CHANGES OF ATMOSPHERIC CHEMISTRY AND EFFECTS ON FOREST ECOSYSTEMS

Nutrients in Ecosystems

VOLUME 3

Series Editor:

Reinhard F. Hüttl

Managing Editor: Bernd Uwe Schneider

Changes of Atmospheric Chemistry and Effects on Forest Ecosystems

A Roof Experiment without a Roof

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Springer-Science+Business Media, B.V.

Library of Congress Cataloging-in-Publication Data:

Changes of atmospheric chemistry and effects on forest ecosystems : a roof experiment without a roof / edited by Reinhard F. Hüttl and Klaus Bellmann.

p. cm. — (Nutrients in ecosystems; v. 3)

 1. Scots pine—Ecophysiology—Germany (East)
 2. Scots pine—Effect of air pollution on—Germany (East)
 3. Scots pine—Effect of atmospheric deposition on—Germany (East)
 4. Forest ecology—Germany (East)
 1. Hüttl, R. F. II. Bellmann, Klaus. III. Series.

 QK494.5.P66C448
 1999
 585'.2-dc21
 99-25199

 ISBN 978-90-481-5224-7
 ISBN 978-94-015-9022-8 (eBook)
 90-25199

Printed on acid-free paper

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©1998 Springer Science+Business Media Dordrecht Originally published by Kluwer Academic Publishers in 1998.

Softcover reprint of the hardcover 1st edition 1998

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1 Introduction to the SANA-project (SANA: regeneration of the atmosphere above the new states of Germany – effects on forest ecosystems)

K. BELLMANN and R. GROTE

1. The history of air pollution and deposition in East Germany

1.1. Emission

Former East Germany was one of the countries in Europe which had extremely high emissions of pollutants. Energy production was mainly based on the use of soft coal. Power plants as well as industry lacked the necessary equipment for pollutant reduction. Thus in 1989, East Germany emitted in total 5.3 Mt of SO₂ and 2.1 Mt of alkaline dusts, representing an average of 48.8 kg km⁻² and 19.0 kg km⁻², respectively (Finkbeiner *et al.*, 1993). The emission per capita was 18-fold higher than in West Germany.

Point sources of energy and industrial production, emitting more than 100.000 t SO₂ a⁻¹, were concentrated in the southern parts of the country, which during meterological inversion situations led to an extraordinary high load of deposition in this region and to peak concentrations of between 2800 $\mu g m^{-3}$ (Bitterfeld) and 4500 $\mu g m^{-3}$ (Leipzig) SO₂ (Figure 1). Between 1970 and 1989, one year before German reunification, the emissions of SO₂, NO_X and NH₃ increased considerably (by 27, 42 and 24%, respectively). Alkaline dust emission, however, decreased by 16% due to the installation of dust filters into power plants (Table 1).

1.2. Deposition

The highest concentrations of air pollutants, particularly SO₂, occurred close to the industrial centre and decreased towards the north-east in accordance with the prevailing wind direction, which is from the south-west. Thus the Dübener Heide, a forested region of about 400 km² situated to the east of the main centre of industry, has been exposed to a steep deposition gradient (Figure 2). In the mid 1980s, the annual SO₂ concentration on the western border of the Dübener Heide reached approximately 150 µg m⁻³, while in the east only half this concentration prevailed (app. 70 µg m⁻³). Background concentrations were reached in the lowlands of north-east Germany, (37 µg m⁻³, average of the years 1979 to 1990) at Neuglobsow. Unfortunately, no information about historical O₃, NO_X and NH₃ concentrations are available.



Figure 1. Location of the investigation area

	1970		1989		1996	
	Mt a ⁻¹	% of 1989	$Mt a^{-1}$	%	Mt a ⁻¹	% of 1989
SO ₂	4328	79	5506	100	1211	22
NOx	0478	71	0677	100	0461	68
NH ₃	0263	81	0325	100	0120	36
Dust	2498	119	2092	100	0188	9

Table 1. Emissions in the former GDR (East Germany) and projection for 1996

(Data from Inst. of Energetic, Stuttgart)

Consequently, the deposition of sulphur and basic cations followed this gradient of deposition (Table 2 a+b), resulting, for example, in a pH value of precipitation of about 6.2 in the west, but 4.6 in the east in 1970 (Table 2c). A slightly different gradient was detected for nitrogen deposition, which decreased generally from the north to the south and from the borders of the region to the centre. This is mainly due to the distribution of agricultural production sites, which emitted large amounts of ammonium (Table 2d).



