Investigation and simulation of pollution effects on pine forests in Eastern Germany

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During past decades, forests in former East Germany have been exposed to high concentrations of air pollutants, in particular to sulphur compounds, with the consequence of severe damage. Since German reunification and the breakdown of much of the industry in this area, atmospheric deposition has declined sharply and its composition has changed as well. Therefore a project was launched to gain a quantitative assessment of future forest development, concentrating on Scotch pine as the most common species. The methodological approach is based on coupling a geographic information system with a dynamic simulation model. This paper gives an overview of the approach taken, and presents first results from comparison of theoretical simulations with forest inventory data.

Introduction

Former East Germany was one of the European countries with extremely high rates of pollutant emissions. Energy production was mainly based on burning lignite, without using pollution reduction technologies. An agglomeration of industrial and energy production in the southern parts of the country led to an extremely high load of pollutants in this region, and to peak concentrations of about 4 mg/m³ SO₂ during meteorological inversion situations, especially in the industrial region of Halle - Leipzig - Bitterfeld and the surrounding area. After German reunification in 1990, the quantity and chemical composition of emissions has changed drastically. Emission of SO₂ and alkaline dusts has been reduced mainly by industrial transformation processes and implementation of reduction technologies by about 50% between 1989 and 1992. NOₓ emission has increased, mainly caused by increased traffic.

In this situation the German research framework SANA was set up to investigate the effects of the changed emission regime, the distribution and transformation of atmospheric pollutants and impacts on ecosystems. The intention of the programme is to accompany pollutant-abatement strategies for the improvement of air quality and restoration of damaged ecosystems. The evaluation of the ecological effects of economic emission reductions within an appropriate time scale is an important objective of SANA.

Investigation area and methods

The main area under investigation area is known as the Dübener Heide. It is located near former major industrial centers and it is influenced directly by the emissions of the Halle - Leipzig - Bitterfeld region (figure 1). With an extent of about 400 km², 75% of the area is covered by forests, mostly consisting of
Two different time intervals are considered for the landscape model:
- a retrospective temporal horizon between 1967 and 1989 for model validation purposes
- a prospective, scenario-oriented simulation horizon from 1990 to the year 2030 to study possible developments of forest stands under changing immission/deposition.

1. The forest growth model
The growth model FORSANA consists of two parts, as it is shown in figure 3. The first is the simulation of responses of the tree, soil and ground vegetation to daily environmental impacts (light, temperature, precipitation, air humidity, wind speed, SO$_2$ air concentration and nitrogen deposition). The second transposes the yearly summary of the traced development into stand growth.

![Figure 3: Simplified scheme of interaction between daily and yearly processes as implemented in FORSANA.](image)

The main processes in the tree, considered in daily steps, are assimilation, respiration, allocation and mortality of different compartments (needles, fineroots, wood, renewal and reserves). Transpiration is estimated for calculation of photosynthesis reduction due to water stress. Additionally, needle age, temperature, SO$_2$ concentration and nitrogen content can decrease potential assimilation (see Bossel$^1$, Mohren et al.$^4$ for further information). Growth is calculated from photoproduction and respiration losses. Assimilates are distributed among the tree compartments by a dynamic allocation system, which depends on the particular sink strength for each day. The dependence of
even-aged stands of Scotch pine (*Pinus sylvestris* L.). Sandy, soils dominate the forest sites, which are characterized by relatively dry climatic conditions.

To evaluate the growth of past emissions as well as scenarios of future emissions, a forest sector oriented landscape model has been developed which consists of:

1. a dynamic, process-oriented simulation model FORSANA, describing growth of Scotch pine ecosystems. It is sensitive to immission/deposition and climate.
2. an immission/deposition database for the region as an interface for an emission/immission-model, combined with a geographic information system (GIS), to capture and manage all data for spatial calibration and validation of FORSANA and to provide model output facilities. Spatial-temporal dynamics of immission/deposition of SO₂, total amount of nitrogen, and alkaline dusts are mapped with this system.

Figure 1: Target area and area of the emission inventory of the case study in Germany

Figure 2: pH increase and Nitrogen deposition in the Dübener Heide between 1967 and 1989
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Fine root- and needle- mortality on average weather conditions (precipitation, \( SO_2 \) concentration) and soil conditions (soil-water potential; dependence on acidification is under development) is of high importance. Each year stand properties such as height, crownbase and average diameter are evaluated by distributing the cumulative wood growth, taking the actual stand properties into consideration (see Bossel\(^1\) and Sievaenen\(^5\)). Stem mortality is established using a natural mortality factor, which can be enhanced by the density of the stand and low productivity.

