Environmental stress in German forests

Assessment of critical deposition levels and their exceedances and meteorological stress for crown condition monitoring sites in Germany

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ABSTRACT

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Site-specific estimations of meteorological stress and atmospheric deposition were made for the systematic 8 x 8 km² forest condition monitoring network in Germany for the years 1987-1995. Winter cold and late frost were important temperature stress variables and relative transpiration was a good indicator of drought stress. All variables showed considerable temporal and spatial variation. Present loads of nitrogen and acidity were modelled with an adapted version of the model EDACS and combined with critical loads and critical deposition levels based on the SMB model. Both present loads and the exceedances showed considerable spatial variation and a clear decrease in time.

Keywords: acidification, nitrogen, drought, frost, cold, interpolation, modeling, forest health

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ALTERRA is the amalgamation of the Institute for Forestry and Nature Research (IBN) and the Winand Staring Centre for Integrated Land, Soil and Water Research (SC). The merger took place on 1 January 2000.

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Contents

Preface

Forest condition (in terms of defoliation and discoloration) in Germany is being monitored since the mid 1980s on the intersections of a systematic 4 x 4 km^2 gridnet. At part of the plots of this network (namely at the 8 x 8 km^2 gridnet), soil chemistry has also been measured, whereas an even smaller subset is also part of the 16 x 16 km^2 Pan-European monitoring network. The monitoring at these sites is limited and includes only few factors that affect defoliation or discolouration.

Since 1995 an approach has been developed to assess site specific estimates for various natural and anthropogenic stress factors for the Pan-European network. This approach has now been fine-tuned for the German situation and consecutively applied on the 1827 monitoring sites of the 8 x 8 km^2 gridnet in Germany. This report describes the assessment of meteorological stress parameters as the most important unknown natural stress factors and the exceedances of critical loads and critical deposition levels for nitrogen and acidity as the most important anthropogenic stress factors.

This work was carried out in close cooperation with the National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu; RIVM, Bilthoven, The Netherlands), who provided the deposition estimates and carried out the interpolation of meteorological data. This work was done for, and sponsored by the Federal Environmental Agency (Umwelt Bundes Amt; UBA, Berlin, Germany) with RIVM as intermediate agency. Furthermore, much of the data available from the sites were obtained from the Federal Research Centre for Foresty and Forest Products (Bundesforschungsanstalt für Forst und Holzwirtschaft (Institut für Forstökologie und Walderfassung); BFH, Eberswalde, Germany), who coordinate the monitoring activities in Germany and are responsible for the proper use of the data from the individual *Bundesländer*. This institute is also responsible for the nation-wide evaluation of the forest condition and crown condition data. Special thanks for Dr. Winfried Riek of BFH, who put a lot of effort in the preparation of these data provided by the *Bundesländer*. The data presented in this report are made available for correlative evaluations with the German forest condition data. The wet and dry deposition data were provided by the Institute for Navigation (Stuttgart, Germany), in cooperation with RIVM. Special thanks for Dr. Thomas Gauger, who put a lot of effort in the preparation and improvement of these data. The water balance model was improved and made applicable for the German sites by Dr. Caroline Van der Salm of Alterra (up to 1999).

The BZE (Bodenzustands Erhebung) delegates of the German Bundesländer were not consulted to evaluate the results prior to publication of this report. The major reason is because of the delay in accurate deposition data for sulphur, needed for the calculation of critical load exceedances. Those data only became available well after the official end of the project.

Summary

Introduction

The lack of measured information on stress caused by meteorological phenomena and atmospheric deposition is a major limitation in the possibilities for a comprehensive evaluation of the results of crown condition monitoring since the mid 1980's in Germany at a 4 x 4 km^2. The present study provides estimations for a set of relevant key factors at the 8 x 8 km^2 grid subset at these plots for which results of a soil survey were available, while accounting for different threshold values with respect to atmospheric deposition.

Methodological approach

Two key factors for temperature stress (Winter Index and Late Frost) and one key factor for drought stress (Relative Transpiration) were selected, along with few less important ones. These key factors were derived from interpolated 6-hourly and daily meteorological data, which were also used for the estimation of atmospheric deposition. The Relative Transpiration was based on a water balance model, which also included physical, physiological and soil physical variables.

Two key factors for present loads (total N deposition and total acidity deposition) were selected. Deposition was estimated by combining estimates of the dry deposition from the EDACS model (using EMEP data) and interpolated wet deposition data. Threshold values for the short-term (critical deposition level) and long-term for both key factors were derived using a SMB model, which includes all relevant (chemical) processes and fluxes in the forest ecosystem, while accounting for certain critical values. Exceedances were calculated by subtracting the threshold values from the present load.

Results

The temperature indices (90% of the mean values over the period 1987-1995) varied between 70 and 230 degree days below 0 °C for the Winter Index and between 1.6 and 4.4 degrees below 0 °C for Late Frost. These factors characterized as important stress factors for forests in Germany. Drought stress, in terms of Relative Transpiration, generally varied between 0.7 and 1.00, with a median value of 0.85 but also with values down to 0.5 (mean values over the period 1987-1995) and can therefore be considered as an important stress factor in many German forests.

The meteorological stress indices showed considerable temporal variation between 1987 and 1995. The coldest winters occurred in 1991, 1993 and 1994, whereas the most harmful late frosts occurred in 1993 (and 1987 and 1995). The driest years occurred in 1989, 1992 and 1994.

The meteorological stress indices showed considerable spatial variation, with clear differences between the different years. The coldest winters -on average- were found in the hilly and mountainous areas, whereas the selected year 1995 was specifically

cold in the Bavarian Alps. Late Frost shows an increase from northwest to southeast and with increasing altitude, whereas in the selected year 1995 relatively high values were found in a north to south belt over the country and along the southern border. The northern half of the country suffered -on average- from a moderate level of drought stress, whereas in the selected year 1995 large areas in the northwestern and northeastern part of the country had serious drought stress.

The calculated nitrogen deposition (averaged over the years 1987-1995) mostly ranged between 1500 and 3000 $mol_c\ ha^{-1}\ a^{-1}$, with a median value of 2000 $mol_c\ ha^{-1}\ a^{-1}$. The deposition of total acidity mostly varied between 3300 and 10000 $mol_c\ ha^{-1}\ a^{-1}$ over the same period, with a median value of 4900 $mol_c\ ha^{-1}\ a^{-1}$. Both variables showed a decreasing tendency over the considered period with a limited number of plots (<5%) with extremely high deposition of acidity in the first couple of years, mostly related to extremely high SO_x deposition.

The average N deposition was highest (>2500 $mol_c\ ha^{-1}\ a^{-1}$) in large part of the northwestern part of the country and in some areas in the southeast. The average deposition of acidity was highest (>8000 $mol_c\ ha^{-1}\ a^{-1}$) in the southern half of the former GDR and adjacent areas with extreme peak values (>20000 $mol_c\ ha^{-1}\ a^{-1}$ in the first couple of years) at a few plots in the Ertz Mountains and Fichtel Mountains.

The estimated critical deposition level for nitrogen mostly varied between 1400 and 3250 $mol_c\ ha^{-1}\ a^{-1}$ (short-term) and between 900 and 2600 $mol_c\ ha^{-1}\ a^{-1}$ (long-term), both with median values of 2000 and 1350 $mol_c\ ha^{-1}\ a^{-1}$, respectively. The estimated critical deposition level for acidity varied between 2900 and 8200 $mol_c\ ha^{-1}\ a^{-1}$ (short-term for the plots with BS<25%) and between 1500 and 10500 $mol_c\ ha^{-1}\ a^{-1}$ (long-term for all plots), with median values of 5400 and 3900 $mol_c\ ha^{-1}\ a^{-1}$, respectively. The results were generally higher than in comparable studies, especially for acidity, mainly due to an improved Al/BC criterion, a large share of plots with loamy/clayey or wet soils (with different denitrification and leaching characteristics) and large variation in other input variables.

Many plots with relatively low values (< 2000 $mol_c\ ha^{-1}\ a^{-1}$) for the critical deposition level (indicating a high vulnerability to N deposition) were found in the north-eastern part of the country, whereas such values cover almost the whole country in the long-term approach. The large area with low values (< 4000 $mol_c\ ha^{-1}\ a^{-1}$) for the critical deposition level and for the critical load of acidity was found in the north, indicating a high vulnerability to acid deposition. Vulnerable plots occurred more scattered also in other parts of the country.

The exceedance of the critical loads and critical deposition levels reflected the results for the present loads and the critical loads and critical deposition levels. Exceedances for nitrogen, averaged over the years 1987-1995, were found at 81% (short-term) or 94% (long-term) of the plots, with extreme values above 400 and 1000 $mol_c\ ha^{-1}\ a^{-1}$, respectively. Exceedances for acidity, averaged over the years 1987-1995, were found at 53% (short-term) or 89% (long-term) of the plots, with extreme values above 4000 and 6000 mol_c ha^{-1} a^{-1}, respectively. All these variables showed a clear decrease over the considered period.

The exceedances of critical N deposition levels were concentrated in the northern half of the country, with some more serious exceedances (> 1000 mol_c ha^{-1} a^{-1}) of the critical loads in the former GDR and in the northwestern part of the country. The exceedance of the long-term critical load for N is far more wide-spread and more serious. Moderate exceedances (< 2000 mol_c ha^{-1} a^{-1}) of the critical load for acidity occurred on a large scale throughout the country. More serious exceedances (> 4000 mol_c ha^{-1} a^{-1}) of both the critical load and critical deposition level were concentrated in the southern half of the former GDR but severe exceedances were concentrated in the Ertz Mountains and Fichtel Mountains.

Uncertainties

The calculated indices for temperature and drought stress contain uncertainties, which largely depend on the reliability of the site-specific meteorological data and the spatial resolution of the interpolation method. The estimations for drought stress are also affected by uncertainties in various model terms in the used water balance model. In general the site-specific meteorological estimates followed the geographical patterns as expected.

The uncertainties in the deposition estimates were mostly related to uncertainties in the model terms and parameters (e.g. the estimated deposition velocity), in uncertainties related to the grid-oriented basis of the air concentration and in simplifications of the model. The uncertainties in the critical deposition levels and critical loads were related to (i) the choice of criteria (e.g. the N leaching rate, assumptions about effects of Al and the use of annual mean values rather than peak values), (ii) model assumptions (e.g. the homogeneity of the rootzone and simplifications of several N transformations and other chemical equilibria) and (iii) the quality of the input data, which were mostly estimated rather that measured whereas the use of more precise estimations was also hampered by limitations in the access to more specific databases, which more precisely describe the German conditions..

1 Introduction

Background

In order to obtain more insight in the possible causes of forest decline in Germany, a systematic 4 x 4 km^2 monitoring network has been set up since the mid 1980s, covering the whole country gridnet (e.g. Waldzustandsbericht der Bundesregierung, 1995). Forest condition (in terms of defoliation and discoloration) is assessed at these plots at an annual basis. Other indicators of the condition of the forest ecosystem (e.g. chemical foliar condition and chemical soil condition) are monitored less frequently or are assessed only once, at a 8 x 8 km^2 grid subset (Deutscher Waldbodenbericht 1996, 1997; Wolff and Riek, 1998). An even smaller but still representative subset of this monitoring network is also part of the 16 x 16 km^2 Pan-European monitoring network, the so-called Level 1 monitoring network (Riek & Haußmann, 1998; Riek & Wolff, 1997).

An evaluation of the first 10 years of monitoring at the Pan-European Level 1 monitoring network revealed that forest condition (in terms of defoliation) is affected by a complex set of stress factors, both natural and anthropogenic (Klap *et al.*, 1997; UN-ECE&EC, 1997). Also several national and regional studies revealed that air pollution and meteorology affect forest condition (e.g. Riek and Wolff, 1998a,b and Riek and Wolff, 1999 for the whole of Germany; Mather, 1994; Nellemann and Frogner, 1994; Hendriks *et al.*, 1994; 1997 and Landmann and Bonneau, 1995 for surrounding countries and Gärtner *et al*., 1990 and Becher, 1999 for some of the Bundesländer).

Like in the European Level 1 monitoring programme, the German Level 1 programme did not include the measurement of various important natural and anthropogenic stress factors at the sites. This refers specifically to meteorological stress (related to drought and adverse temperature condition) and air pollution stress (exceedances of critical deposition levels for acidity and nitrogen). For the European study, an approach has therefore been developed to assess site-specific estimates for meteorological phenomena (natural stress) and atmospheric deposition (anthropogenic stress) at the 16 x 16 km^2 Pan-European monitoring network (Klap *et al*., 1997; UN-ECE&EC, 1997). The present study elaborates this approach for the German Level 1 sites for the years 1987-1995, using more specific data and a more specific model approach, to account for the conditions at the systematic 8 x 8 km^2 monitoring network in Germany. Furthermore, the most recent advances in the model approach have been included.

Aims

The major aims of this study are:

- To provide site-specific estimates for relevant meteorological stress parameters related to drought and adverse temperature conditions at the plots of the 8 x 8 km2 gridnet for the years 1987-1995.

- To provide site-specific estimates for the threshold level of the forest ecosystem for the deposition of nitrogen and acidity, both at the short-term and long-term (resp. the critical deposition levels and the critical loads).
- To provide an overview of the current exceedances of these threshold values for the years 1987-1995.

The results are transferred to the Federal Institute for Forestry and Forest Products (Bundesforschungsanstalt für Forst und Holzwirtschaft; BFH, Eberswalde, Germany). BFH coordinates the monitoring activities in Germany and which will then be able to include these stress factors into a comprehensive evaluation of the crown condition data collected since the mid 1980s.

Contents of this report

Chapter 2 provides information about the applied methods, the input data used and the models applied. This is done separately for the meteorological stress parameters and the air pollution parameters (Sections 2.1. and 2.2, respectively). Chapter 3 gives an extensive overview of the results obtained, also separately for the meteorological stress parameters and the air pollution parameters (Section 3.1. and 3.2, respectively). Chapter 4 includes a discussion about the relevance of the results, mostly related to the uncertainties. Chapter 5, finally, gives the main conclusions of this study.

2 Methodological approach

2.1 Meteorological stress

Meteorological stress factors include drought stress, temperature stress (cold, frost, heat), radiation stress (lower level of global radiation than the potential level) and mechanic stress (storms, snow, glazed frost). This paper focuses on drought stress and temperature stress over the period 1987-1995 in which crown condition data have been assessed at the sites for which also soil chemical data were available. The mean estimations for temperature and precipitation over the considered period were also used as input variables in the calculation of critical loads and critical deposition levels (Section 2.2). The deviation from an estimated long-term normal value for each stress factor at each site was also included, to account for the adaptation of the trees to site-specific growing conditions.

2.1.1 Temperature stress

Based on an analysis of relevant factors and availability of data the following factors related to temperature stress were used (cf. Klap *et al.*, 1997),:

- Winter index: equals the sum of daily mean temperatures below 0 °C in the period from 1 October to 1 April (degree days below 0 °C).
- Late frost: equals the lowest minimum temperature (below 0 °C) in a period starting at 15 days before the growing season started and ending at June 30.

In addition, indices were calculated for Summer Heat, Early Frost and Acute Frost and also two Effective Temperature Sums (ETS's). The Heat Index is an indicator of the summer heat stress, and is calculated by the sum of differences between daily maximum temperatures in the growing season and an (arbitrary) threshold of 30 °C (degree days above 30 °C). The index for Early Frost is calculated for the autumn period, in a similar way as the Late Frost index. Early Frosts may affect the visible tree condition in the next year. The index for Acute Frosts is calculated as an indictor of stress by acute frost after a milder period. (see Eq. 1). The Effective Temperature Sums (ETS's) equal the sum of differences between daily mean temperatures during the growing season and two (arbitrary) threshold values of 10 °C and 15 °C, respectively (ETS10 and ETS15; degree days above 10 °C / 15 °C). These variables, however, are only briefly presented. Variables related to precipitation are presented together with the drought stress variables (see later).

$$AcFrost = MAX_{1oct-1apr}\,(T(\min)_d * T(\max)_{d-1}) \qquad (1)$$

with

$T(min)_d < 0$

$T(max)_{d-1} > 0$ and

$T(min)_{d-1} > 0$, $T(min)_{d-2} > 0$ and $T(min)_{d-3} > 0$

Meteorological data were derived from detailed information interpolated to the site by RIVM (Section 2.1.3) and were aggregated over the growing season or winter period. The beginning and end of the growing season were set to fixed dates, depending on bio-geographic region and the altitude (cf. Klap *et al.*, 1997). The same dates were used for the different tree species or forest types.

Most emphasis is laid on the first two variables, which are expected to have most effects on crown condition in Germany. The Winter Index gives an indication about the severeness of the winter, whereas Late Frost gives an indication about possibly damage by the occurrence of frost in the period of budburst and young leaves. The occurrence of Summer Heat is expected of minor influence in the German forests, since very hot days occur relatively seldom. The impact of prolonged periods of warmth or heat may also be included in the drought stress (see next section). The ETS values give an indication about the temperature related growing conditions.

Since no long-term climatic data (> 30 years of observations or estimations) were available for the considered sites, an estimation had to be made of the `normal' conditions at each site. The mean value for the five mildest years in the nine years period was chosen as an arbitrary measure for the site-specific estimation of `normal, non-harmful conditions'. The five mildest years were defined separately for each stress factor, namely as the five years (per plot) with the lowest values of the Winter Index, Late Frost and Heat Index (i.e. the lowest temperature stress) and the highest values of the ETS (i.e. the warmest, most favourable growing conditions). The deviation of the annual values from this `normal' value was used as a measure for the meteorological stress at each site, while accounting for the adaptation of the trees for the long-term climatic conditions.

2.1.2 Drought stress

Drought stress occurs in situations where the actual transpiration is less than the maximum, or potential transpiration. Consequently, the ratio between actual and potential transpiration (RE_T) was used as indicator for drought stress. Drought stress is expected to be better correlated with relative transpiration (= actual/potential transpiration) than with relative evapotranspiration (= actual/potential evapo-transpiration) as the latter term also includes evaporation of intercepted precipitation and soil evaporation. A mean RE_T for each growing seasons was derived, using the same definition as used for the temperature stress variables.

