

## The impact of atmospheric deposition and climate on forest growth in European monitoring plots: An individual tree growth model

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### ABSTRACT

In the climate change discussion, the possibility of carbon sequestration of forests plays an important role. Therefore, research on the effects of environmental changes on net primary productivity is interesting. In this study we investigated the influence of changing temperature, precipitation and deposition of sulphur and nitrogen compounds on forest growth. The database consisted of 654 plots of the European intensive monitoring program (Level II plots) with 5-year growth data for the period 1994–1999. Among these 654 plots only 382 plots in 18 European countries met the requirements necessary to be used in our analysis. Our analysis was done for common beech (*Fagus sylvatica*), oak (*Quercus petraea* and *Q. robur*), Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*). We developed an individual tree growth model with measured basal area increment of each individual tree as responding growth factor and tree size (diameter at breast height), tree competition (basal area of larger trees and stand density index), site factors (soil C/N ratio, temperature), and environmental factors (temperature change compared to long-term average, nitrogen and sulphur deposition) as influencing parameters. Using a mixed model approach, all models for the tree species show a high goodness of fit with Pseudo- $R^2$  between 0.33 and 0.44. Diameter at breast height and basal area of larger trees were highly influential variables in all models. Increasing temperature shows a positive effect on growth for all species except Norway spruce. Nitrogen deposition shows a positive impact on growth for all four species. This influence was significant with  $p < 0.05$  for all species except common beech. For beech the effect was nearly significant ( $p = 0.077$ ). An increase of  $1 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  corresponds to an increase in basal area increment between 1.20% and 1.49% depending on species. Considering an average total carbon uptake for European forests near  $1730 \text{ kg per hectare and year}$ , this implies an estimated sequestration of approximately 21–26 kg carbon per kg nitrogen deposition.

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### 1. Introduction

In the Kyoto Protocol governments agreed to reduce emissions of  $\text{CO}_2$ . They engaged themselves either to limiting the fossil fuel consumption or to increase the net C sequestration in terrestrial sinks through afforestation and land use or both. Mid-latitude forests play an important role in the net C sequestration of the biosphere (Kauppi et al., 1992; Nabuurs et al., 1997). This apply especially for Europe where a very clear increase of growing stock and annual growth have been observed in all countries where systematic forest inventories have been run for some decades (Spiecker et al., 1996). In this respect, besides the changes in standing growing stock, the changes in net primary productivity

seem to be important (Spiecker et al., 1996). A lot of environmental variables, as  $\text{CO}_2$ , temperature, nitrogen deposition and others have been hypothesized to increase the net primary productivity (NPP) (Melillo et al., 1993; Friedlingstein et al., 1995; Holland et al., 1997; Hasenauer et al., 1999; Nadelhoffer et al., 1999). As summarized in a review article (Hyvönen et al., 2007a), well documented responses on the NPP are an increased photosynthetic rate (main  $\text{CO}_2$  response), an increase in the length of the growing season (main temperature response) and an increase in leaf area index (main N deposition response).

Since nitrogen often is the limiting nutrient in forests, nitrogen deposition is likely to increase productivity, thus increasing carbon sequestration by forests. Using a modelling approach, temperature has been claimed to be relatively unimportant, whereas the combination of  $\text{CO}_2$  rise and elevated N deposition may account for a 15–20% increase in forest net primary productivity (Rehfuess et al., 1999). In this context, N deposition is claimed to be most

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important. Similar results were also obtained by Milne and van Oijen (2005). The results of their analysis, a process-based model, let suggest that the main driver of increased forest growth in the 20th century has been increased nitrogen deposition, rather than increased CO<sub>2</sub> concentrations or climate change. In an analysis of control plots in former fertilizer trials, combined with a retrospective analysis of height increment on selected intensive monitoring sites, Kahle et al. (2005) found an increased height growth of Scots pine, Norway spruce and common beech of around 25% as compared to 40 years ago. Combining these results with a process-based modelling approach using selected intensive monitoring sites for calibration and validation Kahle et al. (2008) also concluded that nitrogen deposition appears to be the main cause of the observed height growth increase. The number of sites used in the study was, however very limited.

In this contribution we tried to assess the combined effect of climate change (temperature and precipitation), acidification and eutrophication (in terms of sulphur and nitrogen deposition) on biomass growth and so also on carbon sequestration of forests, using an empirical model with measured basal area increment at tree level as responding factor. The model was applied by using data from the European intensive monitoring program (Level II plots). Increment data as well as data related to tree competition and soil data were available on all plots. The meteorological data and deposition data were recorded only at a part of plots.