Figure 2. Mean annual SO₂ concentration in 1989 (data from Inst. for Atmospheric Environmental Research, Garmisch-Partenkirchen, see also Erhard and Flechsig, this volume)

1.3. Ecosystem responses

Since forest plantations, particularly Scots pine (*Pinus sylvestris* L.) stands, played an important economic role in the former GDR, investigations of pine forests in the Dübener Heide, including soils and ground vegetation, are available from the late 1950s onwards.

Soil responses

With regard to soil response, two types of development can be distinguished: i) alkalinization and re-acidification, and ii) nitrogen accumulation. Due to the deposition of alkaline dust with large amounts of basic cations, the pH value of the upper soil horizons increased until the mid 1960s despite the deposition of acid SO_4^{2-} and NO_3^{-} . At this time, only 26 % (8.500 ha) of the total forested area in the Dübener Heide showed a pH value below 4.2. With increasing installation of dust filters in lignite fired power plants, the deposition of basic cations (i.e. acid neutralization capacity) started to decrease, whereas acid deposition remained more or less unchanged or even increased until the mid 1980s. Thus, a re-acidification of the upper soil layers began to take place. In 1989, 51% (16.700 ha) of the forest in the Dübener Heide was found to have a pH value below 4.2. This re-acidification is an ongoing process, despite the decrease of acid deposition in recent years (see Konopatzky and Freyer, this volume).

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	West kg SO ₄ -S ha ⁻¹ a ⁻¹	%	East kg SO ₄ -S ha ⁻¹ a ⁻¹	%	North kg SO ₄ -S ha ⁻¹ a ⁻¹	%
1970	43	100	20	100	11	100
1985/89	55	127	28	140	14	127
1993/95	11	26	10	50	12	109
1970		100		46		26
1985/89		100		51		25
1993/95		100		91		109

Table 2a. Deposition development of sulphur at the western and eastern boarder of the Dübener Heide as well as at background sites north of Berlin (after Erhard and Flechsig, this volume)

Table 2b. Deposition development of calcium and magnesium at the western and eastern borders of the Dübener Heide as well as at background sites north of Berlin (after Erhard and Flechsig, this volume)

	West kg (Ca+Mg) ha ⁻¹ a ⁻¹	%	East kg (Ca+Mg) ha ⁻¹ a ⁻¹	%	North kg (Ca+Mg) ha ^{-1} a ^{-1}	%
1970	77	100	30	100	6	100
1985/89	65	84	23	77	6	100
1993/95	11	14	8	27	6	100
1970		100		38		8
1985/89		100		35		9
1993/95		100		72		54

Table 2c. Deposition development of the precipitation pH at the western and eastern borders of the Dübener Heide as well as at background sites north of Berlin (after Erhard and Flechsig, this volume)

	West precipitation pH	%	East precipitation pH	%	North precipitation pH	%
1970	6.2	100	5.1	100	(4.6*)	100
1985/89	5.6	90	4.6	90	4.3	93
1993/95	4.4	71	4.2	82	4.4	96
1970		100		82		74*
1985/89		100		82		76
1993/95		100		95		100

*estimated

	West kg (tot. N) ha ^{-1} a ^{-1}	%	East kg (tot. N) ha ⁻¹ a ⁻¹	%	North kg (tot. N) $ha^{-1}a^{-1}$	%
1970	13	100	13	100	9	100
1985/89	16	123	14	108	10	111
1993/95	13	100	12	92	16	178
1970		100		100		69
1985/89		100		88		63
1993/95		100		92		123

Table 2d. Deposition of nitrogen at the western and eastern borders of the Dübener Heide and of background sites north of Berlin (after Erhard and Flechsig, this volume)

Although pH values are still too high to damage the vegetation directly, there is an increasing danger that potentially toxic (heavy) metals (Al, Fe, Mn), that have been deposited together with the alkaline dust during recent decades, may become more and more available for plant uptake (Heinsdorf *et al.*, 1990).