The procedure to calculate the relative transpiration (RE_T) is illustrated in Figure 1. The first step is the calculation of the potential evapotranspiration (ET_p) using the Penman-Monteith equation (Monteith, 1965). Secondly, the interception (E_I) is calculated, using the model of Gash (1995). As a third step soil evaporation is calculated according to Van den Broek and Kabat (1996). Next, potential transpiration is calculated by subtraction of interception and potential soil evaporation. Finally, actual transpiration is calculated depending on the potential transpiration and the soil moisture content. More detail on the calculation of the relative transpiration and the input data are given in Section 2.1.3.

Like for the temperature stress variables, the deviation from the mean value of the five mildest years was used as a measure for the drought stress at each site, while accounting for the adaptation of the trees for the long-term climatic conditions. The five mildest years were defined as the five years (per plot) with the highest values of the relative transpiration (i.e. the lowest drought stress).

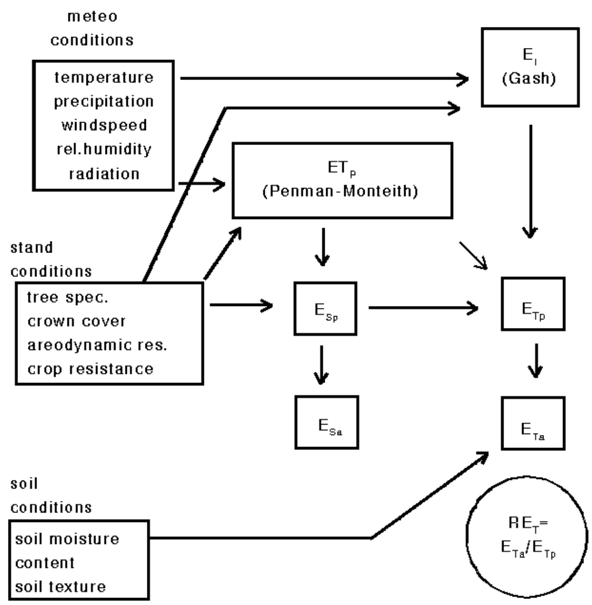

Fig. 1 Procedure to calculate the relative transpiration (RE_T)

The resulting values can vary between 0 and 1, where 1 stands for no reduction of the transpiration and 0 for complete inhibition of transpiration. The value at which visible symptoms of drought stress appear, depends on the tree species (among other factors). In generally, the more demanding species show these symptoms at values close to 1, whereas less demanding species can sustain a stronger reduction of the transpiration.

The calculation of the water balance requires detailed information on various meteorological, physiological and soil physical variables. In this study these variables were all available, either by measurement or by estimation. Many studies, however, use less complex drought stress parameters These are mostly based on (mostly externally derived) combination of information on precipitation, temperatures and potential or actual evapotranspiration (for an overview see Callaert *et al.*, 1997). From the large number of available variables we have chosen the so-called Aridity Index of De Martonne as a simple alternative measure, for reasons of comparison. This measure was calculated both for the entire year (Eq. 2-a) and for the growing season (Eq. 2-b).

$$Aridity_{year} = \frac{Prec_{year}}{Temp_{year} + 10} \tag{2-a}$$

$$Aridity_{gr.season} = \frac{n\_days_{year}}{n\_days_{gr.season}} * \frac{Prec_{gr.season}}{Temp_{gr.season} + 10} \tag{2-b}$$

in which Prec equals the total amount of precipitation in the considered period (in mm), Temp equals the average temperature over the considered period (in ^{o}C) and n_days equals the length of the observed period (in days).

The resulting values vary between 10 and over 100, where 10 stands for very arid conditions and 100 stands for very wet conditions. The value at which visible symptoms of drought stress appear, depends on the tree species (among other factors). For a species with intermediate moisture requirements, such as *Picea abies*, no effects will be expected at levels above 40, whereas serious drought stress can be expected at values below 25. For less demanding species (e.g. *Pinus sylvestris* or *Quercus petraea / robur*) these values are slightly lower, whereas for more demanding species these values (e.g. *Populus* sp.) are slightly higher.

2.1.3 Derivation of model input data

Interpolation of meteorological parameters

As the measurement of meteorological parameters is not included in the Level 1 monitoring programme, all meteorological information was derived from external databases. One consistent database for the whole period 1980-1995 was not available. Therefore, three different databases were combined (ODS, NCAR and DWD), generally containing data from the same meteorological stations on the same time resolution (see Klap *et al.*, 1997 for a description of the databases). The data set contains 6 hourly averaged meteorological observations measured at about 1300 stations over Europe.

Meteorological parameters taken from the different databases were: wind speed, temperature, cloud cover, relative humidity and precipitation amount. Cloud cover is used for calculating the net radiation. Meteorological data available per site were: precipitation amount per day, minimum and maximum temperature per day, daily average temperature and average net radiation.

Site-specific meteorological data were obtained through interpolation of measurements, except for precipitation amounts for which the value from the nearest meteorological station was taken. Interpolation to each site was performed using a simple inverse distance weighting procedure from a maximum of four meteorological stations located in the immediate surroundings of the site. Most emphasis in the method was put on data quality by selection of the most representative stations to be used for the interpolation to each site. The selection procedure was based on the method described by Van der Voet *et al*. (1994), e.g by proximity and by similar altitude. Estimated values for the plots in German can generally be related to measurements from meteorological stations in Germany, but also to measurement from `foreign' stations for plots that are close to the borders.

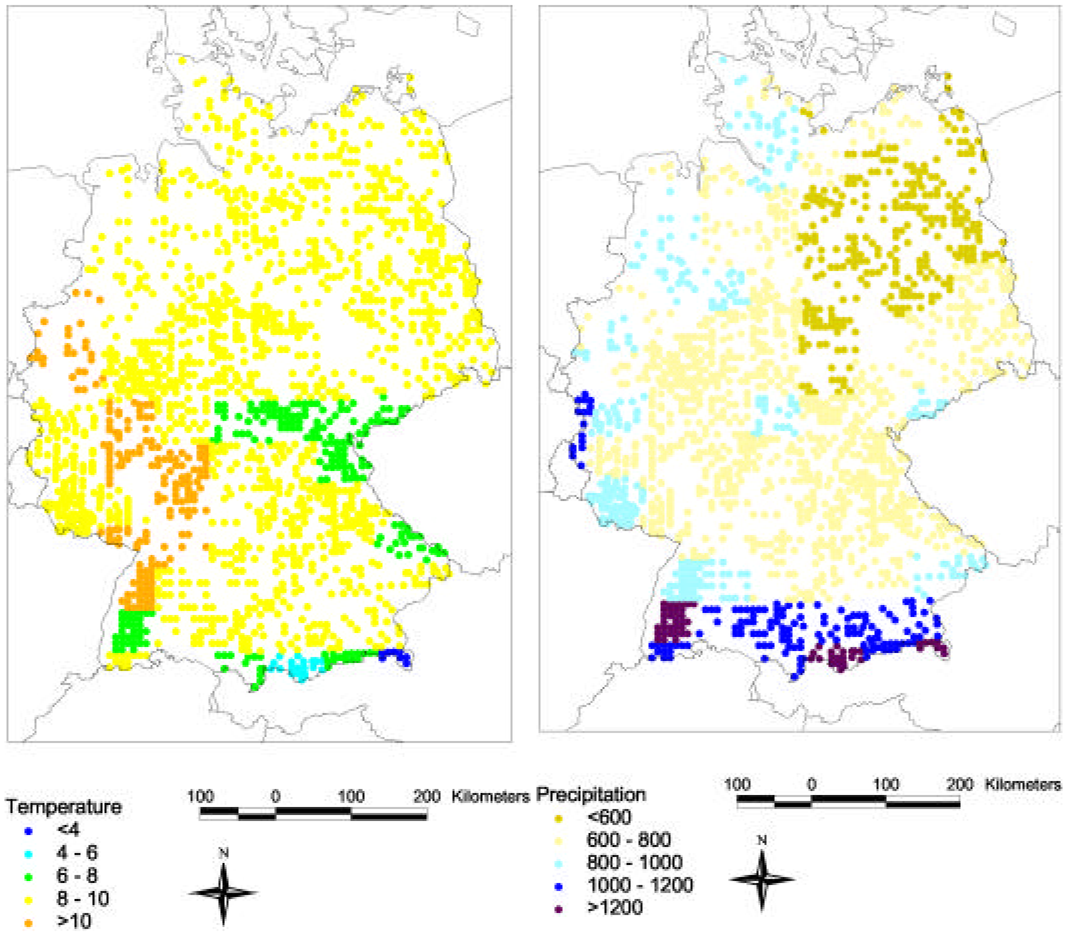

Fig. 2 Spatial variation in the estimated annual mean temperature and annual precipitation at the German Level I plots over the period 1987-1995

Table 1 gives an overview of the distribution of the obtained values for the temperature and the precipitation as a direct result of the interpolation procedure. Temperature and precipitation did not only contribute to the assessment of stress factors, but were also used in the calculation of critical loads and levels. The precipitation excess, which is a by-product of the estimation of the drought stress by executing a water balance model, is also used in the estimation of critical loads and critical deposition levels. The presented variable varies considerably, ranging from very cold to rather warm, and from rather dry to extremely wet.

The spatial distribution of the annual mean temperature is relatively even. Most plots had an annual mean temperature in the period 1987-1995of just below 10°C (Figure 2, left). A cluster with slightly warmer plots was found in an area along the river Rhine and the adjacent Black Forest. The results for this area, however, also seem to be affected by inaccurate selection of suitable meteo stations under the particular topographic conditions of this area. The interpolation procedure seems also to give less accurate estimations for plots in the smaller mountain ranges, such as the Harz Mountains, which are only partly found back on the maps.

Considerably lower temperatures were found in the mountainous areas. The results also reflect the impact of the interpolation itself by the occurrence of rectangular patterns. This is also the case for the precipitation (Figure 2, right). Most plots had a precipitation between 600 and 800 mm a^{-1}. Large parts of the eastern part of the country were slightly drier, whereas plots in mountainous areas were considerably wetter and also plots in the west and northwest showed many plots with a precipitation above 800 mm a^{-1}.

Table 1 Minimum, maximum and 5, 50 and 95 percentiles of the mean temperature and total precipitation sum and precipitation excess, over the entire year and over the growing season, based on estimated values for the years 1987-1995

	Mean temperature (°C)		Precipitation sum (mm)		Prec. excess [1]
	Entire year	Gr. season	Entire year	Gr. season	(mm; entire year)
Minimum	3.8	8.0	547	300	77
5 percentile	7.3	12.6	574	310	132
50 percentile	9.3	14.6	713	371	233
95 percentile	10.3	15.7	1157	676	555
Maximum	11.0	16.5	1607	938	1167

[1] Result of the water balance calculations.

Assessment of water balance terms and input data used

The first step to derive relative transpiration is the calculation of the potential evapotranspiration (ET_p) using the Penman-Monteith equation (Monteith, 1965):

$$l\, E_{Penman\text{-}Monteith} = \frac{sA + R_a c_p (e_s - e_a)/R_a}{s + g(1 + R_c/R_a)} \quad (\mathrm{W\,m^{-2}}) \tag{3}$$

in which:

l	=	latent heat of vaporisation, a function of the daily air temperature (Harrison, 1963): 2501–2.3601*T ($\mathrm{Jkg^{1}}$)
E	=	evaporation rate ($\mathrm{kg\,m^{-2}\,s^{-1}}$)
A	=	available energy ($\mathrm{W\,m^{-2}}$)
s	=	slope of the saturation vapour pressure-temperature curve ($\mathrm{mbar\,^{o}C^{-1}}$)
g	=	psychrometer coefficient (0.67 $\mathrm{mbar\,^{o}C^{-1}}$)
D_a	=	density of dry air (1.2047 $\mathrm{kg\,m^{-3}}$)
c_p	=	specific heat at constant pressure (1004 $\mathrm{J\,kg^{-1}\,^{o}C^{-1}}$)
e_s	=	saturated vapour pressure (mbar)
e_a	=	vapour pressure at temperature T_a (mbar)
R_a	=	aerodynamic resistance ($\mathrm{s\,m^{-1}}$)
R_c	=	crop canopy resistance ($\mathrm{s\,m^{-1}}$)

The available amount of energy, A, can be calculated as:

$$A = R_n - D - G - M - mA \quad (\text{W m}^{-2}) \tag{4}$$

where (all in W m^{-2}):

R_n = net radiation
D = advection
G = soil heat flux
M = energy storage in the forest
mA = energy absorbed for photosynthesis

This equation was simplified to the following, since mA, M and G are small in relation to R_n, whereas advection, D, was also supposed to be negligible (Dolman & Moors, 1994):

$$A = R_n \quad (\text{W m}^{-2}) \tag{5}$$

R_n was calculated according to Beljaars and Holtslag (1990) in the EDACS model (Section 2.2.1). Major parameters needed to calculate R_n are cloud cover, albedo, latitude, day number and relative humidity. From these parameters net short-wave radiation and net long-wave radiation can be estimated, from which, adjusted with the albedo, R_n was calculated.

The slope of the saturation vapour pressure-temperature curve, s, was calculated as:

$$s = e_s(T)[\frac{7.5 * 237.3}{(T + 237.3)^2} \ln 10 \quad (\text{mbar}\,^0\text{C}^{-2}) \tag{6}$$

where:

e_s = saturated vapour pressure (mbar)
T = air temperature (^{o}C)

e_s was calculated according to:

$$e_s = e_s(0)\, 10 \frac{7.5}{T + 273.3} \quad (\text{mbar}) \tag{7}$$

where es(0) is 6,107 mbar.

The actual vapour pressure e_a was calculated according to:

$$e_a = e_s * \frac{RH}{100} \quad (\text{mbar}) \tag{8}$$

where RH is the relative air humidity (%), which is obtained from the meteorological data base.

In EDACS the aerodynamic resistance R_a was calculated following the procedure used by Garland (1978). The crop resistance or stomatal resistance R_c was calculated following the procedure used by Baldocchi *et al*. (1987). Both procedures are discussed in Bleeker *et al*. (1999).

Interception was calculated on a daily basis (following to Moors *et al.*, 1996) using the interception model of Gash (1995). In this model at first the amount of precipitation P', which is needed to saturate the crown, was calculated according to:

$$P' = -R_{avg} \frac{S}{E_{avg}} \ln\left[1 - \frac{E_{avg}}{R_{avg}}\right] \quad (\text{mm d}^{-1}) \tag{9}$$

where:

R_{avg} = mean rainfall rate (mm hr^{-1})
E_{avg} = mean evaporation rate during rainfall (mm hr^{-1})
S = canopy storage capacity (mm)

For small rain-showers when P < P' interception, E_i, was calculated as:

$$E_i = (1-p-p_{tr})\, P \quad (\text{mm d}^{-1}) \tag{10}$$

where:

P = daily precipitation (mm d^{-1})
p = free throughfall coefficient (-)
p_{tr} = stem flow coefficient (-)

For showers of rain when P > P', interception was calculated as:

$$E_i = (1-p-p_{tr})P' + \frac{E_{avg}}{R_{avg}}(P-P') \quad (\text{mm d}^{-1}) \tag{11}$$

Interception of the trunk is often small and was therefore frequently neglected (hence p_{tr} = 0. In the adapted form for sparse forest, the storage capacity of the canopy S was calculated per unit area of cover as $S_c = S/c$ where c is the canopy cover, which is assumed to be 0.8 for all plots.

Mean rainfall (R_{avg}) and evaporation rates (E_{avg}) for the period the crown was saturated, were derived from a review of results on the European scale (incl. Gash *et al*., 1995; 1980; Gash and Morton, 1978; Klaassen *et al*., 1998; Lankreijer *et al*., 1992; Llorens, 1997; Loustau *et al.*, 1992; Pearce *et al.*, 1980; Teklehaimanot & Jarvis, 1991; Valente *et al.*, 1997; Vroom, 1996). The measured values for E_{avg} ranged from 0.08 mm h^{-1} in the Netherlands to 0.36 mm h^{-1} on a high altitude location in Spain. R_{avg} ranged from relatively low values in Atlantic areas (1.22 mm hr^{-1} in Scotland and 1.26 mm hr^{-1} on the French west coast to 3.83 mm hr^{-1} in the Spanish Pyrenees. These results were generalized to mean values per group of climate zones (as defined in UN-ECE&EC, 1996). Confrontation of these climatic zones with the German Level 1 plots resulted in the following assignment of values. R_{avg} was set to 1.46 in the coastal areas (within ca. 100 km from the North Sea) and to 1.91 for all other plots. E_{avg} was set to 0.29 in the mountainous areas (altitude > 1000m) and to 0.20 for all other plots.

The storage capacity of the forest (*S*) and the throughfall coefficient (*p*) were determined by the tree species composition. The information provided by BFH on the forest type was therefore reformulated into a species composition. The values for the separate species were used to calculate species-weighed values for S and p, assuming a more or less closed canopy (Table 2).

Table 2 Storage capacity of the crown (S) and free throughfall coefficient (p) for several tree species (modified after Dolman and Moors, 1994)

Tree species	*S* (mm)			*p* (-)		
	Summer	winter	whole year	summer	winter	whole year
Quercus robur	0.9	0.3		0.3	0.8	
Fagus sylvatica	1.0	0.3		0.1	0.8	
Pinus sylvestris			1.0			0.15
Picea abies			2.8			0.05

According to Van den Broek and Kabat (1996) potential soil evaporation $E_{s,p}$ was calculated based on Beer's Law for the absorption of the radiation flux by the canopy:

$$E_{s,p} = e^{(6*LAI)} E_{Tp} \quad (\text{mm d}^{-1}) \tag{12}$$

where:
6 = extinction coefficient for net radiation
LAI = leaf area index (-)

The LAI was calculated depending on a maximum LAI, differing for each tree species (Table 3), and the level of defoliation. In the calculation of the interception a tree species proportional LAI was used. Deviations of the present LAI from the maximum LAI (due to defoliation) were not taken into account.

Table 3 Maximum leaf area index (LAI) for several tree species during summer and winter

Tree species	Summer	Winter
Pinus sylvestris	3.0	2.5
Picea abies	12.0	10.0
Quercus robur+Q. petraea	4.0	0.5
Fagus sylvatica	6.0	0.5

Actual soil evaporation, $E_{s,a}$, was calculated as a function of time since the last rainfall event, following Black *et al.* (1969):

$$E_{s,a} = w(\sqrt{t_d + 1} - \sqrt{t_d})\, E_{s,p} \tag{13}$$

in which:
t_d = time since last rainfall (d)
w = an empirical parameter ($d^{-1/2}$), taken 0.33 according to Tiktak *et al*. (1995).