In performing the multi-factor analyses, we tested the following hypotheses:

1. Individual tree growth can be modelled on a European scale as depending on site factors and competition.
2. Individual tree growth responds to changing climatic factors like precipitation and temperature.
3. Individual tree increment also responds to nitrogen and sulphur deposition.

The way how we tested these hypotheses was to develop an individual tree growth model for basal area increment, depending on tree size (dbh), tree competition (stand density index, basal area of larger trees), and site factors like elevation, latitude, soil pH, and others. We added climate and deposition variables, which are assumed to describe environmental change and see if they contribute significantly to the model. If they do, their coefficients will describe the response of growth on these environmental change variables, for given site factors, tree size and competition. Because basal area increment is highly correlated with biomass growth we used as a base concept Wykoff's (1990) basal area increment model. Having multilevel data, some on plot and others on tree level we had to upgrade this multiple regression model to a multilevel-mixed model. Mixed models have also been applied to this kind of data for example by Lappi and Bailey (1988), Hökkä et al. (1997), or Uzoh and Oliver (2006).

## 2. Materials

### 2.1. Locations and plot selection

Overall we had data of 97,773 individual trees (77 tree species) in 654 plots from 20 European countries available. All plots are located in subjectively selected stands by each country, in order to represent typical forest types and growing conditions. The plots are typically designed as a 0.25 ha homogenous and rectangular area (Haußmann and Lorenz, 2004). For nearly two thirds of all trees the diameter at breast height (dbh) at the beginning and the end of the investigation period, mainly 1995–2000, were measured.

In a first step we had to exclude some plots and trees due to different reasons: fertilization, obviously errors in measurement, missing plot size or missing other necessary data (compare to Solberg et al., 2009). Secondly we had to define criteria for tree species and plot selection to be able to get reliable models. At least 50 plots per species were needed, because we had stand and site variables per plot, and there should be (i) enough degrees of freedom left for the error term, and (ii) confounding of effects with locations should be avoided. For reliable results it is necessary to use only really measured increment data, and in some plots there were only a few trees where the dbh has been measured twice. Thus, we defined the following criteria:

- The investigated species must have at least 20 measured individuals per plot.
- The basal area of the species must be higher than 10% of the total plot's basal area.
- Although, due to inaccuracies in measurements negative increments could occur, we only used trees with positive increments.

The result was the selection of four tree species, Norway spruce (*Picea abies*), Scots pine (*Pinus sylvestris*), common beech (*Fagus sylvatica*), and oak (*Quercus robur* and *Quercus petraea*) in 382 plots in 18 countries for the growth model (Fig. 1). In most of the plots only a few tree heights were measured and because of that we decided not to use tree height and volume in our model. Instead we used 5-year basal area increment per tree (BAI) as the growth variable. Mean values for the BAI were 46.7 cm<sup>2</sup>, 57.8 cm<sup>2</sup>, 81.4 cm<sup>2</sup>, and 85.4 cm<sup>2</sup> for Scots pine, Norway spruce, common beech and oak, respectively. Information on the environmental variables is described later (Section 2.2).

In Fig. 1 it can be seen that Scots pine and Norway spruce grow from France to the north of Norway. Both broadleaves, oak and common beech were located mainly in central Europe up to the latitude of 57° in the UK and in Denmark. A few plots of common beech can be found in the south of Italy.

In total 382 plots were selected: 152, 101, 87 and 61 plots for Norway spruce, Scots pine, common beech and oak, respectively. In some plots more than one selected species fulfilled all criteria and therefore the sum of the respective plots is 401 and thus larger than the total number of plots used. This numbers differs slightly from the selection results of Solberg et al. (2009) mainly caused by the use of different selection criteria, which were adapted to the respective research question. The much smaller number of plots for Scots pine in our study results from not using Solberg et al. (2009) automatic routine for assigning observations to arbitrary tree numbers of some Poland plots. Because of developing an individual tree model rather than a stand model we needed the exact assignment of trees from the first to the second measurement year for accurate information of increment of every single tree of a plot.