Like many other regions in Germany, the Dübener Heide was also exposed to considerable nitrogen deposition, originating from industrial processes and agricultural production, particularly through manure fertilisation from animal farming. Additionally, large forest areas were fertilised with urea by plane. This kind of fertilisation was applied from the early 1970s until the mid 1980s, generally at total amounts of 300 kg N ha⁻¹, distributed over three to four years. Especially in damaged forests, this procedure was repeated three to four times, leading to an additional input of up to 1000 kg N ha⁻¹. So far, no net loss of nitrogen (due to increased percolation) has been detected even at these sites. Thus, total nitrogen storage increased (in average over all forests in the Dübener Heide) by 518 kg N ha⁻¹ between 1967 and 1989. During the same period the C/N ratios of the humus layer decreased from 31 to 24, which led to a change in humus types. Raw humus forms decreased from about 71 to 18%, whereas raw humus-type moder increased from 18 to 68% (see Konopatzky and Freyer, this volume).

Tree responses

Needle yellowing, relative needle losses and necroses of pine trees within the Dübener Heide area were investigated as early as 1965 by Lux (Lux, 1965), who distinguished between different degrees of damage (Figure 3). These levels of damage generally matched the regional distribution of SO_2 concentration (compare with Figure 2). The correlation of the spatial distribution of direct foliage damage with the distribution of the SO_2 concentration is supported by the repetition of the investigations in 1974 (Lux and Stein, 1975) as well as by recent results (Table 3).



Figure 3. Forest damage classes as evaluated from 1987 to 1989

	Relative foli Dübener Heide,	age longevity (%)*	Radial growth Dübener Heide,	index (mm a^{-1})**
	west	Background	west	Background
1961/63	55	100	0.9	1.05
1984/89	56	94	0.8	0.85
1990/95	67	75	1.33	0.75

Table 3. Development of foliage longevity and annual diameter increase (statistically cleared from weather impacts) at the western borders of the Dübener Heide and areas north of Berlin (background site)

*(after Gluch, in Anonymus, 1997), ** (after Neumann, this volume)

Clearly visible symptoms of foliage damage may reduce the photosynthetically active surface and, thus, decrease the assimilate gain of the trees. In addition, direct damage to the photosynthetic apparatus (e.g. Kropff, 1989; Meng *et al.*, 1994) and the surface structure of the needles (Huttunen, 1983; Hüttl, 1997; Manninen and Huttunen, 1995) is known to occur at high SO_2 concentrations. This impact may result in a further decrease of assimilation capacity as well as in an increased nutrient loss via crown leaching. Furthermore, the functioning of stomata, and thus, the water use efficiency, is negatively affected under these conditions (Meng and Arp, 1994).

The overall response of trees to SO₂ pollution, however, is difficult to estimate, because not only the direct but also the indirect effects have to be considered, which may mitigate or increase the negative direct impact. For example, light conditions are improved in a sparsely foliated canopy and thus, the photosynthetic production per foliage area may be increased. Although an affected stomata functioning may lead to further damage of the photosynthetic apparatus, nitrogen uptake through stomata can be increased, which may improve the nutrition of the trees (McLeod et al., 1990). If stomata are still effective, however, co-occurring drought stress is able to reduce the uptake of SO_2 to a certain degree (Tesche *et al.*, 1989). The drought stress, on the other hand, is possibly affected by competition from ground vegetation (Hofmann et al., 1990), as well as the nitrogen content of the soil, which influences the fine root distribution and can potentially impact fine roots and mycorrhiza (Heinsdorf, 1976; Ritter, 1990). Finally, the ability of the trees to compensate for tissue damage through changes in allocation has to be taken into account (Mooney et al., 1988). These considerations demonstrate clearly that the dominant processes in the whole ecosystem, including soil and ground vegetation, and their relationships have to be identified, if the overall effect under changing conditions is to be evaluated.