Actual transpiration, E_{Ta}, equaled the potential level, E_{Tp}, when the soil moisture supply is unlimited. Actual transpiration, E_{Ta}, was calculated as a function of the available soil moisture, using the forest water balance. Critical soil moisture contents were used, below which water uptake by plant roots is hampered (Van Keulen, 1986). As long as the critical soil moisture content is not exceeded, E_{Ta} equals E_{Tp}. The more physiologically relevant value of a pressure head (*h*) of -1000 cm (Van Roestel, 1984), above which actual transpiration is reduced, was used to estimate a soil type-dependent critical depletion factor *p*. These depletion fractions were used to calculate critical soil moisture contents by multiplication of the depletion fraction and the available soil water capacity (*AWC*). When the critical soil moisture content (SMC_{cr}) is exceeded, actual transpiration was assumed to decrease from 1, at SMC_{cr}, to 0 at the wilting point (*h*= -16000) (Van Keulen, 1986). Thus E_{Ta} now was calculated as:

$$E_{Ta} = E_{Tp} \qquad \text{for } SMC_i \geq SMC_{cr} \tag{14a}$$

and

$$E_{Ta} = E_{Tp}\,(SMC_i / SMC_{cr}) \qquad \text{for } SMC_i < SMC_{cr} \tag{14b}$$

where:
SMC_i = soil moisture content at day i (mm)
SMC_{cr} = critical soil moisture content

SMC_{cr} was calculated as:

$$SMC_{cr} = (1-p)\,AWC \tag{15}$$

where:
AWC = available water content (mm)
p = soil water depletion fraction (-)

The soil water depletion factor was derived as a function of the maximum transpiration rate (E_{Tp}). Doorenbos and Kassam (1979) give indicative p-values for different groups. On the average, the *p*-values decrease 66% going from E_{Tp} = 2 mm d^{-1} to E_{Tp} = 10 mm d^{-1}. We also applied this reduction of p in our model. With the model of Van Keulen (1986) we calculated a basic *p*-value (p_b) for the different soil types for *h*= –1000 cm and E_{Tp} = 2 mm (Table 4).

Table 4 Soil water depletion fraction (p) above which actual transpiration is reduced as a function of the texture class (derived from soil type and parent material; see Section 2.2.4)

Soil texture class	Depletion fraction *p* (-)
sand	0.63
loam	0.49
clay	0.42
peat	0.46

p was calculated as:

$$p = p_b - \frac{p_b - 0.33\,p_b}{8}(E_{Tp} - 2) \qquad (-) \qquad (16)$$

2.2 Exceedances of critical deposition levels

2.2.1 Assessment of present loads

In Europe, the large-scale concentration and deposition distribution of acidifying components is commonly described with the EMEP model (e.g. Tuovinen *et al.*, 1994). For estimating site-specific estimates the model resolution of 150 x 150 km^2 is much too coarse. Therefore the EDACS model (European Deposition of Acidifying Components on a Small scale) was developed to estimate site-specific dry deposition fluxes of acidifying components (i.e. SO_x, NO_y and NH_x) and base cations. An extensive description of the EDACS model as well as the derivation of wet deposition estimates can be found in Van Pul *et al*. (1995), Erisman *et al.* (1996), Van Leeuwen *et al.* (1995) and Draaijers *et al.* (1997).

Dry deposition estimates of the acidifying components for the years 1987-1995 were obtained using ambient air concentrations calculated with the EMEP long-range transport model (daily averages). The EMEP values were based on emissions of SO_2, NO_x and NH_3 (e.g. Tuovinen *et al.*, 1994). These results were combined with parameterized dry deposition velocities (Erisman *et al.*, 1994a; 1994b). The acidifying components considered were SO_2 and SO_4^{2-}-aerosol (SO_x); NO, NO_2 (NO_x); HNO_3 and NO_3-aerosol; NH_3 and NH_4^+-aerosol (NH_x). Concentrations at 50m above the surface were used. At this height it is assumed that concentrations and meteorological parameters were not influenced by surface properties to a large extent. Dry deposition velocities of gases and particles at this height were calculated for each site with the inferential technique (Erisman *et al.*, 1994c; Van Pul *et al*., 1995) using stand information and routinely available meteorological information (see Section 2.1.3). Stand-specific roughness lengths were used which were derived from available data on stand height or stand age. The dry deposition velocity fields (calculated for every 6 hourly period) were averaged to daily values and combined with concentration fields from the EMEP-model. Daily fluxes were subsequently summed to annual totals.

Due to the spatial variability of the ammonia emissions (and concentrations) the resolution of the EMEP concentrations can not adequately be used for calculating the dry deposition of NH_x. Therefore the atmospheric transport and deposition model EUTREND (Van Jaarsveld, 1995) has been used, together with high resolution emissions of ammonia, to calculate the dry deposition on a 5x5 km^2 resolution. The ammonia emissions were provided by the Umwelt Bundes Amt and are taken from the CORINAIR database.

In order to estimate the total deposition at each site, wet deposition obtained from the University of Stuttgart (Institut für Navigation) was added to the dry deposition. The wet deposition was derived from measurements of the rain water concentrations multiplied by high resolution precipitation data. Wet deposition estimates obtained by this approach were only available for the years 1987-1989 and 1993-1995. Values for the intermediate years were estimated by interpolating the annual mean rain water concentrations, multiplied by the annual precipitation sum.

In this study, we only use the deposition of total nitrogen and total acidity. The deposition of total nitrogen was calculated as the sum of the dry and wet deposition of NH_x and NO_y. The deposition of total acidity was calculated as the sum of total nitrogen, combined with dry and wet SO_x. This result was also corrected for the sea salt contribution in the SO_x deposition, in order to obtain results that are comparable with the estimated critical deposition levels and critical loads.

2.2.2 Assessment of critical deposition levels and critical loads

Critical deposition levels and critical loads were calculated for each stand while accounting for effects of location, tree species and soil type. Critical deposition levels and critical loads refer to two different approaches (Table 5). Critical deposition levels refer to actual thresholds at the monitoring plots for the time of consideration (1985-1997), whereas critical loads refer to long-term acceptable loads, used for policy making (e.g. Posch et al., 1995a; 1995b). Critical loads (long-term) were derived with a simple mass balance (SMB) model, assuming a steady-state situation (e.g. De Vries, 1993; Sverdrup and De Vries, 1994). Critical deposition levels (short-term) were calculated with an adapted version of the SMB model, as described below.

Table 5 Difference in the calculation of (long-term) critical loads used for policy making (critical load maps in the UN/ECE framework) and (short-term) critical deposition levels that are relevant with respect to impacts on forest (crown) condition.

Aspect [3]	Critical load (long-term)	Critical deposition level (short-term)
general	long-term critical loads for grids	actual critical deposition levels for plots (in the considered period 1987-1995)
base cation deposition [1]	30 a average value [2]	average for 1987-1995
uptake	average during rotation period	actual average uptake for 1987-1995
immobilization	long-term acceptable value	actual immobilization for 1987-1995
denitrification	related to critical N load	related to actual average N deposition level for 1987-1995
critical N leaching	related to vegetation changes	related to elevated foliar N contents

1) Applies also to precipitation excess, used to calculate critical leaching rates of acidity.

2) In this study the average for the period 1987-1995 was used instead.

3) Sulphate adsorption was not considered in the approaches, since input-output budgets for most forest soils in Europe indicate sulphate saturation (Berdén et al., 1987; Van Breemen and Verstraten, 1991; De Vries et al., 1995a).

Mass balance models approach to calculate critical loads

The SMB model calculates critical loads and critical deposition levels by including relevant processes influencing acid production and consumption. The long-term critical loads approach excludes dynamic processes (De Vries, 1993; UN-ECE, 1996). These dynamic processes can not be neglected in the short-term critical deposition level approach. Therefore, the method to derive some of the considered processes will differ. The classic SMB model (developed for the long-term critical load approach) calculates critical loads for the acidifying impact of S and N, $(S+N)_{td}(crit)$, according to (all fluxes in $mol_c\ ha^{-1}\ a^{-1}$):

$$(S + N)_{td}(crit) = BC^*_{td} + BC_{we} - BC_{gu} + N_{gu} + N_{im} + N_{de} + Al_{le}(crit) + H_{le}(crit) \qquad (17)$$

where BC^*_{td} is the chloride (sea salt) corrected total deposition flux of base cations, BC_{we} is a base cation weathering flux, BC_{gu} and N_{gu} are the net uptake fluxes of base cations and nitrogen needed for forest growth, N_{im} is a long-term nitrogen immobilization flux at critical load, N_{de} is a denitrification flux at critical N load, whereas, $Al_{le}(crit)$ *and* $H_{le}(crit)$ are a critical leaching fluxes of Aluminium and protons, respectively. A critical load of S and N is thus calculated as the sum of major processes buffering the incoming acidity and a critical leaching rate of acidity.

The critical Al leaching flux, $Al_{le}(crit)$, was calculated by multiplying the net base cation leaching rate $(BC_{td} + BC_{we} - BC_{gu})$ with a critical molar Al/(Ca+Mg+K) ratio in the soil solution. The critical H leaching flux was calculated by multiplying a critical H concentration with the precipitation excess leaving the root zone. The critical H concentration was calculated from the critical Al concentration (the critical Al leaching flux divided by the precipitation excess), using a gibbsite equilibrium equation (see also Section 2.2.4).

In addition to acidification, N deposition may cause adverse effects due to eutrophication of an ecosystem. Critical N loads related to these effects were calculated according to (De Vries, 1993; UN/ECE, 1996):

$$N_{td}(crit) = N_{gu} + N_{im} + N_{de} + NO_{3,le}(crit) \qquad (18)$$

where $N_{td}(crit)$ is the critical N load with respect to eutrophication and $N_{le}(crit)$ is a critical N leaching flux. Calculation of the critical N load with this simple steady-state model is based on the assumption that any N input above a net N uptake by forest growth, N immobilization, denitrification and an acceptable rate of N leaching will finally lead to unacceptable high N contents in foliage and soil organic matter. Those contents may cause adverse affects such as nutrient imbalances, increased sensitivity to frost, drought and diseases and vegetation changes. In the present study, critical loads were calculated in relation to effects on (i) the understorey of forests (vegetation changes) and (ii) the sensitivity of trees to stress (see also Section 2.2.4).

The short-term critical deposition level approach requires provisions for dynamic processes buffering the acid input at present can not be neglected. Simulation of such processes by a dynamic model, such as SMART (De Vries *et al.,* 1989), requires detailed and very reliable information of soil parameters, especially CEC, base saturation and C/N ratio. Given the uncertainties in these data, an intermediate approach was used. Critical deposition levels were only calculated for soils with a base saturation below 25% or a pH below 4,5. Above this value, all the incoming acidity was assumed to be buffered by base cations only and the critical deposition level was assumed to equal the present deposition level (the excess equals 0). Below this value, Al release was considered to start which may cause the exceedance of a critical Al/(Ca + Mg + K) ratio. The base saturation of 25% was based on model simulations (De Vries et al., 1989) and laboratory data (De Vries, 1997) indicating a significant Al release starting in a range between 10 and 25%. Furthermore, the estimation of nearly all input variables was limited to the period 1987-1995, instead of using long-term averages (Table 5). The value of various input variables can vary from the long-term approach, since the system is not yet at a steady state. These differences will generally result in higher short-term critical deposition levels, compared to the long-term critical loads, especially for acidity.

2.2.3 Calculation of exceedances

The exceedances of the critical deposition levels and critical loads were calculated by subtracting the critical values from the present load of total acidity (SO^*_x+NO_y+NH_x) and total nitrogen (NO_y+NH_x), respectively. Negative outcomes were set to 0. The exceedance of the critical deposition level for acidity (short term) was set to 0 for the plots for which the critical deposition level for acidity was not calculated (where base saturation > 25%).

2.2.4 Derivation of model input data

Overview

Input data for the SMB model used in this study are chloride corrected base cation deposition, base cation weathering, growth uptake of base cations and nitrogen, N immobilization, denitrification and precipitation excess (precipitation minus evapotranspiration), which affects the critical acidity leaching rate. To obtain these data for all forest stands, we used or derived transfer functions (relationships) with available data on basic land characteristics, such as tree species and soil type and geographic site characteristics such as elevation and temperature. Below we give a summary of the derivation of the various input data (Table 6).

Table 6 Influence of location, tree species and soil type accounted for in the assessment of input data for the SMB model

Data related to	Location	Tree species	Soil type
Base cation deposition	x	x	X
Weathering	x	-	X
Growth uptake	x	x	X
N immobilization	x	-	X
Denitrification	x	-	X
Precipitation excess	x	x	X

Atmospheric deposition

S and N deposition data for each stand for the period 1987-1995 was derived with the models EDACS and EUTREND (Section 2.2.1). For estimating dry deposition of base cations (Na^+, Mg^{2+}, Ca^{2+} and K^+) essentially the same method was used as for calculating the deposition of the acidifying components by means of EDACS. Unlike the acidifying components, 6-hourly dry deposition velocity fields for base cations were aggregated to annual means before they were combined with annual mean concentration fields (Draaijers *et al.*, 1997). Currently, reliable information on the spatial and temporal variation of base cation emissions is not available, hampering accurate concentration modeling with long-range transport models. For this reason, surface-level air concentrations were estimated from precipitation concentrations and scavenging ratios (Draaijers *et al.*, 1997). Annual mean precipitation concentrations were used to infer annual mean air concentrations of Na^+, Mg^{2+}, Ca^{2+} and K^+. Detailed precipitation concentration fields for 1987-1989 and 1993-1995 were obtained from the University of Stuttgart (INS). These concentration fields are based on measurements, which are interpolated by means of a kriging interpolation procedure. The resulting BC deposition for these six years was used as input for the model calculations (Mg^{2+}(ssc)+Ca^{2+}(ssc)+K^+(ssc)). The mean values of the sea salt corrected deposition figures were used in the short-term critical deposition levels. Since the base cation deposition decreased considerably in the observed period, the minimum values over the observed period were considered as representative for the future, and were therefore used in the long-term critical load calculations. The results may, however, be affected by peculiarities in the considered years.

Base cation weathering

Base cation weathering rates for the root zone were derived by assigning a weathering rate to each of the combinations of soil texture and substrate group ('Substrat gruppen'). Substrate and soil texture are known for each of the plots. To each of the German substrate groups a classification 'acidic', 'intermediate', 'basic' or 'calcareous' was given, whereafter the associated weathering rate was derived from Table 8 using the soils texture class. Table 7 shows the assignment of parent material class to substrate group.

The weathering rates in Table 8 were derived from results of the weathering model PROFILE that has been developed to estimate field weathering rates based on the soil mineralogy (Sverdrup and Warfvinge, 1992), as a general estimate for European forest soils. Within the project it was not foreseen to compute more specific, site-determined weathering rates, neither were such data provided. Values for the rootzone were derived by multiplying the weathering rate in Table 8 with an assumed standard soil depth of 0.5 m, except for Lithosols, where a depth of 0.1 m was used. For peat soils (parent material class 0) a constant weathering rate of 200 $mol_c\ ha^{-1}\ a^{-1}$ was used based on literature information (Van Breemen *et al*., 1984). For calcareous soils (parent material class 4) an arbitrary high weathering rate of 10 000 $mol_c\ ha^{-1}\ a^{-1}$ was used to avoid any exceedance of critical acid deposition levels on these soils. Note, however, that direct effects of SO_2 can not be neglected at these loads (De Vries *et al*., 1994).

Table 7 Assignment of parent material classes

Group	Description	Parent material class
1	Karbonathaltige Lockersedimente über karbonathaltigen Ausgangs-gesteinen bzw. Karbonathaltiges Ausgangsgestein	Calcareous
2	Karbonatfreie Lockersedimente über karbonathaltigem Ausgangs-material	Calcareous
3	Umgelagerte kalkfreie Lockersedimente	Intermediate
4	VWL bzw. Decklehme über Ton- und Schluffstein; Ton, Tonsteine, Grauwacken	
5	Verwitterungslehme und Decklehm über quarzreichen Ausgangs-gesteinen sowie quarzreiche Ausgangsgesteine	Intermediate
6	Arme (pleistozäne) Sande	Acid
7	Basische Magmatite oder Metamorphite sowie Lehme oder Misch-substrate über basischen Magmatiten oder Metamorphiten	Basic
8	Intermediaire und saure Magmatite oder Metamorphite sowie Lehme oder Mischsubstrate über intermediaire oder sauren Magmatiten oder Metamorphiten	Acid
9	Moore	Peat
10	Anthropogene Substrate und nicht den Gruppen 1-9 zugeordnende Substrate	Unknown; assigned Intermediate

Table 8 Weathering rates ($mol_c\ ha^{-1}\ a^{-1}\ m^{-1}$) for the various combinations of parent material class and texture class. The given values have to be multiplied by 0.5 to obtain figures for a 0.5 m thick forest rootzone.

Parent material	Texture class		
	Coarse (1)	Medium (2)	Fine (3)
Acidic	500	1500	2500
Intermediate	1000	2000	3000
Basic	1500	2500	-

A more accurate estimate of weathering rates could be obtained if weathering rates or weathering rate classes were made available from closed German databases or even if such classes would be directly assigned to substrate groups based on their mineralogical composition. The latter, however, would involve new assessments with the PROFILE model, whereas the former was impossible due to administrative procedures.

The weathering rates thus assigned were corrected for the effect of temperature according to (Sverdrup, 1990):

$$BC_{we}(T) = BC_{we}(T_o) * e^{(A/T_o - A/T)} \qquad (19)$$

where $BC_{we}(T)$ is the weathering rate at the local mean annual temperature T (K), $BC_{we}(T_o)$ is the average weathering rate defined in Table 8 for each combination of parent material class and texture class at a reference temperature T_o (K) and A is a pre-exponential temperature factor (K). For A, a value of 3600 K has been taken (Sverdrup, 1990). The reference temperature was calculated for each weathering rate (class) as the average of the mean annual air temperatures of all soil types in a given weathering rate (class).