### 2.2. Data assessment and selection of predictor variables

#### 2.2.1. Predictor variables

The various predictor variables used in explaining the 5-year basal area increment per tree (forest growth) are tree characteristics, stand and site characteristics, meteorological characteristics and atmospheric deposition of major nutrients from the atmosphere, as summarized in Table 1. Table 1 is based on both the relevance of predictors and the availability of data. In all cases, use was made of the data that were available in the Intensive Monitoring database from the EU Forest Focus and UN/ECE ICP Forests Programmes. Since temperature data were not recorded on

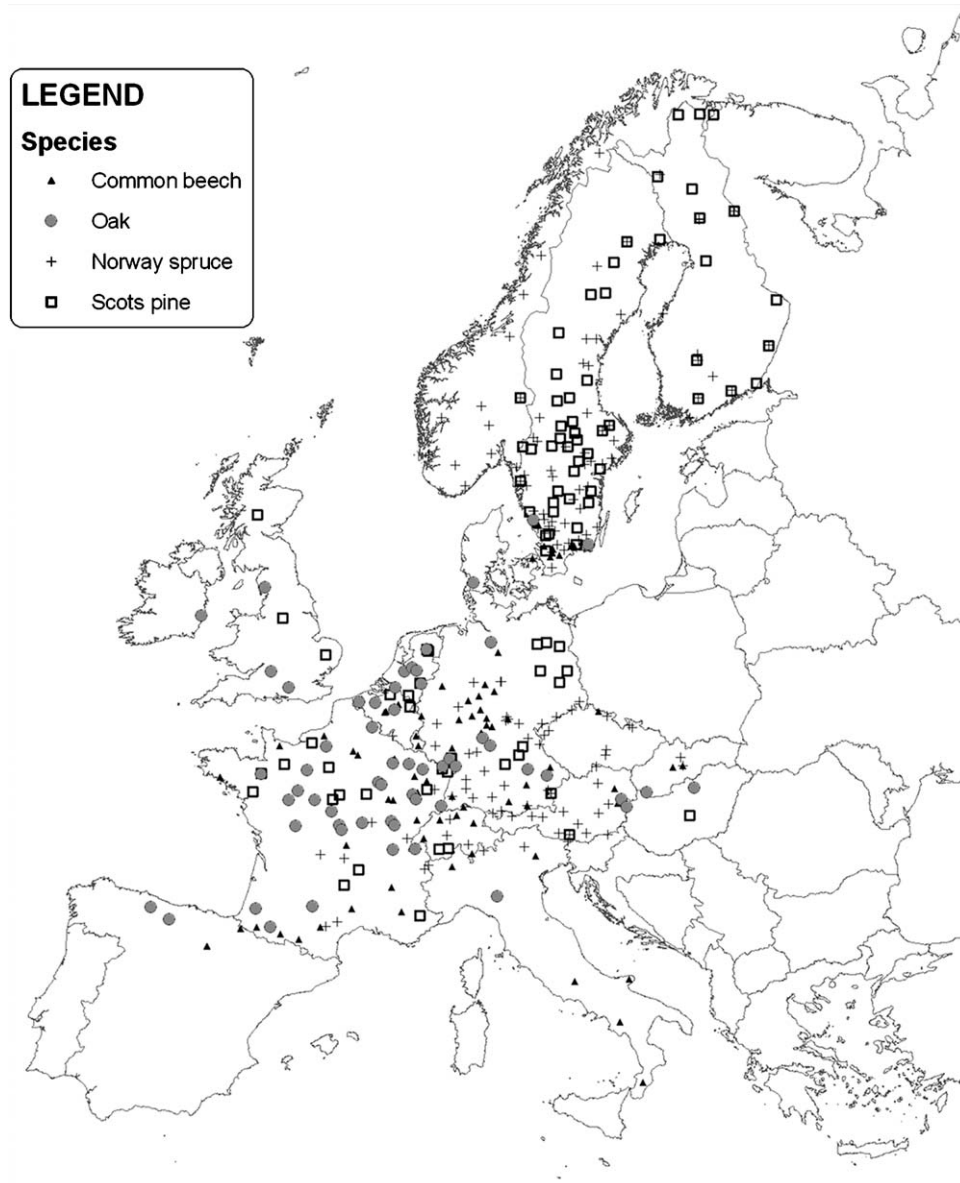


Fig. 1. Distribution of the selected plots by species.

all plots we derived it by interpolating data from nearby meteorological stations. The analyses were performed on plots where all information, mentioned in Table 1, was available, either directly measured or derived from external databases, as described below.

### 2.2.2. Tree characteristics

Since just a few tree height measurements were available we include only tree diameter at breast height (dbh) to describe tree size. We transformed the dbh logarithmically and added the squared dbh as an additional independent variable, which effectively serves to prevent unlimited growth for large diameter trees according to natural conditions. Furthermore, we were not able to include crown ratio (ratio between crown length and tree height), as it is contained in the models of Wykoff (1990) and of Monserud and Sterba (1996) as it was only available in very few plots.

### 2.2.3. Competition variables

As competition variables we included one tree competition parameter, basal area of larger trees per hectare (BAL), and one

stand competition parameter, stand density index (SDI) (Reineke, 1933). Basal area of larger trees per hectare (BAL) is a competition parameter which we expected to be negatively correlated with growth. The less competition a tree experiences (BAL is low), the higher its increment is expected to be.