Stand responses

In response to the continuous influence of pollution, both the productivity and stability of forests are likely to decrease (see e.g. Ulrich and Pankrath, 1983). In

the Dübener Heide, a substantial decrease of stemwood production and an increased tree mortality, resulting in a sparser stand density, was observed (see Table 3). To compensate for this decrease in productivity, the plantations were fertilised with nitrogen to counterbalance the negative photosynthetic effects of SO_2 (Heinsdorf, 1978). Indeed, a substantial increase in wood production was successfully brought about, particularly in stands on poor sites (Heinsdorf, 1986; Niefnecker, 1982; Niefnecker, 1985; see Table 4). However, stemwood production decreased again when the nitrogen concentrations in the needles – that increased with increasing nitrogen availability – exceeded a value of approximately 2.1% (Hofmann *et al.*, 1990; Krauß *et al.*, 1986).

Table 4. Relative responses of diameter growth and relative foliage mortality on nitrogen fertilisation and SO_2 air pollution

	Diam	eter growth	Folia	ge losses
	Polluted sites	Non-polluted sites	Polluted sites	Non-polluted sites
Fertilised	105	140	80	85
Non-fertilised	75	100	145	100

Changes in ground vegetation

In response to the increasing alkalinity and nitrogen availability, changes in the composition of ground vegetation were observed from the early 1960s onwards, particularly at formerly nutrient poor sites (Bergmann and Flöhr, 1988; Lux, 1964; Tölle and Hofmann, 1970). Generally, a higher species diversity with an increasing proportion of nitrophilic species was found (see also Konopatzky and Freyer, this volume). With the ongoing increase in nitrogen availability, during the 1980s more and more broad-leaved species developed in the understorey. This development was supported by an increased availability of light, due to SO₂-induced needle losses and an increased stem mortality. The dominant grass species in most pine plantations in 1989 were found to be *Calamagrostis epigejos* (app. 1.4 t DW ha⁻¹ in the west and 1.9 t dw ha⁻¹ in the east) and *Avenella flexuosa*. Typical representatives of woody plant species in these ecosystems were *Padus serotina* and *Sambucus nigra*.

Since (1) the understorey accumulates nutrients (app. 15 kg N ha⁻¹, above ground) and since (2) the daily transpiration rate of the understorey can reach the same magnitude as the transpiration from a sparsely foliated pine canopy, there has been discussion about whether the competition may affect the tree physiology and/or the stem growth significantly (e.g. Hofmann *et al.*, 1990). However, it has not been possible to show any clear results so far.

2. Expected developments

In 1990, after the German reunification, it became apparent that the industrial structure of the former GDR would change drastically. This was forced by the general breakdown of industry in the test region, and supported by the introduction of more sophisticated emission reduction technologies at the main point sources (see Table 1 for projections). Additionally, it was expected that further restrictions of polluting emissions would be rapidly demanded from policy.

As far as nitrogen emissions from non-industry sources (i.e. from traffic) were concerned, the situation was more complicated. On the one hand, emissions from agriculture (mainly NH_3) were expected to decrease, either due to economically forced changes or because of stricter legal regulations. On the other hand it became apparent that increased car traffic would lead to increased emissions of nitrogen in the form of NO_X . Thus, the regional pattern of total nitrogen deposition would change considerably. An additional factor was that forest fertilisation had been discontinued since the mid 1980s.

In this situation, it was not known how forest ecosystems would respond to the severe environmental changes in the region of the Dübener Heide, but it was assumed that the relevant developments would be of considerable importance for forest production and ecosystem stability. An understanding of the underlying processes was required not only to assist the policy of Germany, but also to provide information for pollution abatement strategies in the neighbouring countries of Poland and the Czech Republic. For scientific research, it was a unique opportunity to study developments of forests under gradients of deposition as well as under different initial conditions. The task addressed was thus similar to that addressed by various roof projects in different European countries (Visser *et al.*, 1994), but the investigation could be executed with much less effort and much more realistic conditions (roof experiment without roof) and on a much broader scale.

3. Former integrated assessments of forest decline and production

The analysis of available investigation results showed that forest growth and stand development depend on a number of influences that are more or less interrelated on different scales in time and space. Therefore, special attention was given to the development of computer models that integrate from the physiological or patch level up to the regional scale, are sensitive to air pollution and deposition and can be evaluated by means of experimental data.