Growth uptake

Growth uptake was calculated at each site by multiplying the annual average growth rate of stems and branches with the density and the element content in stems and branches. The average annual growth rate of stems and branches (yield) was estimated from available information on forest type, stand height and stand age. This information was used to select the most suitable yield table or combination of yield tables, assuming a regularly managed stand and average thinning intensity. Generalized yield tables for groups of species were created by Klap *et al*. (1997), using the most widely used yield tables for the most common species (e.g. Schober, 1974). These tables were then used to estimate the current increment in stems and branches and the long-term average increment in stems. Long-term increment of branches was not calculated, since it was assumed that branch volume increases in the early ages to a certain steady state level with a known stem-to-branch ratio, and that all branches are left in the forest during thinnings and clearcuts.

Densities and element contents of stems and branches were derived from the literature. Data for the density of stem wood and branch wood have been assumed to be equal. Average values used were 500 kg m^{-3} for the coniferous species (*Pinus sylvestris* and *Picea abies*) and 700 kg m^{-3} for the deciduous species (*Quercus robur/petraea* and *Fagus sylvatica*). Data used for the branch to stem ratios of mature tree species were 0.15 kg kg^{-1} for *Pinus sylvestris*, 0.10 for *Picea abies*, 0.30 for *Quercus spp.* and 0.25 for *Fagus sylvatica*. Data are based on Kimmins *et al*., 1985 and De Vries *et al.*, 1990.

Current increment values for stems and branches were used in the calculation of (short-term) critical deposition levels, whereas the long-term increment values for stems were used in the (long-term) critical loads. Uneven-aged stands (e.g. *Plenterwald*) were treated as steady-state ecosystems. For these stands the long-term increment values were also applied for the critical deposition levels (short-term). Values for entire stands were calculated as weighed mean values of the species in the stand. The species composition was estimated from the forest type.

Data for the element contents of base cations in stems and branches were based on Rosén (1990) as given Klap *et al.* (1997). Above a certain threshold value, a linear relationship between N contents in stems and branches and N deposition was assumed according to:

$$ctN = ctN_{min} + a * (ctN_{max} - ctN_{min}) \tag{20}$$

where ctN_{min} and ctN_{max} are the minimum and maximum N content in leaves and fine roots (mol_c kg^{-1}).

The value of a was calculated according to:

$$a = \frac{N_{dt} - N_{dt,min}}{N_{dt,max} - N_{dt,min}} \quad \text{for } N_{dt,min} < N_{dt} < N_{dt,max} \tag{21a}$$

$$a = 0 \quad \text{for } N_{dt} < N_{dt,min} \tag{21b}$$

$$a = 1 \quad \text{for} \quad N_{dt} > N_{dt,max} \qquad (21c)$$

where $N_{dt,min}$ and $N_{dt,max}$ are the minimum and maximum values between which the N deposition influences the N content of leaves.

Values used for Ndt_{min} and Ndt_{max} were 1500 and 7000 mol ha^{-1} a^{-1} respectively, based on data given by Van den Burg *et al*. (1988) and Van den Burg and Kiewiet (1989). Values used for the minimum and maximum N content in stems and branches, are given in Table 9. Data are based on the literature compilations by Kimmins *et al.* (1985) and De Vries *et al*. (1990).

Table 9 Values use for the minimum and maximum N content in stems and branches of the considered tree species

Tree species	N content in stems (%)		N content in branches (%)	
	min.	max.	min.	max.
Pinus sylvestris	0.08	0.20	0.20	0.50
Picea abies	0.08	0.20	0.35	0.75
Deciduous [1)]	0.15	0.25	0.35	0.75

1) *Quercus robur*, *Q. petraea* and *Fagus sylvatica.*

Actual and long-term acceptable N immobilization

Two different methods were applied for the N immobilization, depending on the time scale considered.

Actual N immobilization

The actual N immobilization was described as a fraction of the net N input to the soil (N deposition minus net N uptake and a natural N leaching rate) over the considered nine year period (1987-1995). In this study, N immobilization was thus described as a fraction of the net N input to the soil. The immobilization fraction was described as a linear fraction of the C/N ratio of the soil, according to:

$$N_{im} = \left(N_{td} - N_{gu} - N_{le,\min}\right) * \left(\frac{C/N_{om} - C/N_{\min}}{C/N_{cr} - C/N_{\min}}\right) \quad \text{for } C/N_{cr} > C/N_{om} > C/N_{\min} \qquad (22)$$

Where C/N_{om} is the C/N ratio of the soil, C/N_{cr} is the critical C/N ratio above which all excess nitrogen $(N_{td} - N_{gu} - N_{le,min})$ is assumed to immobilize and C/N_{min} is the minimum C/N ratio where N immobilization is negligible. The minimum N leaching rate ($N_{le,min}$) was calculated by multiplying the precipitation excess by a natural background NO_3 concentration in drainage water of 0.02 mol_c m^{-3} (Rosén, 1990).

The use of C/N ratios as a function of the humus types was considered as an alternative (like presented in the Deutsche Waldbodenbericht 1996, 1997), but not chosen, because the presently observed humus type may already be a result of prolonged exposure to nitrogen and/or acidity and not a refection of the natural nutrition status. Furthermore, the use of the humus type may only be valid for the short-term approach (critical deposition level), since the humus type may also vary during the coming centuries, due to strong changes in deposition and changes in forest management, succession of young forest ecosystems etc.

Critical and minimum values used for the C/N ratio of five major soil clusters distinguished in calculating critical deposition levels are shown in Table 10. More information on the background of these data is given in Klap *et al.* (1997).

The minimum C/N ratios were based on 5 percentile values of ca 2500 values of C/N ratios reported in a European Forest Soil Data Base (Reinds, 1995) and reported in extensive surveys in German (BZE) and Dutch forest soils (Deutscher Waldboden Bericht, 1996; De Vries & Leeters, 1999; Klap *et al*., 1999). Critical C/N ratios reported in literature for coarse textured soil are generally close to 25 (Ågren and Bosatta, 1988; Tietema, 1992), although values near 40 have been reported as well (Berg and Staaf, 1981). These ratios, however, refer to the situation that net N mineralization starts to occur, whereas the use of this critical ratio in Eq. 22 refers to a situation where the external N input ceases to be completely immobilized. The latter value is likely to be somewhat higher. Critical values given in Table 10 were based on 75 percentile values of circa 2500 data reported for European forest soils (see above).

Table 10 Minimum and maximum C/N ratios ($g\ g^{-1}$) used in the calculation of the N immobilization

Soil type	Minimum	Critical
Peat	15	40
Coarse textured soils (sand/loam)	15	35
Fine textured soils (clay)	10	25
Volcanic soils	10	20
Calcareous soils	10	20

This approach for the actual immobilization was only used for the calculation of critical deposition levels in relation to forest growth. The assumption that all nitrogen is immobilized before it become available in the root zone is not realistic for the forest floor vegetation. The applied concept is therefore not applied for the critical deposition level of N for biodiversity. Consequently, no results can be presented on this item in Chapter 3.

Long-term acceptable N immobilization

In deriving critical loads related to a steady-state situation, a long-term acceptable rate of net immobilization of stable organic N compounds in the soil (stable forms of humus) is calculated (De Vries, 1993). This amount is likely to be much lower than the actual N immobilization during the considered time period (1987-1995), in which the system was not yet at steady state. A long-term acceptable N immobilization rate was set at 1 kg N ha^{-1} a^{-1} (ca. 70 mol_c ha^{-1} yr^{-1}) based on the total N accumulated in soils during the period of soil formation (De Vries, 1993).

Actual and long-term acceptable denitrification

Two different methods were applied for the acceptable denitrification, depending on the time scale considered.

Actual denitrification
As with the actual N immobilization actual denitrification is described as a fraction of the net input (now defined as N deposition minus net N uptake and net N immobilization) to the soil according to (De Vries, 1993):

$$N_{de} = fr_{de} * (N_{td} - N_{gu} - N_{im}) \tag{23}$$

where fr_{de} is a denitrification fraction. Using this sequence of descriptions for N transformations, it is implicitly assumed that N immobilization is a faster process than denitrification.

Denitrification fractions were related to soil clusters based on data given in Breeuwsma *et al*. (1991) for agricultural sand, clay and peat soils in The Netherlands. Data were corrected for the more acid circumstances in forest soils. Values used are 0.8 for peat soils, 0.7 for clay soils with texture class 3, 0.4 for clay soils with texture class 2, for sandy soils and for loess soils with gleyic features and 0.1 for sandy soils and for loess soils without gleyic features.

Long-term acceptable denitrification
In calculating the long-term acceptable denitrification, the same formula is used as for the actual denitrification, but the N deposition is replaced by the critical N load. Substituting this equation in Eq. 23 leads to a formula that describes the long-term acceptable denitrification as a function of the critical N leaching according to:

$$N_{de} = \frac{fr_{de}}{1 - fr_{de}} . NO_{3.le}(crit) \tag{24}$$

Values used for fr_{de} are given above, whereas information on the calculation of the critical N leaching is given below. It was assumed that the value for the potential long-term denitrification (N_{de}) could never exceed the value for the short-term critical actual denitrification. Larger values for $N_{de}(potential)$ were therefore set to the value of $N_{de}(crit.actual)$.

Critical acidity leaching

The critical acidity leaching flux, $Ac_{le}(crit)$, was calculated as the sum of Al leaching and H leaching $H_{le}(crit)$ (both in $mol_c\ ha^{-1}\ a^{-1}$). The critical Al leaching flux, $Al_{le}(crit)$, was calculated as (De Vries, 1993):

$$Al_{le}(crit) = \frac{3}{2} . \frac{Al}{BC}(crit).(BC_{td} + BC_{we} - BC_{gu}) \tag{25}$$

where $\frac{Al}{BC}(crit)$ is a critical molar Al/(Ca+Mg+K) ratio in the soil solution.

The critical Al/(Ca+Mg+K) ratio has been set at 0.8 for coniferous tree species (*Pinus sylvestris* and *Picea abies*) and at 1.7 for deciduous tree species (*Quercus robur, Quercus petraea, Fagus sylvatica* and *Quercus ilex*). These values were based on an extensive literature review of numerous pot experiments with seedlings or young trees (Sverdrup and Warfvinge, 1993).

In various studies (De Vries, 1993), a critical Al concentration was calculated by also requiring that depletion of secondary Al compounds does not occur to avoid a strong decrease in pH. This does, however, not cause an actual risk to the forests and has thus not been included in this study.

The critical H leaching flux, $H_{le}(crit)$, was calculated as:

$$H_{le}(crit) = PE\ [H](crit) \tag{26}$$

where PE is the precipitation excess leaving the root zone ($m^3\ ha^{-1}\ a^{-1}$) and $[H](crit)$ is a critical H concentration ($mol_c\ m^{-3}$), which is related to the critical Al concentration according to:

$$[H](crit) = ([Al](crit)\ /\ KAl_{ox})^{0.33} \tag{27}$$

where KAl_{ox} is the Al hydroxide equilibrium constant. KAl_{ox}, was set at $10^8\ mol^{-2}\ l^2$ for mineral soils (based on Heij *et al.*, 1991) and at $10^6\ mol^{-2}\ l^2$ for peat soils (based on Wood, 1989). The value of the critical Al concentration was calculated by dividing the critical Al leaching flux by the precipitation excess. Finally, the precipitation excess was calculated with the water balance model described before, using interpolated meteorological data for each site. The values used were an average of the annual results over the considered period 1987-1995.

Critical nitrogen leaching

The value of the critical nitrogen leaching is strongly related to the ecosystem compartment selected as receptor for the impacts of nitrogen excess, either the ground vegetation (biodiversity) or the forest trees (vitality and foliar condition).

In deriving critical N loads, related to vegetation changes, a natural low N leaching flux of has been used, since vegetation changes may already occur in that situation (Bobbink *et al*., 1995). This flux has been calculated by multiplying a critical NO_3 concentration of 0.05 $mol_c\ m^{-3}$ (Sverdrup and Warfvinge, 1993) with the estimated precipitation excess (see Section 2.1.3). Under conditions with a moderate precipitation excess of 200-500 mm a^{-1}, this leads to a N leaching flux of 100-250 mol $ha^{-1}\ a^{-1}$ (appr. 1.5-3.5 kg $ha^{-1}\ a^{-1}$). This approach, however, may lead to very high rates of N leaching at sites with a considerably larger precipitation excess, and thus to much higher critical load and critical deposition values at such sites.

Critical loads for N related to effects on forest vitality were, on the contrary, derived by relating the critical N leaching rate to a critical N content in foliage, associated with an increased sensitivity to natural stresses, such as drought, frost and fungal diseases. This approach is new compared to previous studies, and relates much stronger to real threads than the older studies. In a fertilization experiment in Sweden, it was found that frost damage to the needles of Scots pine strongly increased above an N content of 1.8% (Aronsson, 1980). At this N level, the occurrence of fungal diseases such as *Sphaeropsis sapinea* and *Brunchorstia pinea* also appears to increase. This can be derived from correlative field research in The

Netherlands about the N content in needles of Corsican pine and Scots pine and the occurrence of these fungal diseases (Roelofs *et al*., 1985; Boxman and Van Dijk, 1988; Van den Burg *et al.*, 1988). In this context, Van den Burg *et al*. (1988) suggested critical levels of 1.6 and 1.8% for Corsican pine and Scots pine, respectively. Based on these results, an N content of 1.8% in needles was considered to be critical for coniferous forests. This is also the value at which the growth of coniferous forests does not (or only slightly) respond any more to an increase in N content. For deciduous forests an arbitrary value of 2.5% was used, being the value at which the growth of deciduous forests does not respond any more to an increase in N content.

In order to calculate a critical N leaching, a relationship is needed between the N contents in foliage (needles/leaves) and the N concentration in the soil solution. Such relationship was derived for standard conditions with well-drained sandy soils, with a correction of a different level of denitrification in poorly drained soils and in clay and peat soils (see under denitrification). The standard relationships were derived for 26 coniferous (spruce and Douglas) and 42 deciduous (oak and beech) stands in the Netherlands by applying log-linear regression relationships according to:

$$N_{fol} = a_0 + a_1 \cdot \log [NO_3] \qquad (28)$$

Where N_{fol} is the foliar N concentration (%) and $[NO_3]$ is the nitrate concentration in the soil solution ($mol_c.m^{-3}$). Values for a_0 and a_1 thus derived equaled 1.97 and 0.44 for coniferous forests (R^2_{adj} = 0.51) and 2.70 and 0.39 for deciduous forests (R^2_{adj} = 0.20). The critical nitrate concentration was calculated by inverting Eq. 28 according to:

$$[NO_3] = 10^{\frac{N_{fol} - a_0}{a_1}} \qquad (29)$$

and applying the critical N concentrations of 1.8 and 2.5%. Critical nitrate concentrations thus obtained equaled approximately 0.4 $mol_c.m^{-3}$ for coniferous forests and 0.3 $mol_c.m^{-3}$ for deciduous forests. This relationship was adapted for wet soils by correcting for the occurrence of denitrification. In a common precipitation excess range of 200-500 mm a^{-1}, the critical N leaching rate thus varies between 800-2000 mol_c ha^{-1} a^{-1} (ca. 11-28 kg ha^{-1} a^{-1}) for coniferous forests and between 600-1500 mol_c ha^{-1} a^{-1} (ca. 8-21 kg ha^{-1} a^{-1}) for deciduous forests. Tietema and Beier (1995) found a direct relationship between N contents in foliage and N leaching for a number of intensively monitored coniferous stands where nitrogen experiments have been carried out (NITREX sites). Applying their relationship and a critical N content of 1.8% leads to a critical N leaching rate of approximately 20 kg N ha^{-1} a^{-1} or 1400 mol ha^{-1} a^{-1}. This value is exactly in the middle of the range that was calculated for coniferous trees. This approach, however, may lead to very high rates of N leaching at sites with a considerably larger precipitation excess, and thus to much higher critical load and critical deposition values at such sites.

2.3 Presentation of results

The results are presented in tables and maps. First, a table is given, presenting the overall distribution of the obtained results by the minimum and maximum values and the 5, 50 and 95 percentiles. For variables with annual values (meteorological variables and exceedances over critical loads/levels), these results refer to the mean values over the considered nine years period (1987-1995). For the meteorological variables this table also gives an impression about the distribution of the deviations from the (arbitrary) normal values per plot. The most recent year 1995 is selected as an example for the spicific results for a single year for these variables. This table sometimes also contains a few variables that are not presented in the successive figures, but that still give valuable information about the explanation of the results of the key variables.

Secondary, a map is presented with the spatial distribution over Germany of the obtained results. For variables with annual values (meteorological variables and exceedances over critical loads/levels), this map contains the mean values over the considered nine years period (1987-1995). For the meteorological variables also a map is presented with the deviations from the (arbitrary) normal values per plot, for the year 1995 (like in the preceding table).

Finally, a bar diagram is given for the variables with annual values, to present the temporal variation in these variables within the considered nine years period (1987-1995). For the meteorological variables a similar diagram is given presenting the temporal variation in the deviations from the (arbitrary) normal values per plot (for all years, not only the year 1995).

3 Results

3.1 Meteorological stress

3.1.1 Temperature stress

Overview

All the temperature stress indices show a considerable variation with a very skew distribution for the most indices (Table 11). The overall variation of temperature indices (90% of the mean values over the period 1987-1995) varies between 70 and 230 degree days below 0 °C for the Winter Index. Late Frost varies between 1.6 and 4.4 degrees below 0 °C, Early Frost between 0.3 and 2.5 degrees below 0 °C, Acute Frost between 14 and 24 degrees squared, and Heat Index between 0 and 8 degree days. The results for the first five variables show that these factors are likely to be important stress factors for most German Level I sites. The results for the two ETS's show that there is considerable variation in the growing conditions related to temperature. The variation is even larger than the variation in the annual mean temperature (compare Table 1). Very low (i.e. unfavourable) values were found for a limited number of plots, which are located at very high elevations.

The deviations from `normal' for the various temperature stress indices also showed considerable variation. The selected year 1995 could generally be characterized as normal, although there were large areas that were significantly cooler or warmer than normal. The indicators for winter frost, late frost and acute frost indicate that the previous winter (1994/95) had mostly higher risks than average for damage caused by the frost indices. Also the risk of summer heat damage was generally slightly higher than normal.