2. Regional database

For calibration and validation of the dynamic forest growth model an intensive evaluation of available data of the region was carried out. All georeferenced data is stored in a GIS which is related to a relational database system (ORACLE). Model input data were compiled from forest inventories, soil and topographic maps, and additional information such as soil descriptions and chemical analysis. Additional attributes will be derived using GIS-functionality or algorithms (table 1). Comparison of humus-type, \( pH \) and species composition of ground vegetation between 1967 and 1989 gives a first qualitative idea about gradients of deposition rates within short horizontal distances in this area (figure 2).

The forest stand level is considered to be the smallest homogenous units (SHU) where all different datasets can be analyzed and interpreted. Therefore a „supervised map overlay“ will be performed, assigning information from the other map layers to stand level SHUs by different strategies (e.g., areal maximum, mean and weighted mean). Classification of each input parameter is performed according to the sensitivity of the dynamic model.

Driving forces and scenarios

Immission/deposition of \( SO_2 \), total amount of nitrogen and alkaline dusts, combined with meteorological data, are the driving forces of FORSANA. For the retrospective validation between 1967 and 1989, meteorological data is available from meteorological stations near the investigated area, while spatially and temporally resolved immission records are missing. Thus, the following approach has been set up by other SANA research groups:

Immission rates of pollutants for the target area Duebener Heide will be calculated by designing matrices based on an emission inventory data set for the area of former East Germany (figure 1). Each set of matrices is related to a wind direction and atmospheric stability classification and is derived from the Gaussian distribution model. Calculations of daily immissions within the target area are based on superposition of the weighted matrices. A deposition model will be used for calculating the forest deposition. Consequently, for each day of the validation period, spatially resolved immission / deposition values will be available in the appropriate database to be coupled to the landscape model.
Table 1: Sources, available and derived data for the landscape model

<table>
<thead>
<tr>
<th>driving forces</th>
<th>data</th>
<th>derived data</th>
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<tbody>
<tr>
<td>emission per grid element</td>
<td>pollutants (SO₂, nitrogen, alkaline dusts)</td>
<td>deposition</td>
</tr>
<tr>
<td>weather stations (daily values)</td>
<td>temperature (air / soil) wind velocity and direction, air humidity radiation / cloudiness precipitation, snow cover</td>
<td>atmosph. stability classes for Gaussian distribution matrices, wind fields, climatic water balance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ecological data</th>
<th>aspect</th>
<th>slope</th>
<th>net - irradiance groundwater table</th>
</tr>
</thead>
<tbody>
<tr>
<td>contour lines (topographic maps)</td>
<td>nutrient / pollutant contents soil texture soil depth</td>
<td>nutrient amounts field capacity increase of alkaline compounds (Ca, Mg)</td>
<td></td>
</tr>
<tr>
<td>soil maps (1967)</td>
<td>changing of humus type and ground vegetation</td>
<td>acidification</td>
<td></td>
</tr>
<tr>
<td>soil mapping program (1990)</td>
<td>changing of nutrient concentrations</td>
<td>nitrogen load</td>
<td></td>
</tr>
<tr>
<td>chemical analysis (1967-1990)</td>
<td>stand age, height, mean diameter, stand density / canopy closure, yield class, (N-) fertilisation</td>
<td>canopy roughness</td>
<td></td>
</tr>
<tr>
<td>forest inventory database (1970/80/92) and maps</td>
<td>needle loss needle vitality / necrosity growth</td>
<td>leaf area index, needle - biomass</td>
<td></td>
</tr>
<tr>
<td>biomonitoring</td>
<td>species composition</td>
<td>biomass</td>
<td></td>
</tr>
<tr>
<td>ground vegetation maps</td>
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<td></td>
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</table>

After the process of iterative validation, a similar approach will be performed for scenario creation: primary emission reduction scenarios result in an immission/deposition scenario database using secondary climate scenarios from the meteorological records of the validation period (e.g., increase of the frequency of extreme years). Depending on the availability of emission data, the following scenarios are planned:
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- a „worst case scenario“, extrapolating the emission situation of 1989 until 2030
- a „reunification scenario“, extrapolating the emission situation of 1992 until 2030. In 1992, emission reached in total approx. 50% of the year 1989. These scenarios will enable ecosystem stability to be investigated in its spatial heterogeneity and different paths of future development to be compared.

Results and Discussion

Simulated pollution impacts on forest stands
In a first attempt at evaluation of pollution impacts, forest development was investigated by growth simulations. A weather record from Wittenberg weather station, which is located within the Duebener Heide area, was used, covering the years from 1967 to 1990. Background SO$_2$-air concentration was obtained by repeating a one-year measurement from a weather station north of the area (Neuglobsow station, year 1994) for every year (low SO$_2$-conc.: 42 ppb average, 100 ppb maximum). High air pollution was simulated by multiplying these data by three (nitrogen input was set at a constant rate of 12 kg/(ha*a) for both runs).