In 1990, three different approaches for regional assessments of forest development were available that were sensitive to air pollution stress:

 The Regional Risk Model (Mäkelä, 1989), which is based on forest damage data of Norway spruce in the Ore Mountains, Germany, and is used to calculate risk levels for European forests (Alcamo *et al.*, 1985).

- The Forest Dieback Model (Lenz and Schall, 1987), which is based on investigations into Norway spruce in the German Fichtel-Mountains, calculates tree vitality as a response to direct and indirect deposition impacts.
- The Environmental Prediction and Decision Support Model (PEMU) (Bellmann *et al.*, 1988) is based on empirical tree growth functions for Scots pine, which are modified according to a multitude of stress conditions. It has been evaluated for areas in north-east Germany and has been used for estimations of forest production on a European scale (Nilsson *et al.*, 1992).

None of these approaches aims to provide a holistic picture of the forest ecosystem. They are, in fact, highly empirical and thus cannot easily be transferred from one region or species to another. Furthermore, a negative or positive feedback can only be considered within the range of conditions used for developing the dose-response functions, a factor which has been particularly critical for the first two models, as they were developed under conditions of an acidic environment with poor nutrient supply.

On the other hand, many investigations all over the world have led to an increased understanding of ecosystem processes, resulting in new models that represent tree growth based on a mechanistic approach requiring only initial conditions and external driving variables (e.g. Bossel and Schäfer, 1989; Mohren, 1987; Running and Coughlan, 1988). Those models had been designed to simulate full carbon balances of forest plantations. However, they were not suitable for long-term assessments because they had been evaluated with high-resolution data of physiological measurements. Stand processes, like tree mortality, had been based on empirical relations or were not been included at all in the models, and soil processes had been generally underrepresented. Furthermore, the initialisation requirements of the models are difficult to satisfy, which generally prevents application on a regional scale.

4. Tasks

As outlined above, severe changes of the environmental conditions in the Dübener Heide were expected, but the response of forest ecosystem development to these changes were largely unknown. It was obvious, however, that the possible impacts would not be the same over the whole area, but had to be differentiated according to the different regional patterns of SO_2 and nitrogen deposition, and different initial conditions. Thus, three tasks were identified, which could be used in a stepwise assessment of the regional forest development:

- Analysis of basic physical and eco-physiological processes at selected test sites, which had been exposed to different deposition loads, in order to

obtain and to deepen the understanding of responses and feedback mechanisms within the ecosystem. Measurements should be accompanied by the construction of a new physiologically-based model, which includes the most important state variables and fluxes of carbon, nitrogen and water between atmosphere, pedosphere and biosphere. Based on these balance estimates, the model should be used to describe stand development processes mechanistically as a function of stem carbon.

- Collection of information about soil and forest conditions on a regional scale. This information includes past as well as current stand and soil conditions to explore cumulative effects on forest growth. To relate the quantified responses to the past environmental conditions, regional differentiated climate and deposition data are necessary and management information at each site to be assessed is required. All regional information should be implemented in a geographical information system (GIS) and should serve for initialisation and evaluation of the stand growth model, which could thus be applied on a regional scale.
- Development of deposition scenarios and regional impact assessment. Starting with the current conditions of forest soils and forest stands, possible future developments under different deposition scenarios should be assessed using the evaluated forest growth model. On the basis of the results, possible abatement strategies and management options should be discussed.

As models should play the part of a control in the project, they should not only be related to the collection of data at the intensively investigated site, but should also coordinate and interrelate the activities of the measuring groups.

The resulting model should be suitable to represent small-scale measurements as well as long-term forest developments, recorded on a regional scale. Thus, the model must be sensitive to daily climate and deposition input data, but must also account for forest management effects including fertilisation. Furthermore, the demand on initialisation data must be in accordance with the soil and stand data that are available within the region.