Table 11 Minimum, maximum and 5, 50 and 95 percentiles of the temperature stress indices

Statistic	Winter Index (°C.days)	Late Frost (°C)	Early Frost (°C)	Acute Frost (°C²)	Heat Index (°C.days)	ETS 10 (°C.days)	ETS 15 (°C.days)
Mean values 1987-1995							
Minimum	51	0.61	0.00	8.8	0.00	245	33
5 percentile	72	1.6	0.29	14	0.05	693	183
50 percentile	113	2.6	1.3	18	3.9	970	311
95 percentile	231	4.4	2.5	24	8.4	1164	423
Maximum	486	9.4	4.7	34	16	1324	520
Deviation in 1995 from `normal'							
Minimum	-23	-0.80	-0.90	-1.8	0.00	-163	-96
5 percentile	-13	0.26	-0.47	0.92	0.00	-86	-43
50 percentile	5.1	1.9	0.00	8.2	3.6	-2.9	9.8
95 percentile	25	4.7	1.0	23	11	70	55
Maximum	136	6.8	2.6	34	25	131	105

The presentation of further results is limited to the Winter Index and Late Frost.

Winter Index

The mean values of the Winter Index shows that, in general, there was not much variation in this stress factor within Germany (Fig. 4, left). The mildest winters (Winter Index < 100 degree.days) occurred in the lowlands and in the southwest. An area with elevated values (Winter Index > 300 degree.days) was found in the center of the country, whereas very high values are found in the Bavarian Alps (Winter Index > 400 degree.days).

The time series shows that the severest winter occurred in the year 1991, followed by the winters of 1993 and 1994 (Fig. 3, left). Relatively mild winters were found for 1988 and 1989. Similar patterns were found when the deviations at each plot deviation from a normal mild winter were considered. In the extreme winter of 1991, almost all plots had a 50 degree.days larger Winter Index, of which 40% had an exceedance of more than 100 degree.days.

Although the selected year 1995 as a whole seems an average year (Fig. 3, right), there are considerable spatial differences, when considering the deviations from a normal mild winter at each plot (Fig. 4, left). Areas with milder winters were found around Saarland and around Northern Bavaria. However, there were also several areas with more severe winters than normal, especially at the Southern border. The winter in the Bavarian Alps was even considerably more severe than normal, whilst this area was already the most severe of the country.

Late frost

The occurrence of late frost shows a clear northwest to southeast trend, related to an increasing continentality and altitude (Fig. 6, left). The areas with the highest values for this index (> 4 degrees below 0 °C) are found in the Alpine area, in the central hilly area and in part of the Black Forest.

The most wide-spread occurrence of late frost was found for the year 1993, followed by 1987, 1991 and 1995 (Fig. 5, left). These differences become even more significant, when the results are compared plot-wise with the results for a normal spring (Fig. 5, right). It is likely that damage to trees occurred in these years, especially in the year 1993.

A spatial analysis of the results for the selected year 1995 shows that serious late frost in this year mainly occurred in a north to south belt over the country, along the southern border and in an area in Saxony (Fig. 6, right). These results indicate that there was a high risk of serious damage to newly formed foliage (or even needles) in these areas in this particular year.

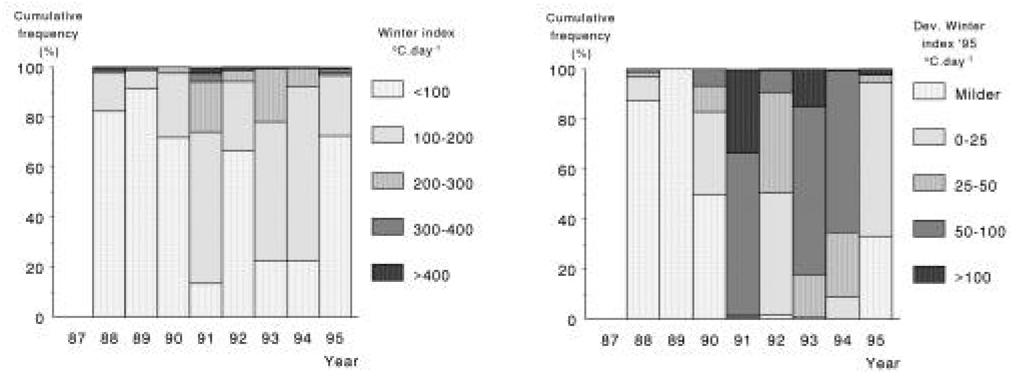

Fig. 3 Temporal variation in the estimated values for the Winter Index; left as absolute values; right as deviations from an arbitrary normal value. Note that no results could be displayed for the winter of 1987, since no data were available for the last months of 1986

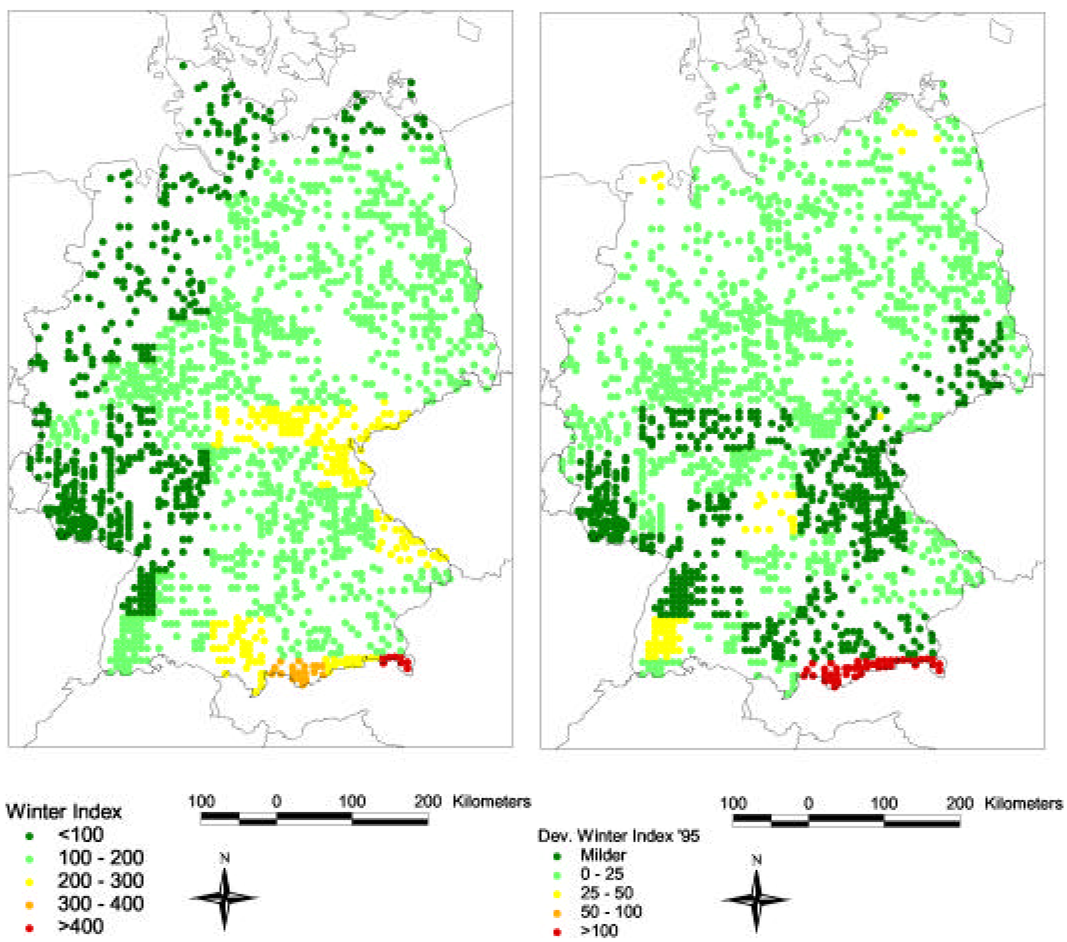

Fig. 4 Spatial variation in the estimated Winter Index (degree.days) at the German Level I plots; left the mean values over the period 1987-1995; right the deviations in 1995 from an arbitrary normal value

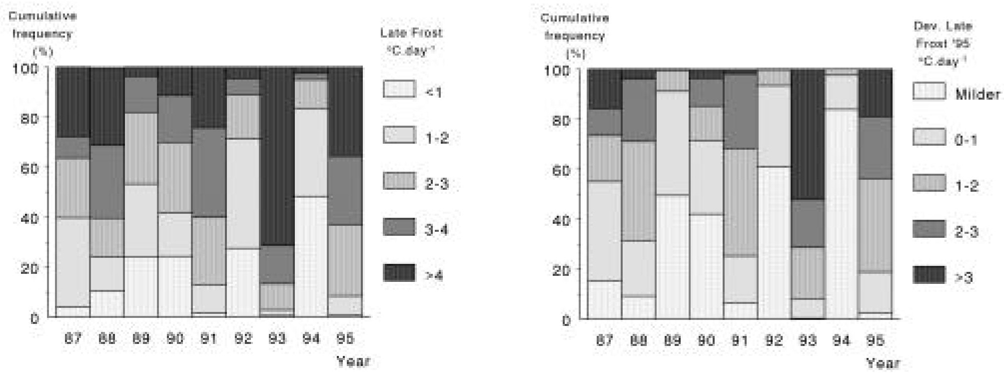

Fig. 5 Temporal variation in the estimated values for the Late Frost; left as absolute values; right as deviations from an arbitrary normal value

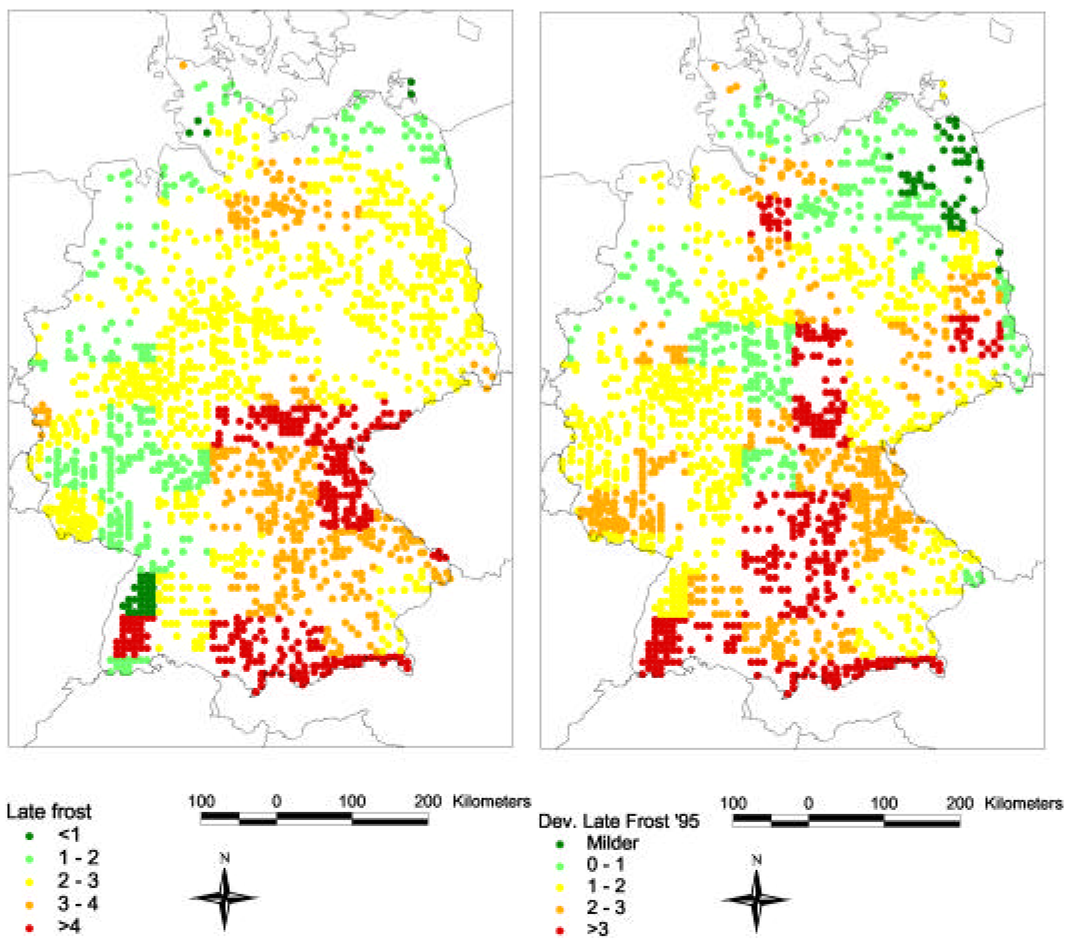

Fig. 6 Spatial variation in the estimated values for late Frost at the German Level I plots; left the mean values over the period 1987-1995; right the deviations in 1995 from an arbitrary normal value

3.1.2 Drought stress

Drought stress is expressed as the relative transpiration, which is the ratio between the potential transpiration of the trees, compared with the potential transpiration under optimal conditions. In addition we also briefly present the ratio between the total precipitation and the average temperature (both in the growing season) as a simple alternative measure to estimate drought stress.

The mean values over the years 1987-1995 for the relative transpiration show that only few plots were hardly or not affected by drought (Table 12; relative transpiration close to 1). A considerable number of plots were affected by long-term or permanent drought, with mean values below 0.8. There were even plots with, on average, a relative transpiration below 0.6. These low values are most likely related to the plots with the low values for precipitation and precipitation excess. On the other hand, the plots without any reduction of the transpiration most likely coincided with sites with high to very high precipitation values. The aridity indices also show that moderate drought stress (values < 35) occurred at almost 50% of the plots. However, severe drought (values < 25) could not be detected. On the other hand, the Level 1 monitoring programme also includes a limited number of plots with extremely high values, which can be an indication of water excess.

The deviations from `normal' for the drought stress indices also showed considerable variation (Table 12). The selected year 1995 could generally be characterized as a normal year, with only minor deviations in 1995 from an arbitrary normal value. There were, however, also plots with serious drought stress compared to `normal'.

Table 12 Minimum, maximum and 5, 50 and 95 percentiles of the relative transpiration (mm mm^{-1}) and the aridity indices (mm degree^{-1})

Statistic	Relative transpiration		Aridity Index Year		Aridity Index Gr. Season	
	Avg.1987-95	Dev. 1995	Avg.1987-95	Dev. 1995	Avg.1987-95	Dev. 1995
Minimum	0.53	-0.39	28	-12	24	-14
5 percentile	0.69	-0.29	30	7.4	25	-8.1
50 percentile	0.85	-0.08	38	-0.8	31	0.6
95 percentile	0.98	0.00	64	7.9	59	8.6
Maximum	1.00	0.06	117	34	105	28

The further analysis is limited to the relative transpiration as the most important indicator of drought stress.

The results of the mean values over the period 1987-1995 are relatively scattered (Fig. 8, left). A large area with moderately dry conditions occurs in a large part of the northern (except the coast), eastern and central part of the country. Relatively favourable conditions occur in a strip along the southern border.

Within the period 1987-1995, most of the years show a considerable amount of plots with moderate drought stress (Fig. 7, left). The years 1987 and 1993 are relatively favourable, most likely due to higher precipitation in these years. This pattern of dry and wet years appears even more distinct when the deviations from the normal values for each plot are considered (Fig. 7, right). The selected year 1995 has an intermediate position with, on average, slightly less drought than in the driest years.

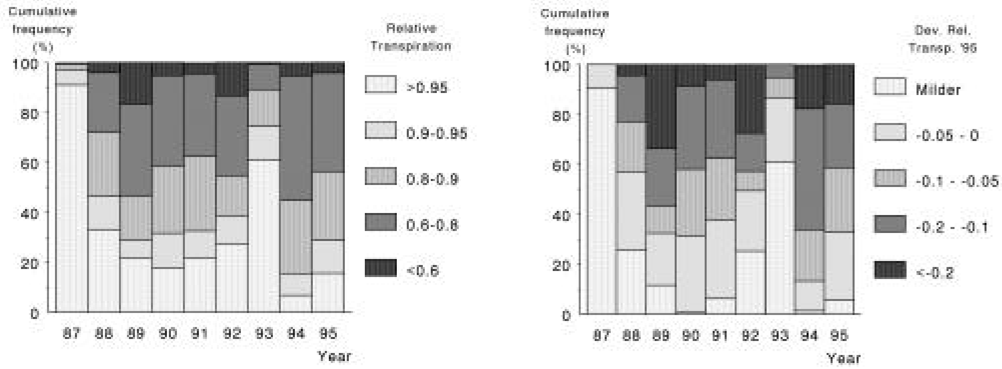

Fig. 7 Temporal variation in the estimated values for the Relative Transpiration; left as absolute values; right as deviations from an arbitrary normal value

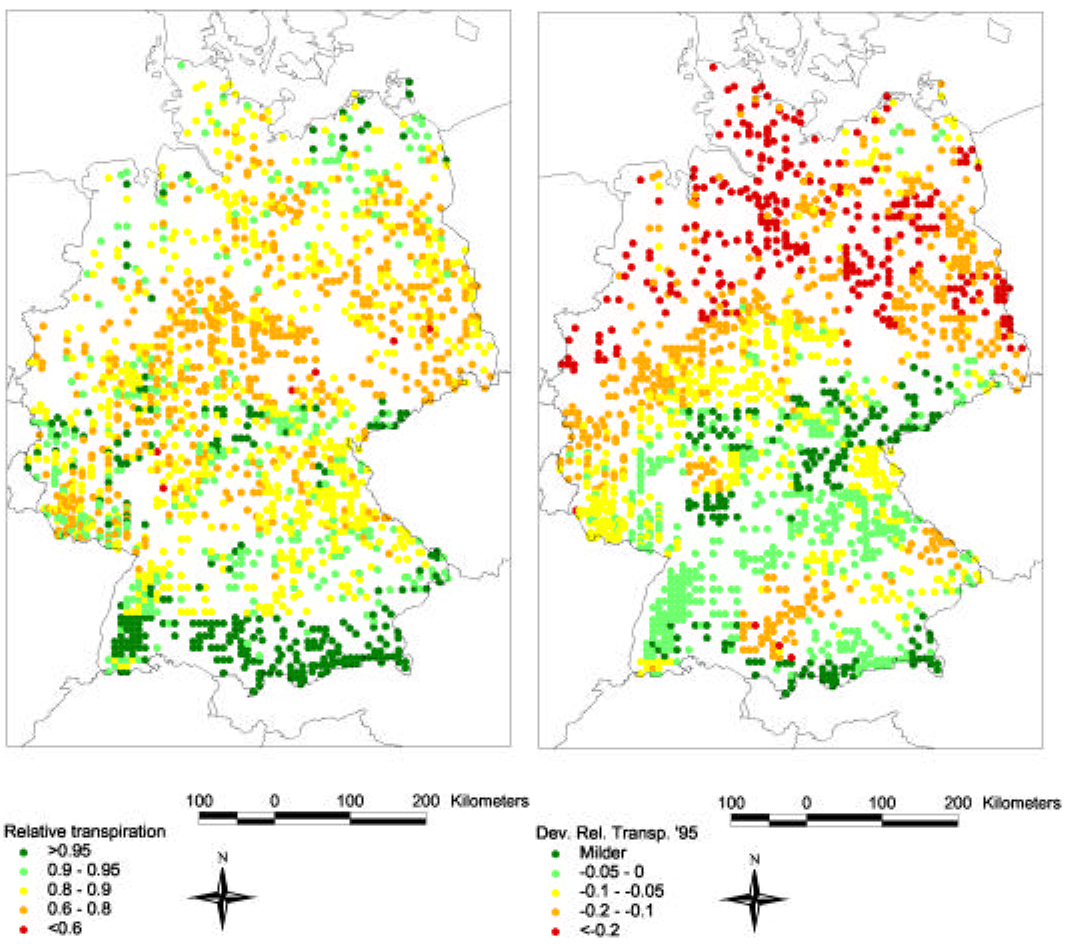

Fig. 8 Spatial variation in the estimated values for Relative Transpiration at the German Level I plots; left the mean values over the period 1987-1995; right the deviations in 1995 from an arbitrary normal value

Spatial analysis of the results of the seemingly average selected year 1995 show a very large area with serious drought problems in the lowlands and in large areas in the eastern part of the country, with also a few areas with drought stress in the south (Fig. 8, right).

