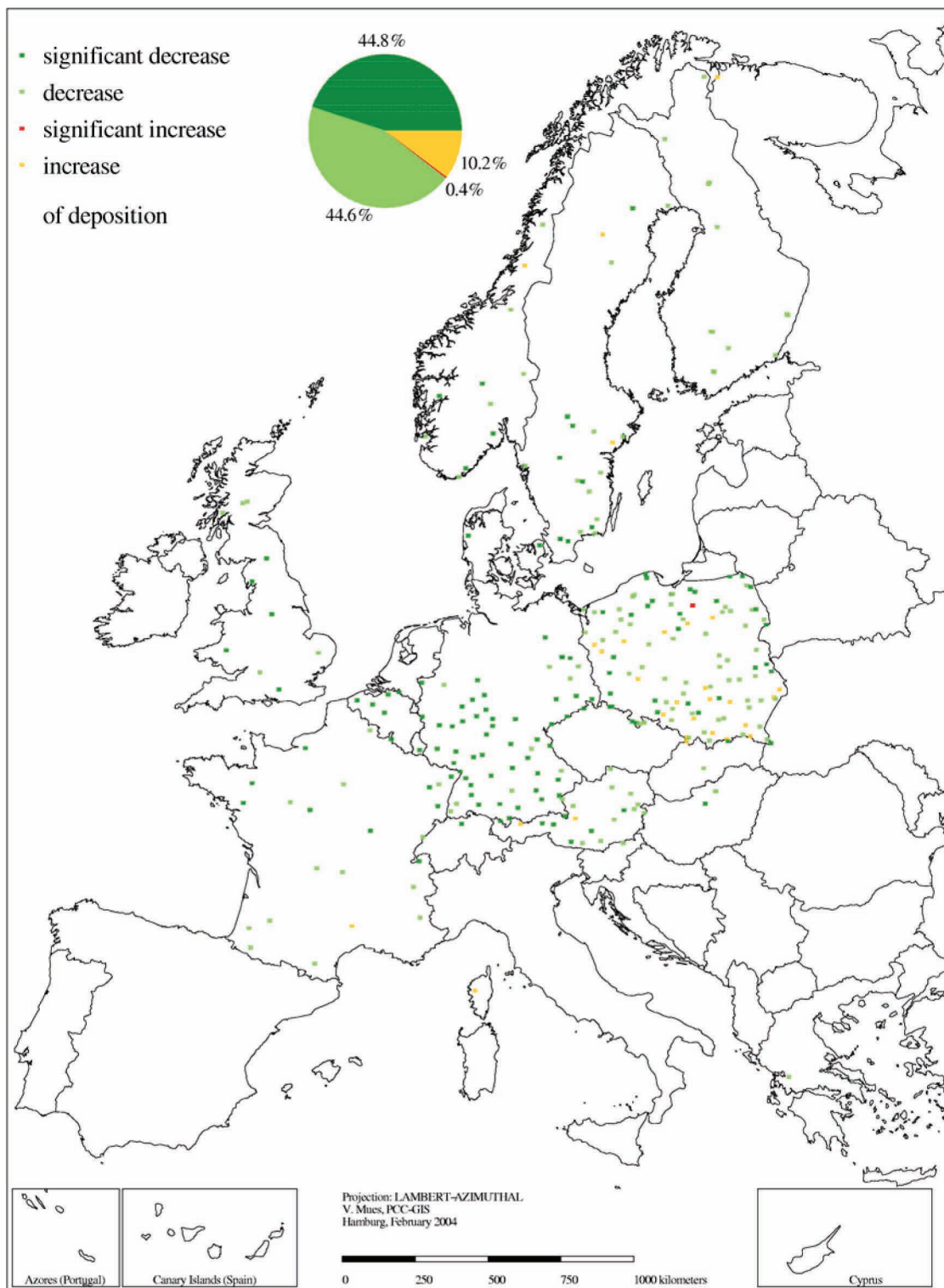


Figure 4. Geographic variation of the linear trends of the volume weighted mean S-SO₄ concentrations in mg/l between 1996 and 2001 on 285 Level II plots.

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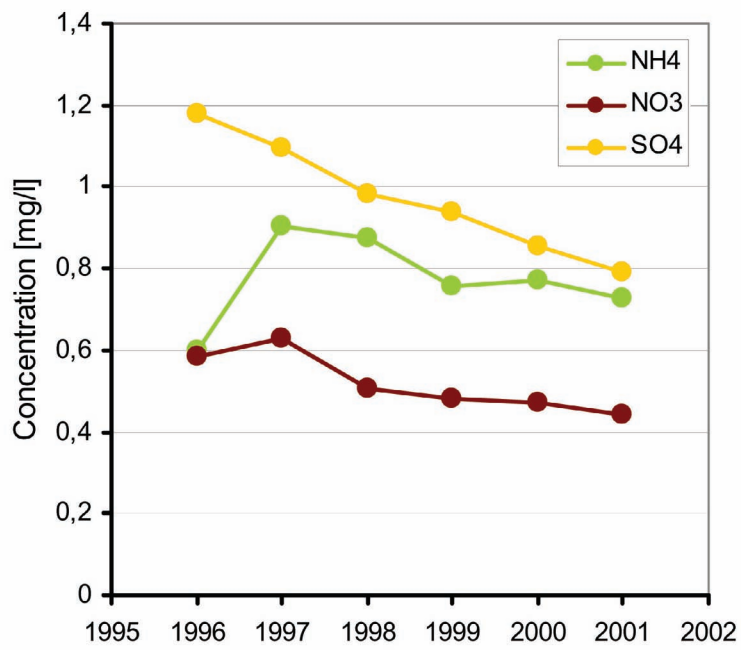


Figure 5. Development of the volume weighted mean concentrations in mg/l between 1996 and 2001.