In figure 4 development of whole stand biomass and gross production is shown, starting with either young or old stands. It can be seen that somewhat lower production is simulated under conditions of high air pollution, but the difference is very much dependent on yearly weather conditions. In particular in dry years (1975, 1976) it is high, whereas in wet and cool years (1974, 1981) production with SO$_2$ pollution is approximately the same as without. It is also remarkable that the difference of simulation output between low and high pollution impact is lower in older stands. Also the recovery from dry years seems to be easier in older stands than in younger stands.

The simulation results can be explained by the fact that SO$_2$ is responsible not only for a direct reduction of assimilation, but also for an increase of needle mortality. Because of the strong plant reaction in dry years, where stomatal closure should lead to a low pollution effect, the former seems to be quite unimportant. The latter, however, leads to an increasing investment of assimilates in the production of new needle mass. This results in a higher rate of dynamics in the total leaf area over the year, and therefore to a higher dependence of production conditions in mid- and late summer. This may be the reason for different reactions in years with similar weather statistics (e.g. 1976 (dry summer) /1982 (dry spring)). Additionally, the higher investment in needles generally reduces the possibility of growth in other compartments, in particular the reserve pool, which is important for needle growth of the following year. Because the model assumes that the older stands are beginning with a higher reserve pool (which would be otherwise if they had grown under conditions of high air pollution), this group shows generally smaller reactions.

It has to be noted that the projection of total biomass in a stand does not say anything about the dimensions of the trees within this stand. Thus, also in stands which grow under high pollution pressure, the volume growth of the single tree
can be high, if the number of trees is markedly reduced. In the simulation, stand density under pollution pressure was decreased compared with the control run only in the young forests. However, average tree growth was also somewhat lower. This shows the need for further development with respect to a better regulation of tree mortality and growth distribution among different tree size classes.

Figure 4: Simulated forest development of young (A) and old (B) pine stands under low and high SO\textsubscript{2} air concentrations (climate data: Wittenberg station, years 1967-1990)

Pollution impacts at the landscape level
Coupling forest inventory data with results of the soil mapping program gives a first idea about the influence of different pollutants on forest tree growth and stand density. Figure 2 shows a gradient of pH increase as the result of emissions of basic ashes mainly from the industrial area of Bitterfeld. High rates of ash deposition are correlated with high air-concentrations of SO\textsubscript{2}. Nitrogen deposition in this area is mainly influenced by fertilizer production north of the area and local emission sources such as animal farms and crop production.
Because the response of the forest ecosystem to air pollution may affect the growth rate of the single tree as well as the number of trees per ground area, both were tested against deposition rate using ANOVA analysis of variance. Tree growth was expressed as the relationship between tree height and diameter as a function of tree age.

<table>
<thead>
<tr>
<th>age class (yrs.)</th>
<th>pH increase</th>
<th>nitrogen dep.</th>
<th>pH increase</th>
<th>nitrogen dep.</th>
</tr>
</thead>
<tbody>
<tr>
<td>20-40</td>
<td>.662</td>
<td>.486</td>
<td>.000</td>
<td>.336</td>
</tr>
<tr>
<td>40-60</td>
<td>.000</td>
<td>.470</td>
<td>.080</td>
<td>.161</td>
</tr>
<tr>
<td>60-80</td>
<td>.000</td>
<td>.875</td>
<td>.040</td>
<td>.922</td>
</tr>
</tbody>
</table>

The results show firstly that pH increase is much more closely correlated with stand density and tree growth than nitrogen deposition (table 2). Therefore, pH increase has to be considered as indicator for stress, supposed due to high concentrations of SO2 at the same areas. This result supports the assumptions described in the simulation attempt, and makes clear that both single tree growth and stand density have to be considered for forest ecosystem dynamics under different deposition situations.

**Further developments**

First of all, future investigations will include more realistic scenarios with respect to SO2 development in the prescribed period. Also other impacts, in particular the change in nitrogen input, should be considered. Nitrogen supply has shown to affect respiration (e.g. De Wit) and allocation (e.g. Ingestad & Agren), so that a considerable changes may lead to a significant modification of stand growth reactions.

It is suspected that a better picture of average tree growth can be obtained if growth and mortality of a stand are considered for different tree size classes. In that case, simulation would predict an increase in mortality and a concentration of growth in particular parts of the stand. This would lead to a better use of assimilates by concentration on the surviving trees at polluted sites. In the context of stand density impacts, another aspect should be looked at in more detail: all stands which will serve for validation of simulated growth, being under forestry management, also the influence of thinning effects in combination with other site specific impacts should be taken into account.

Further investigations have to be done for a first approach of coupling emission-immission-impact modelling. At the landscape level this includes the interpolation of soil chemical data using geostatistical methods such as Kriging, and the analysis of the most sensitive factors affecting forest growth. Therefore soil and humus type, groundwater level, slope and other factors describing site conditions have to be tested with multivariate statistics. Spatial resolution of immission grid size with an initial value of 500 m x 500 m and validation and
calibration of the emission/immission model with selected immission records are further problems which should be discussed.

Acknowledgements

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References