3.2 Exceedances of critical loads and critical deposition levels

3.2.1 Present loads

This section only gives a brief overview of the modeled deposition at the German Level 1 sites. More detailed results are given by Bleeker *et al*. (1999). This section is limited to a discussion of the overall variation in the most important variables and of the spatial and temporal variation in the deposition of total nitrogen (NH_x + NO_y) and sea salt corrected total acidity (SO^*_x + NH_x + NO_y). The deposition of nitrogen and acidity varied (for 90% of the plots) between 1500 and 3000 mol_c ha^{-1} a^{-1} and between 3300 and 10000 mol_c ha^{-1} a^{-1}, respectively.

The deposition estimates for nitrogen and the nitrogen compound were generally considerably higher than the results for Germany in a comparable study on the European scale (Klap et al., 1997). The higher values are mainly due to improved methods (use of EUTREND and CORINAIR data instead of EMEP data), which can account much better for small-scale variations in the ambient concentrations of the various compound. This improvement particularly affects the (dry) deposition of N compounds (but not so much the S compounds), and thus predominantly the deposition of total N and not so much the deposition of total acidity. The (wet) deposition figures are also affected by the high precipitation values in some regions.

Table 13 Minimum, maximum and 5, 50 and 95 percentiles of deposition of the various compounds and sums (mol_c ha^{-1} a^{-1}) over the period 1987-1995

Statistic	NH_x	NO_y	Total nitrogen 1)	SO_x	SO^*_x (ssc)	Tot. acidity 2)	Tot. acidity (ssc) 2)
Minimum	444	472	997	1020	983	2503	2470
5 percentile	703	716	1526	1531	1480	3365	3325
50 percentile	1047	962	2034	2778	2681	4952	4870
95 percentile	1867	1311	2932	7804	7744	10089	10023
Maximum	3700	2232	4727	14003	13897	17531	17425
	BC 3) (present)	BC 3) (present, ssc)	BC 3) 4) (long-term)	BC 3) 4) (long-term, ssc)			
Minimum	487	337	194	178			
5 percentile	590	459	407	276			
50 percentile	916	680	614	391			
95 percentile	1480	1216	857	532			
Maximum	2297	1925	1397	671			

1) Total nitrogen = NH_x + NO_y
2) Total acidity = NH_x + NO_y + SO_x (or SO^*_x)
3) BC = Base cations = Ca+Mg+K (only for the years 1987-1989 and 1993-1995)
4) Long-term BC deposition is based on minimum values of sea salt corrected BC deposition in the considered years. The contribution related to sea salts is based on mean values of this contribution in the period 1987-1995

The same combination of factors has also lead to high deposition of base cations in some regions. There is, however, a strong difference between the mean deposition of base cations during the observed periode and the minumum value during this period. This is mainly due to the strong decrease in the emissions of base cations, resulting in a sharp decrease in the deposition of these cations. It was assumed that the low level of base cation deposition in the latest years would be representative for the deposition in the coming years and centuries. Therefore, the minimum value over the considered period of the (sea salt corrected) BC deposition was used for the long-term critical load calculations (see Section 3.2.2).

Most important acidifying substance in this study is SO_x, which generally accounts for more than half of the total deposition of all acidifying substances (Table 13). Extremely high values of SO_x deposition (> 4000 mol_c ha^{-1} a^{-1}, ssc) were found at less than 10% of the plots. The deposition, in general, consisted of equal amounts of NO_y en NH_x. However, in industrial and urbanized areas, the N deposition is generally dominated by NO_y, whereas NH_x generally dominated in areas with high concentrations of animal husbandry.

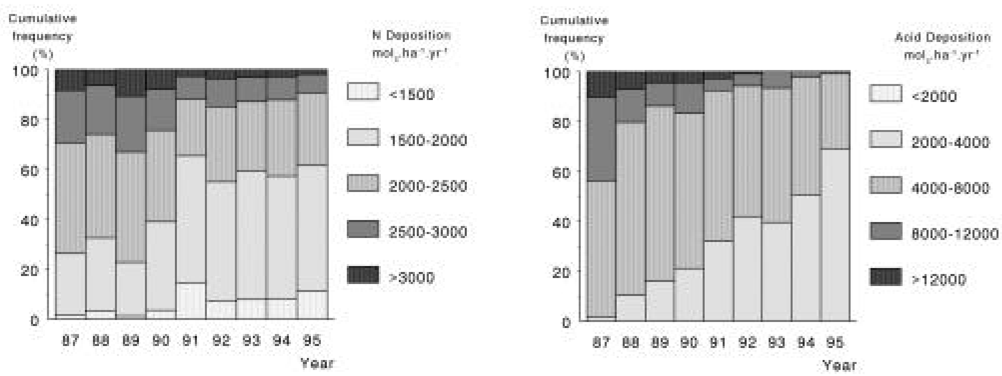

Fig. 9 Temporal variation in the modeled deposition of total nitrogen (left) and total acidity (right)

The average deposition of total nitrogen in the period 1987-1995 shows a rather scattered pattern over Germany (Fig. 9, left). Relatively high shares of plots elevated N deposition (> 1500 mol_c ha^{-1} a^{-1}) were found in the central, western and northwestern part of the country. The highest N deposition values were found in the north and northwest of the country, in the south-east and in an area stretching from the Czech border to the center of the country. The N deposition shows a slight decrease over the first couple of years and hardly any trend afterwards (Fig. 10, left).

The average deposition of total acidity in the period 1987-1995 shows very clear gradients (Fig. 9, right). A large area with high deposition (> 8000 mol_c ha^{-1} a^{-1}) was found in the southern half of the former GDR and adjacent areas, and in the northeastern part of the former GDR. Extremely high values (more than 20,000 mol_c ha^{-1} a^{-1}) were found in an area close to the Czech border (Ertz Mountains and Fichtel Mountains). The deposition of total acidity shows a strong decrease (Fig. 10, right). The strongest decrease occurred after the year 1990, after which hardly any plots with a deposition larger than 12,000 mol_c ha^{-1} a^{-1} were found, whereas deposition values below 2,000 mol_c ha^{-1} a^{-1} were found for at least 10% of the plots after this year. The strongest decrease was found in the areas with originally the highest deposition (not shown). The map (Fig 10, right) would even show a much stronger trend in the worst (earlier) years, but a less pronounced pattern in the later years.

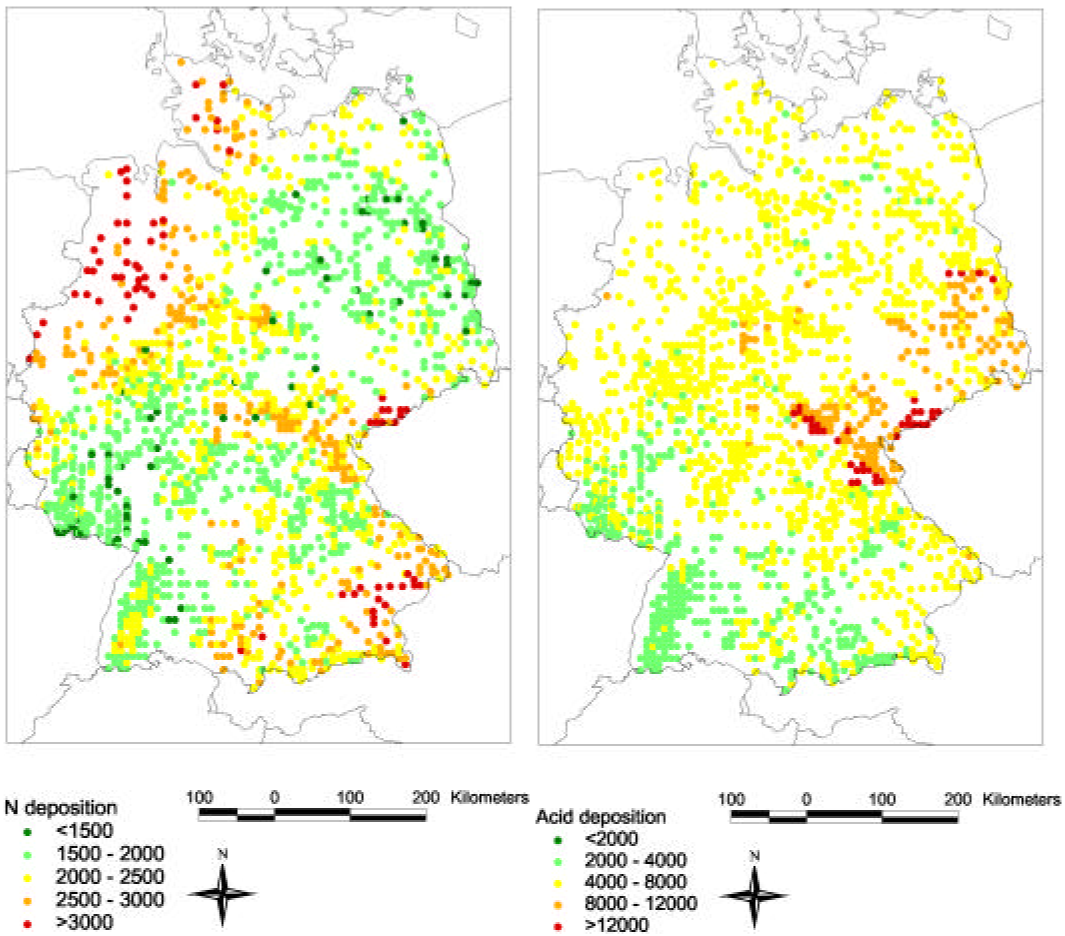

Fig. 10 Spatial variation in the mean value over the period 1987-1995 of the modeled deposition of total nitrogen (left) and total acidity (right)

3.2.2 Critical loads and critical deposition levels

General overview

Critical loads and critical deposition levels were determined related to long-term and short-term impacts, respectively. The critical load for nitrogen with the impacts on the undergrowth as the leading criterion was also determined. The distribution of the results is given in Table 14. Similar figures were calculated for the critical deposition levels and critical loads for acidity on a subset of the plots with a base saturation below 25% (BS<25%). The estimated threshold values of all these variables show considerable variation, both for the short-term critical deposition level and for the long-term (Table 14). All variables include a significant number of relative high values, compared to other studies. However, these values are still within plausible ranges, and can well be explained from the considerable variation in the values of the model input. This will be discussed separately for nitrogen and acidity, respectively, in more detail in the following sub-sections.

Table 14 Minimum, maximum and 5, 50 and 95 percentiles of critical loads and critical deposition levers for acidity and nitrogen ($mol_c\ ha^{-1}\ a^{-1}$)

Statistic	Nitrogen [1]			Acidity			
	Short-term	Long-term	Long-term biodivers.	Short-term (all)	Long-term (all)	Short-term (BS<25%)	Long-term (BS<25%)
N	1827	1827	1827	1827	1827	1147	1147
Minimum	952	610	320	1664	996	1664	996
5 percentile	1407	913	369	3305	1554	2934	1507
50 percentile	1957	1348	675	6807	3912	5444	3760
95 percentile	3250	2586	1123	8 [2]	10535	8225	6247
Maximum	5647	4248	2099	8 [2]	11497	12503	10697

1) Critical N deposition levels (short-term) for vegetation (biodiversity) were not calculated, since the concept used was not suitable for this application (see Section 2.2.4; Critical N leaching).

2) Critical deposition levels were not calculated when the base saturation was above 25%. It was assumed that no harmful effects occur related to Al toxicity at any level of acid deposition.

Nitrogen

The estimated critical deposition level for nitrogen varied (for 90% of the plots) between 1400 and 3250 mol_c ha^{-1} a^{-1} (short-term) and between 900 and 2600 mol_c ha^{-1} a^{-1} (long-term), with median values of about 2000 and 1350 mol_c ha^{-1} a^{-1} (Table 14). These values are slightly higher than the results found in similar studies (e.g. De Vries, 1993), but this mainly due to not including nutrient ratios in the present study. The relatively large share of high values is also related to typical site conditions, the models applied and the large variation in the input variables. The results for the critical loads for nitrogen for the vegetation as the criterion are considerably lower than for the tree condition as the criterion, due to the higher vulnerability of the undergrowth for changes.

Examination of the input variables of the model showed, that high values for the critical N deposition are mainly related to high values for the precipitation excess (> 500 mm a^{-1}), leading to high values for $N_{le}(crit)$. High critical N deposition values were also partly related to (i) high values for N_{im} as a result of high N deposition values and (ii) high values for N_{de}, mainly in peat and clay soils. High values for the (long-term) critical loads are also related to an inadequate description of the impact of high levels of denitrification, besides the impacts of the precipitation excess on the critical N load. Several adaptations in the SMB model have been made to account for conditions, which were not considered in the basic scope of the model (e.g. the correction of extreme values for the potential denitrification; see Section 2.2.4).

The short-term critical deposition levels for nitrogen show a double gradient from the northwest to the center and from the south to the center, forming a wide west to northeast belt with sensitive plots in which the sensibility slightly further increases to the northeast (Fig.11, left). Most sites with low values (< 2000 mol_c ha^{-1} a^{-1}; i.e. high vulnerability) were located in the east and northeast of the country, but there were also other vulnerable sites distributed over most of the rest of the country. High values for the critical deposition level (> 3000 $mol_c\ ha^{-1}\ a^{-1}$; i.e. low vulnerability) were generally found in the western and central part of the country and in the mountainous areas in the south. The pattern for the critical loads (Fig. 11, right) shows more contrast than the pattern for the critical deposition levels, with a considerably larger number of very vulnerable sites (low critical loads).

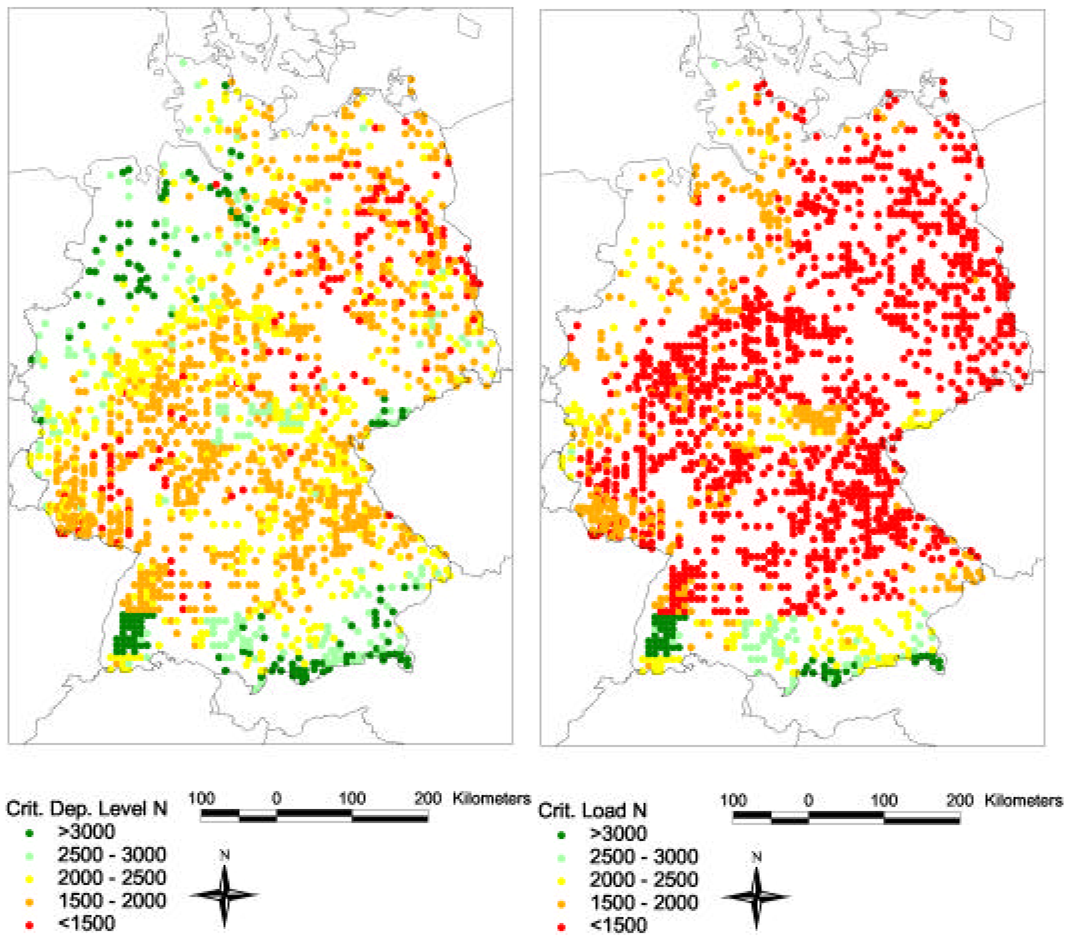

Fig. 11 Spatial variation in the estimated (short-term) critical deposition level (left) and critical load (right) for nitrogen at the German Level I plots. Mind that the class limits are the same in both maps, and that these limits are mainly determined by the distribution in the critical deposition levels.