5. Project implementation

5.1. The framework of SANA

The ecological impact research programme itself is part of a larger research framework, which was suggested shortly before the German reunification by researchers from both parts of the country. The first sub-projects were launched in 1991 and the main investigations were executed during 1993 until the end of 1995, supported by the Federal Ministry for Research and Technology and co-ordinated by the Fraunhofer Institute for Atmospheric Environment Research

in Garmisch-Partenkirchen. The whole framework is divided into the following programmes:

- Pollutant emission inventory, co-ordinated by the Institute for Energetic, Stuttgart.The project includes analysis and modelling of (daily) emission from point and non-point sources in the former GDR since 1970.
- Distribution and transport of pollutants, chemical transformation and modelling of regional pollution development, co-ordinated by the Fraunhofer Institute for Atmospheric Environment Research, Garmisch-Partenkirchen
- Ecological impacts, co-ordinated by the Potsdam Institute for Climate Impact Research in Potsdam and the Institute for Forest Ecology, Eberswalde at the Centre for Agricultural Landscape and Land Use Research, Müncheberg.

As outlined above for the ecological impact research, each of these programmes covers a number of sub-projects necessary to fulfil its specific task within the framework. Like the sub-projects of each programme, the programmes themselves are related to the other in a hierarchical order. Thus, it was possible to assess the whole chain of air pollution impact efficiently.

5.2. The research programme on ecological impacts

According to the tasks identified above, the specific sub-projects are determined firstly by the dominant gaps in knowledge, secondly by the modelling demand on initialisation data, and thirdly by the demand to summarise results and to formulate them on a regional scale (Table 5). A number of sub-projects investigated processes in the soil, humus, ground vegetation and trees at specific sites, which were selected along a gradient of air pollution:

The first site (Rösa) is located on the western border of the Dübener Heide, close to the former industrial centres. It represents a typical high-pollution site, which was exposed to extreme SO_2 concentrations but also received high amounts of alkaline dusts as well as nitrogen from fertilisation. The second site at Taura was exposed to medium pollution load, less dust deposition and relatively small amounts of nitrogen. It is located in the east of the target area. The third site at Neuglobsow was used as a background site, because it is located further north and was relatively unaffected by the industrial emissions. The results from these measuring groups served for process identification and parameterisation as well as short-term evaluation of the forest growth model.

A specific project was implemented for regional soil monitoring to support the modelling activities with initialisation data for regional assessments. This included a re-measuring of old soil samples taken in the same region in 1970, as well as the gathering of new data. Forest inventory data were supplied by the

Number	Task	
1.1	Foliage dynamics and nutrition	
1.2	Regional soil dynamics under pine forest ecosystems	
1.3	Element transport and transformation within the soil	
1.4	Transpiration and hydraulic conductance of pine forests	
1.5	Carbon and nitrogen dynamics in the humus layer and litterfall	
1.6	Canopy photosynthesis and respiration	
1.7	Diameter and stem volume growth dynamics	
1.8	SO ₂ induced biochemical stress indicators	
1.9	Dynamics of fine roots and mycorrhiza	
1.10	Lichen occurrence as indicators for SO ₂ deposition	
2.1	Ecosystem modelling	
2.2	Regional modelling	

Table 5. Sub-projects within the SANA programme for ecological impact research

State Forest Service and digitised by the regional modelling group, and deposition estimates were taken from the other programmes within the SANA framework. Weather data were directly available from weather recording stations close to the Dübener Heide. The modelling activities are divided into two groups, which are concerned with forest growth modelling on the one hand and regional computations on the other.

6. Concluding remarks

During the past few years several integrated research projects have been completed, which were concerned with pollution impacts on forests. The programme on 'Response of Plants to Interacting Stresses' (ROPIS) in the United States and the 'Dutch Priority Programme on Acidification' in the Netherlands are prominent examples of such projects. As in SANA, field investigations were executed which served to construct complex forest growth models, which in turn were used to analyse past and possible future impacts of pollutants and other stress factors on forest growth (Heij *et al.*, 1991; Weinstein *et al.*, 1991). More recently, focussing on the impact of climatic changes, such models were also used to assess the impact on a regional scale, simulating net primary production or stemwood growth in selected (representative) forests subject to atmospheric deposition loads along a gradient of conditions (Aber *et al.*, 1995; Bowes and Sedjo, 1993; Running, 1994).

There is no single case, however, where environmental conditions changed on a regional scale as drastically as in Eastern Germany, resulting in ecosystem changes that can actually be observed from year to year. Therefore, the ecological part of SANA can be considered as a 'roof experiment without a roof'. Furthermore, the availability of long-term climatic and deposit informa-