Acidity

The estimated critical deposition levels (short-term) for acidity varied (for 90% of the plots with BS<25%) between 2900 $mol_c\ ha^{-1}\ a^{-1}$ and 8200 $mol_c\ ha^{-1}\ a^{-1}$, with a median value of 5400 $mol_c\ ha^{-1}\ a^{-1}$ (Table 14). The limitation to the plots with BS<25% was made since it was considered that at the short term these plots are not adversely affected by acid deposition, since the occurrence of Al toxicity is very unlikely at these sites. The acidic input is then buffered by the release of base cations rather than of aluminium. The estimated critical loads (long-term) for acidity varied (for 90% of all plots) between 1500 and 10500 $mol_c\ ha^{-1}\ a^{-1}$, with a median value of 4000 mol$_c$ ha^{-1} a^{-1}. These values are 1500, 6200 and 3700 mol$_c$ ha^{-1} a^{-1}, respectively, when the same limitation is applied as for the critical deposition levels (i.e. BS<25%).

The estimated critical deposition levels for acidity are generally in line with a recent study for the whole of Europe (Klap et al., 1997), but considerably higher than older studies for Germany (e.g. the German NFC report in Posch et al., 1995b). The main reason for this difference is a change in criteria for Al depletion. The older studies were based on a strict Al/BC ratio with a fixed value of 1 mol^{-1} mol^{-1}, whereas presently less strict values are used, which also differ between the tree species (cf. Sverdrup & Warfvinge, 1993; see this report section 2.2.4). Furthermore, the present study also uses input data with considerable variation, e.g. high values of BC deposition (BC_{td}), particularly for the short-term critical deposition levels, and high values in the nitrogen terms (N_{im} and N_{de}). Critical acid deposition levels are not affected by the precipitation excess, since the ratio of Al and BC in the drainage is used water as a measure for the critical acidity leaching ($H_{le}(crit)$ and $Al_{le}(crit)$), rather than the Al concentration.

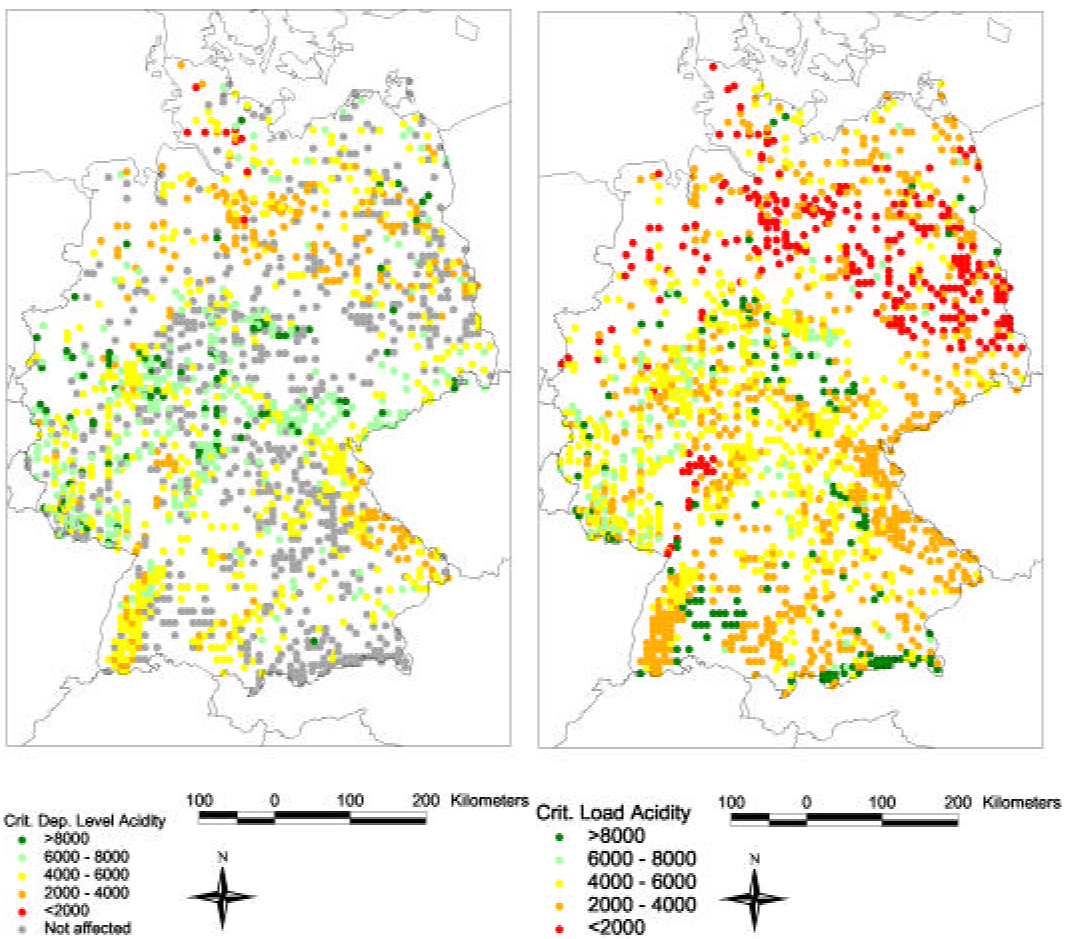

Fig. 12 Spatial variation in the estimated (short-term) critical deposition level (left) and (long-term) critical load (right) for acidity at the German Level I plots. Note that no critical deposition level for acidity was calculated when base saturation was above 25% (`not affected')

The critical deposition levels and critical loads for acidity show a different pattern as the patterns for nitrogen. The sites with the lowest values (< 4000 mol_c ha^{-1} a^{-1}; i.e. highest vulnerability) were found in the northern and northeastern lowlands (Fig 12). The most vulnerable sites are located in the northwest. The sites with a low vulnerability (high critical deposition level; e.g. > 6000 mol_c ha^{-1} a^{-1}) are concentrated in the center of the country, but there are also sites with a low vulnerability in other parts of the country (e.g. in the southern mountains). The critical deposition levels for the plots in these mountainous areas were not calculated because the base saturation at these plots was above 25%. The other sites with base saturation larger than 25% also occurred scattered throughout the country. The scattered plots without a critical deposition, however, appeared in all different classes of critical loads.

3.2.3 Exceedances

The exceedances were calculated by subtracting the critical load or critical deposition levels from the present loads. Negative results were set to 0. It was assumed that the critical deposition level for acidity at the plots with base saturation larger than 25%, was not exceeded (i.e. the exceedance equals 0). The results of these calculations show that there are exceedances for all considered variables (Table 15). The exceedances at a limited number of plots can even be considered as extremely high. On the contrary, there are also plots at which the threshold values are not exceeded (except for the critical nitrogen load for undergrowth).

Table 15 Minimum, maximum and 5, 50 and 95 percentiles of the exceedances of critical loads and critical deposition levers for acidity and nitrogen (mol_c ha^{-1} a^{-1})

Statistic	Nitrogen [1)]			Acidity	
	Short-term	Long-term	Long-term biodiversity	Short-term	Long-term
Minimum	0	0	29	0	0
5 percentile	0	0	742	0	0
50 percentile	129	710	1383	46	1046
95 percentile	592	1451	2231	3812	7230
Maximum	1195	3004	3929	11128	13769

1) Critical N deposition levels (short-term) for vegetation (biodiversity) - and thus no exceedance - were not calculated, since the concept used was not suitable for this application (see Section 2.2.4; Critical N leaching).

Nitrogen

Exceedances for the critical deposition level for nitrogen were found at 84% of the plots, whereas the critical load was exceeded at 94% of the plots (Table 15). The critical load is exceeded at all plots when in the biodiversity of the undergrowth is used as the primal criterion. The percentages of plots with exceedances for the entire period is larger than the percentages for the separate years, since a (mean) exceedance over the entire period is reported, even if the critical value was exceeded in only one or a few years. The number of plots with exceedances or the critical levels decreased from 81% to 38% and from 94% to 83% of the plots, for the short-tem and long-term approach respectively.

Most observations for the exceedances of (short term) critical deposition levels for nitrogen are still close to 0, whereas significant exceedances are found when the long-term approach is applied (Fig. 14; Fig 13 left, especially the first years). Most exceedances, including extremely high values, are found and in the northern lowlands and in the eastern and southeastern part of the country. The exceedances of both critical deposition levels and critical loads show a decreasing tendency, although the results seem to stabilize in the latest years (Fig. 13).

Acidity

The critical deposition levels and critical loads for acidity were exceeded at 53% and 89% of the plots, respectively (Table 15). Severe exceedances (> 4000 $mol_c\ ha^{-1}\ a^{-1}$) were calculated for approximately 4% and 16% of the plots, whereas very severe exceedances (> 8000 $mol_c\ ha^{-1}\ a^{-1}$) were calculated for 1% and 3% of the plots for the short- and long-term, respectively. Like for nitrogen, the percentages of plots with exceedances for the entire period is larger than the percentages for the separate years, since a (mean) exceedance over the entire period is reported, even if the critical value was exceeded in only one or a few year. The number of plots with exceedances of the critical levels decreased from 54% to 12% and from 89% to 41% of the plots, for the short-term and long-term approach respectively.

Most of the exceedances of the critical deposition levels and critical loads for acidity can be classified as moderate (less than 2000 $mol_c\ ha^{-1}\ a^{-1}$; Fig. 15). However, in the southern part of the country these threshold values were exceeded at relatively small numbers of plots. Serious exceedances were found in two distinct areas, one at the border of the Czech Republic (with exceedances even above 20,000 $mol_c\ ha^{-1}\ a^{-1}$ in the first years). Some more plots with exceedances above 2000 $mol_c\ ha^{-1}\ a^{-1}$ were found in the lowlands. The time series shows a similar pattern as the present loads of acidity, with a slightly decreasing tendency in the exceedances, with the strongest decrease in the first few years (Fig. 16).

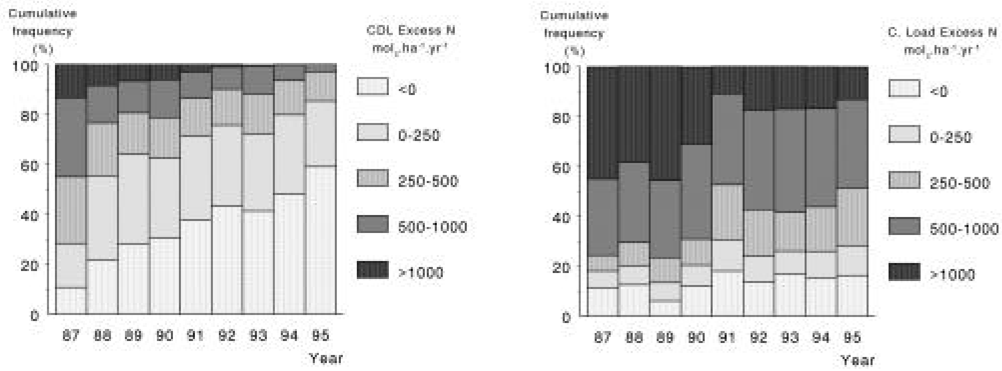

Fig. 14 Temporal variation in the exceedances of the (short-term) critical deposition level (left) and the (long-term) critical load (right) of total nitrogen

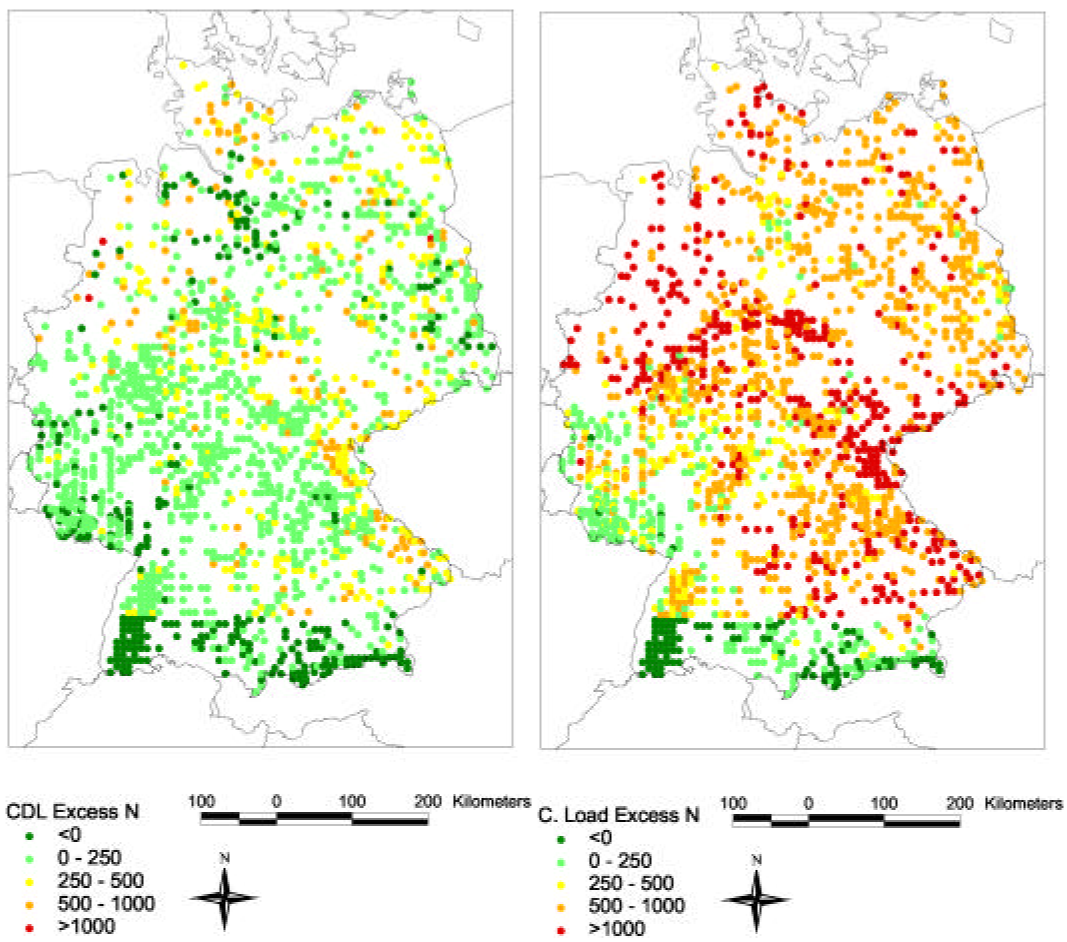

Fig. 13 Spatial variation in the mean value over the period 1987-1995 for the exceedances of the (short-term) critical depositions levels (left) and the (long-term) critical loads for total nitrogen

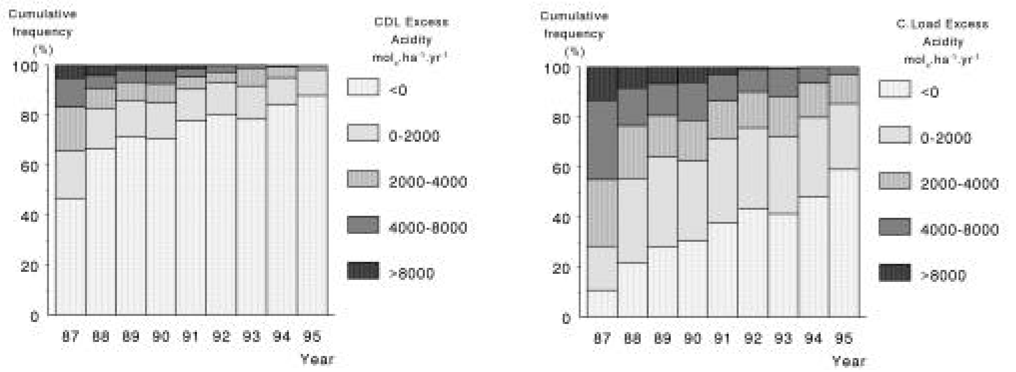

Fig. 15 Temporal variation in the exceedances of the (short-term) critical deposition level (left) and (long-term) critical load (right) of total acidity

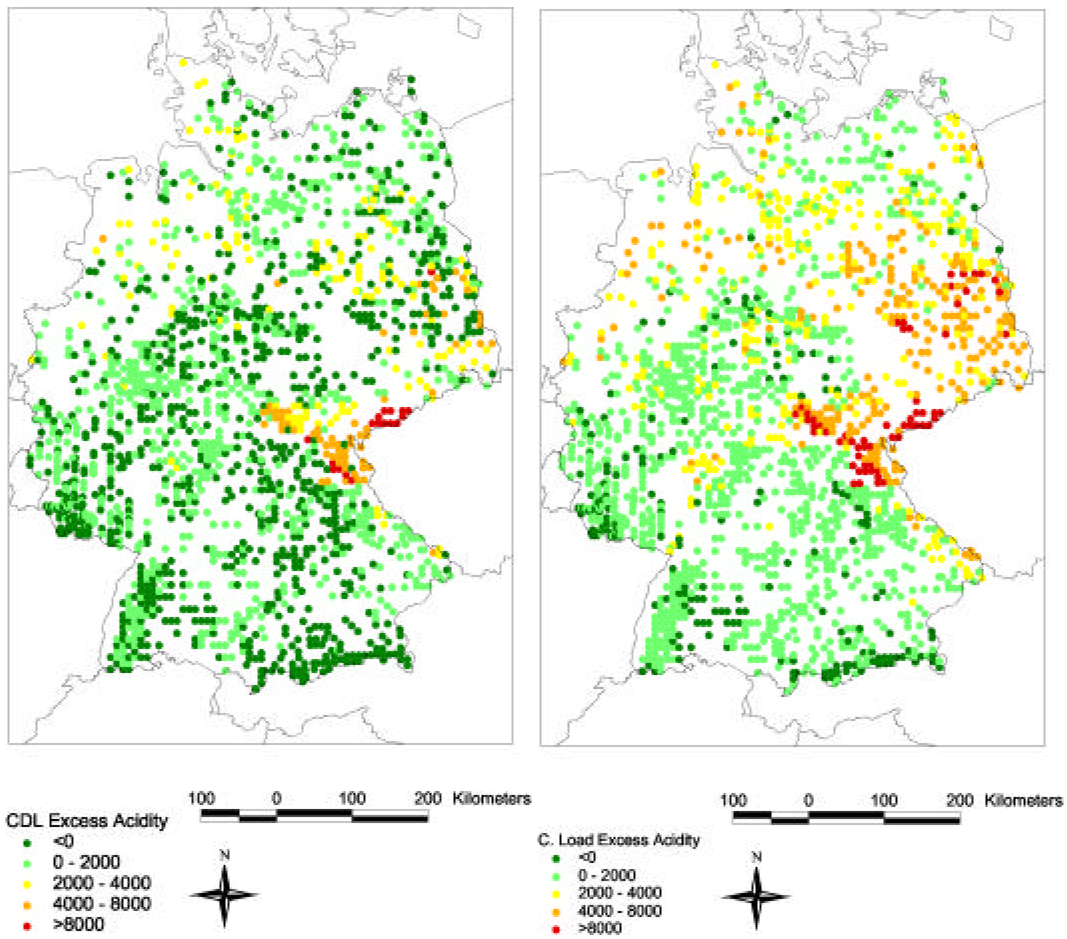

Fig. 16 Spatial variation in the mean value over the period 1987-1995 for the exceedances of the (short-term) critical depositions levels (left) and (long-term) critical loads (right) of total acidity

4 Discussion

This chapter gives a description of the uncertainties related to the methods applied to derive the various data and the resulting stress factors. Section 4.1 gives an overview of the uncertainties in the estimation of meteorological parameters and the resulting stress factors. Section 4.2 gives an overview of the uncertainties related to the assessment of the exceedances of critical loads and critical deposition levels for nitrogen and acidity. First a summary is given of the uncertainties in the derivation of present loads of the compound (Section 4.2.1) and then an overview is given of the uncertainties in the estimation of the critical loads and critical deposition levels, separately for nitrogen and acidity (resp. Section 4.2.2 and 4.3.3).

4.1 Meteorological data and meteorological stress factors

The method used to quantify the uncertainty associated with the interpolation of the meteorological data is described in Klap *et al*. (1997). It is difficult to quantify the total uncertainty in the interpolated meteorological parameters accurately, because uncertainty arises from several factors:

- Errors in the selection procedure (interpolation errors)
- Errors in the meteorological measurements and data transmission and handling
- The use of (three different) invalidated data sets from ECMWF, NCAR and DWD (meaning that they are not screened for errors and unrealistic values), in which moreover quite some missing data values are archived.

The last error source contributes to the total uncertainty to a large extent. The uncertainty as obtained with cross validation can be considerable, especially for parameters showing strong regional differences, such as precipitation amount. Air temperature and relative humidity perform well in large parts of Europe (average uncertainty about 25%), but for individual plots uncertainty can be large (up to 100%). Wind speed, cloud cover and dew point temperature seem to perform fairly well (average uncertainty about 50%), but for individual plots uncertainty can amount 200%. Largest uncertainty is associated with the interpolated precipitation amounts (average uncertainty about 100%), though locally uncertainty can be much higher, especially in area with strong topopgraphical differences (e.g smaller mountain ranges)

The uncertainties in temperature key parameters can be divided into two groups of causes. At first, uncertainty results from inaccuracies in the meteorological data and the interpolation procedure. The second uncertainty source is a physiological one. Threshold values for the temperature indices were based on available knowledge: 0°C for the winter index and the late frost index, 10°C and 15°C for the effective temperature sums or summer indices, and 30°C for the heat index. Effects of chosen threshold values on the relationships with defoliation are unknown. Furthermore, no difference was made between sensitivity per tree species.

The uncertainties in the calculated relative transpiration have many causes. First, the uncertainty in the basic meteorological input data affects the accuracy of the calculated RET. Several estimations are needed to calculate global radiation, and the meteorological conditions at crown height. As mentioned, derivation of site-specific precipitation data is very difficult and leads to high uncertainty. Besides uncertainties in input data, also the calculation method yields uncertainties. Several assumptions were needed to calculate process parameters such as the soil moisture content, stomatal resistance, plant available water, and drainage. Moreover, the model that calculates interception evaporation and actual transpiration has not been validated. Furthermore, because of lack of local data, large-scale, long-term average data had to be used. For instance a mean evaporation during rainfall was calculated per climatic region, instead of per plot. All these uncertainties together may lead to large uncertainty in RET estimates. The spatial patterns in RET at the national (this study) and European scale (Klap *et al.*, 1997), however, are in accordance to the expectation.

4.2 Exceedances of critical loads and critical deposition levels

4.2.1 Present loads of nitrogen, acidity and base cations

The uncertainty in EDACS results is derived from Draaijers *et al.* (1996a, 1997) concerning dry deposition of base cations, Erisman (1995) and Van Pul *et al.* (1995) concerning dry deposition of acidifying compounds, and Van Leeuwen *et al*. (1995, 1996) concerning wet deposition of acidifying compounds and base cations (see Klap *et al.*, 1997, for a synthesis).

The uncertainty in regional scale deposition estimates strongly depends on the pollution climate and on landscape complexity of the area under study. The uncertainty in total deposition is determined by the uncertainty in wet, dry and cloud and fog deposition. Fog and cloud water deposition is not taken into account. Therefore, deposition estimates are more uncertain in areas with complex terrain were fog and cloud deposition might be important. Deposition estimates are also more uncertain in areas with strong horizontal concentration gradients, e.g. in source areas.

Using error propagation methods and assuming that presented uncertainties in deposition velocities and air concentrations represent random errors, the total uncertainty in dry deposition for a grid cell (on the one σ level) was roughly estimated to amount ca. 80-120% on average (Draaijers *et al.*, 1996a), both for acidifying components and base cations. Van Leeuwen *et al*. (1995) estimated the uncertainty in wet deposition at 50-70% on average. The uncertainty in total deposition can be calculated to amount 90-140% (Draaijers *et al.*, 1996a).

A comparison of model estimates with throughfall measurements showed a variable level of accordance. The observed deviation, however, were usually within the limits of uncertainty related to propagation of the mentioned possible errors (Klap at al., 1997).

4.2.2 Critical loads and critical deposition levels for nitrogen

The uncertainty in the calculated critical N deposition levels is mainly due to uncertainties in the assumed critical N leaching rates in relation to effects, model assumptions and input data as described below.

Criteria

The choice of the critical N leaching rate strongly affects the critical deposition levels of N. The two chosen criteria have a stronger relationship with possible threads for the forets ecosystem, but are different from previous studies, which may hamper the comparability, especially the second one. The nearly negligible N leaching rate that was taken to calculate critical N deposition levels related to vegetation changes might not be appropriate in certain situations, esepcially at high precipitation excess values (>>500 mm a^{-1}). Empirical data on vegetation changes in forest (e.g. Bobbink *et al*., 1992; 1995) are slightly higher than the calculated critical N deposition levels, although the results are in a similar order of magnitude. The same is the case with the critical N deposition levels related to effects on trees. Assuming an uncertainty in the critical N leaching rate of 50%, the resulting uncertainty in critical N deposition levels will be in the same order of magnitude. Also these results may less appropriate at large precipitation excess values.

Model assumptions

Uncertainties related to the description of N dynamics in the SMB model result from (i) neglecting N fixation which is important for trees such as red alder, (ii) neglecting NH_4 fixation which may play a role in clay soils, (iii) assuming that nitrification is complete, while it is likely to be inhibited at high C/N ratios, (iv) the simple description of net N immobilisation as a function of net atmospheric N input and the C/N ratio, while the carbon pool in the soil is fixed and (v) neglecting the interaction between net N uptake and a change in soil conditions (De Vries *et al.*, 1994b). Even though the dynamics of the N transformation processes are strongly simplified, the resulting fluxes for net N uptake, N immobilisation and denitrification seem plausible in view of available data on these processes for forest soils (De Vries *et al.*, 1994a).

Input data

Assuming that the model structure is correct, the effect of the uncertainty in the input data can directly be quantified (Eq. 18). The most important input parameter is the net uptake, which is affected by the interpolated yield values and the assumed N contents in stemwood. Comparison between model inputs used in a previous study carried out at a European scale and values derived in various individual countries indicated that the overall uncertainty in N uptake was generally less than 50%, although it can be more than 100% at specific plots (De Vries *et al*., 1994a). Most input data are well applicable in European-wide assessments and cover the European-wide variation in these variables. The limited availability of more precise information for the variation within Germany is certainly an additional source of uncertainty. Consequently, considering the previously mentioned uncertainty in critical N leaching rates, the resulting uncertainty will also vary mostly within a range of plus or minus 50%. The plausibility of the input data is also affected by limitations in the access to more specific databases, which more precisely describe the German conditions.

4.2.3 Critical loads and critical deposition levels for acidity

As with nitrogen, the critical acid deposition levels, which were derived by applying the SMB model, are subject to (large) uncertainties due to the uncertainties in the assumed critical Al/(Ca+Mg+K) ratios in relation to effects, model assumptions and input data.

Criteria
Uncertainties in critical values for the Al/(Ca+Mg+K) ratio, related to direct toxic effects of Al, are mainly due to a lack of knowledge about the effects of Al in the field situation. Values are mainly based on laboratory experiments and the applicability in the field situation seems often limited. The uncertainty is also partly due to a natural range in the sensitivity of various tree species for Al toxicity (Sverdrup and Warfvinge, 1993). Note also that we used critical annual average values whereas the temporal variation can be large, with peak values in the summer. Finally, the Al/(Ca+Mg+K) ratio may be irrelevant for peat soils, since Al mobilization hardly occurs in these soils. When one wants to avoid a decrease in base saturation or pH, the critical acid deposition level is likely to be much lower.

Model assumptions
First of all the derivation of critical loads with a simple mass balance model, limited to abiotic effects on the soil only, is questionable. The development of multi-stress models, including interactions of desiccation, acidification and eutrophication on forests and effects of drought, pests and diseases, are necessary to support the results of such simplified models. A first comparison of critical deposition levels for a Norway spruce stand in Solling (Germany), derived with integrated forest-soil models and simple mass balance models seems promising in this context (De Vries *et al*., 1995b).

An important assumption in the SMB model is the assumed homogeneity of the rootzone both in a horizontal and vertical direction. Use of a one-layer model such as SMB implies that the critical Al/(Ca+Mg+K) ratio used refers to the situation at the bottom of the rootzone, whereas most roots occur in the topsoil. Values for the Al/(Ca+Mg+K) ratio generally increase with depth due to Al mobilization, BC uptake and transpiration. Other assumptions in the SMB model such as (i) disregarding SO_4 interactions, (ii) neglecting complexation of Al with inorganic and organic anions and (iii) a simple hydrology are likely to be less significant (De Vries *et al*., 1994b).

Input data
Assuming that the model structure is correct, the effect of the uncertainty in the input data can directly be quantified (Eq. 17). The uncertainty in the calculated net

base cation input (deposition and weathering minus uptake), combined with the uncertainty in Al/(Ca+Mg+K) ratio, which affects the associated acidity leaching, has the largest effect on the calculated critical acid deposition level. Comparison between model inputs used in a previous study carried out at a European scale and values derived in various individual countries indicated that the overall uncertainty of these model inputs was generally less than 50%, although it can be more than 100% at specific plots (De Vries *et al.*, 1994a. Most input data are well applicable in European-wide assessments and cover the European-wide variation in these variables. The limited availability of more precise information for the variation within Germany is certainly an additional source of uncertainty. Considering the above-mentioned uncertainties in input data, it is likely that the overall uncertainty in critical acid deposition levels varies mostly between plus or minus 50%. The plausibility of the input data is also affected by limitations in the access to more specific databases, which more precisely describe the German conditions.

5 Conclusions

The following conclusions with respect to the overall, temporal and spatial variation of calculated meteorological stress factors and their uncertainties can be drawn.

1. The overall variation of temperature indices (90% of the mean values over the period 1987-1995) varies between 70 and 230 degree days below 0 °C for the Winter Index and between 1.6 and 4.4 degrees below 0 °C for Late Frost. These factors, together with a few other ones considered, could be characterized as important stress factors for forests in Germany. Drought stress, in terms of 90% of the mean values over the period 1987-1995 of the Relative Transpiration values, varies between 0.7 and 1.00, with a median value of 0.85 and values down to ca. 0.5. Drought can therefore be considered as an important stress factor in many German forests.
2. The meteorological stress indices showed considerable temporal variation between 1987 and 1995. The coldest winters occurred in 1991, 1993 and 1994, whereas the most harmful late frosts occurred in 1993 (and 1987 and 1995. The driest years occurred in 1989, 1992 and 1994.
3. The meteorological stress indices showed considerable spatial variation, with clear differences between the different years. The coldest winters -on average- were found in the hilly and mountainous areas, whereas the selected year 1995 was specifically cold in the Bavarian Alps. Late Frost showed a distinct northwest to southeast pattern, whereas in the selected year 1995 relatively high values were found for a north to south belt and along the southern border. The northern half of the country suffered -on average- from a moderate level of drought stress, whereas in the selected year 1995 large areas in the northwestern and north-eastern part of the country had serious drought stress.
4. The calculated indices for temperature and drought stress contain uncertainties, which largely depend on the reliability of the site-specific meteorological data and the accuracy of the interpolation method. The estimations for drought stress are also affected by uncertainties in various model terms in the used water balance model. In general the site-specific meteorological estimates followed the geographical patterns as expected.

With respect to the overall, temporal and spatial variation of calculated anthropogenic stress factors (present loads, critical loads and deposition levels and their exceedances) the following conclusions can be drawn.

1. The calculated nitrogen (NH_x + NO_y) deposition, averaged over the years 1987-1995, ranged between 1500 and 3000 $mol_c\ ha^{-1}\ a^{-1}$ (5 and 95 percentiles), with a median value of 2000 $mol_c\ ha^{-1}\ a^{-1}$. The average deposition of total acidity (NH_x + NO_y + SO^*_x) varied between 3300 and 10000 $mol_c\ ha^{-1}\ a^{-1}$ (5 and 95 percentiles), with a median value of 4900 $mol_c\ ha^{-1}\ a^{-1}$. Extremely high maximum values for the deposition of acidity (>20000 $mol_c\ ha^{-1}\ a^{-1}$ in some years) are mainly due to a limited number of plots (<5%) with extremely high SO^*_x deposition. Both variables showed a decreasing tendency over the considered period.

2. The average N deposition was highest (>2500 mol_c ha^{-1} a^{-1}) in large part of the northwestern part of the country and in some areas in the southeast. The average deposition of acidity was highest (>8000 mol_c ha^{-1} a^{-1}) in the southern half of the former GDR and adjacent areas with extreme peak values (>20000 mol_c ha^{-1} a^{-1}) in the Ertz Mountains and Fichtel Mountains.
3. The estimated critical deposition level for nitrogen mostly varied between 1400 and 3250 mol_c ha^{-1} a^{-1} (short-term) and between 900 and 2600 mol_c ha^{-1} a^{-1} (long-term), with median values of 2000 and 1350 mol_c ha^{-1} a^{-1}, respectively. The estimated critical deposition level for acidity mostly varied between 2900 and 8200 mol_c ha^{-1} a^{-1} (short-term; for the 63% of the plots with BS<25%) and between 1500 and 10500 mol_c ha^{-1} a^{-1} (long-term; for all plots), with median values of 5400 and 3700 mol_c ha^{-1} a^{-1}, respectively. The relatively large share of high values (compared to other studies) is mainly related to the models and model criteria applied, typical site conditions and the large variation in the input variables. Special adaptations had to be made to account for unrealistic values for the potential denitrification and N leaching.
4. Many plots with relatively low values (< 2000 mol_c ha^{-1} a^{-1}) for the critical deposition level (indicating a high vulnerability to N deposition) were found in the north-eastern part of the country, whereas such values cover almost the whole country in the long-term approach. The large area with low values (< 4000 mol_c ha^{-1} a^{-1}) for the critical deposition level and for the critical load of acidity was found in the north, indicating a high vulnerability to acid deposition.
5. The exceedances of critical loads and critical deposition levels reflected the results for the present loads and the critical loads and critical deposition levels. The critical deposition levels en critical loads for nitrogen were exceeded at 84% and 94% of the plots, respectively, with extreme values (95 percentiles) up to 600 mol_c ha^{-1} a^{-1} and 1500 mol_c ha^{-1} a^{-1}, respectively. The critical deposition levels en critical loads for acidity were exceeded at 53% and 89% of all plots, respectively, with extreme values (95 percentiles) up to 3800 mol_c ha^{-1} a^{-1} and 7200 mol_c ha^{-1} a^{-1}, respectively. All these variables showed a considerable decrease over the observed period.
6. The exceedances of critical N deposition levels were concentrated in the northern half of the country, with some more serious exceedances (> 1000 mol_c ha^{-1} a^{-1}) of the critical loads in the former GDR and in the northwestern part of the country. The exceedance of the long-term critical load for N is far more wide-spread and more serious. Moderate exceedances of the critical load for acidity (< 2000 mol_c ha^{-1} a^{-1}) occurred on a large scale throughout the country. More serious exceedances (> 4000 mol_c ha^{-1} a^{-1}) of both the critical load and critical deposition level were concentrated in the southern half of the former GDR but severe exceedances were concentrated in the Ertz Mountains and Fichtel Mountains.
7. The uncertainties in the deposition estimates were mostly related to uncertainties in the model terms and parameters (e.g. the estimated deposition velocity), in uncertainties related to the grid-oriented basis of the air concentration and in simplifications of the model. The uncertainties in the critical deposition levels and critical loads were related to (i) the choice of criteria (e.g. the N leaching rate, assumptions about effects of Al and the use of annual mean values rather than

peak values), (ii) model assumptions (e.g. the homogeneity of the rootzone and simplifications of several N transformations and other chemical equilibria) and (iii) the quality of the input data, which were mostly estimated rather that measured, whereas the use of more precise estimations was also hampered by limitations in the access to more specific databases, which more precisely describe the German conditions.

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