According to Reineke (1933) SDI is defined as:

$$SDI = N \cdot \left( \frac{25}{dg} \right)^{-1.605} \quad (1)$$

where  $N$  is the number of trees per hectare and  $dg$  is the quadratic mean diameter at breast height. As for BAL on individual tree level, individual tree growth is expected to decrease with increasing tree density at stand level.

In Table 2, the variation in the used tree competition variables, SDI and BAL at the time of the first measurement, are listed. Results show that oak and Scots pine stands have lower stand densities (lower SDI values) than the Norway spruce and common beech stands. The basal area of larger trees per hectare (BAL) is also much higher for Norway spruce and common beech than for the oak and

**Table 1**  
Predictor variables used in the statistical analysis of individual tree growth.

Predictor variables	Description
<b>Tree characteristics</b>	
Diameter in breast height (dbh)	Continuous; in cm
Basal area of larger trees (BAL)	Calculated for every tree per plot; m <sup>2</sup> ha <sup>-1</sup>
<b>Stand and site characteristics</b>	
Latitude	Continuous; decimal degrees
Longitude	Continuous; decimal degrees
Altitude	Continuous; based on discrete intervals in meter
Orientation	Eight directions (1–8) plus “9” for plane surface
Number of trees per hectare	Counted data
Stand density index (SDI)	Calculated from number of trees/ha and dbh
Available water capacity	Continuous, values for the upper 50 cm; mm
pH (CaCl <sub>2</sub> )	Values of the mineral topsoil (0–20 cm) and organic layer
Base saturation	Values of the mineral topsoil (0–20 cm) and organic layer; percent
C and N content (C/N ratio)	Values of the humus layer and mineral topsoil (0–20 cm)
<b>Climatic variables/water availability</b>	
Temperature, <i>T</i>	Annual average, average in the growing season <sup>a</sup> ; °C
Precipitation, <i>P</i>	Annual total, total in the growing season; mm
Potential evapotranspiration (PET)	Annual total, total in the growing season; mm
Actual evapotranspiration (AET)	Annual total, total in the growing season; mm
<b>Deposition data/forest nutrition</b>	
Deposition of NO <sub>x</sub> , NH <sub>3</sub> , SO <sub>x</sub> , Ca, Mg, K, Na, Cl	Annual total: kg/ha/yr

<sup>a</sup> June, July, August and every month with a mean temperature >10 °C.

Scots pine stands. This implies that the tree competition is strongest in Norway spruce and common beech stands.

#### 2.2.4. Site characteristics

Apart from position parameters like latitude, longitude, altitude and orientation all relevant site variables influencing water and nutrient availability and soil acidity status and thereby forest growth, have been recorded at all plots (see Table 1). The C/N ratio is used as an indicator of N availability (high C/N is low availability) in connection with N deposition. Soil acidity (pH–CaCl<sub>2</sub>) is expected to have a negative effect on forest growth, due to

decreased nutrient availability at a lower pH and possibly root damage by dissolved aluminium and heavy metals. A comparable effect is expected for the base saturation. An increase in base saturation reduces aluminium concentrations and increases pH. For all soil properties, data are available for the humus (organic) layer and mineral topsoil (0–20 cm).

#### 2.2.5. Climatic variables/water availability

Meteorological variables affecting forest growth are temperature (*T*) and precipitation (*P*), which both determine the potential evapotranspiration (PET) and actual evapotranspiration (AET). Increasing temperature leads to an increase in growth by lengthening of the growing season and an increase in the rate of photosynthesis during the growing season. For precipitation two kinds of effects can be expected: a positive effect may be expected on water limited sites. At very high precipitation sites, larger amounts of precipitation may cause a decreased nutrient availability by increased nutrient leaching, thus causing a negative effect on forest growth. On poorly drained soils high precipitation may lead to oxygen deficiency in the roots and thus again to a decrease in growth. Apart from the *T*, *P*, PET and AET during the 5-year period for which the increment data are available (1995–2000), two extra years in view of lag time in effects were included (1993–2000). Information on the previous 30-year average values (1961–1990) is used to gain insight in the deviation from a long-term average. The hypothesis behind it is that the larger the deviation from the long-term average, the larger the impact on growth. By using the difference between temperature of the investigation period and the long-term temperature a relative temperature-change variable was computed which is independent of the geographical location or altitude of the plots. Hence, the influence of temperature change on increment can be detected more precisely.

Temperature has been only measured at some plots. The temperature data thus derived correlated very well with interpolated temperature data in an available meteorological dataset (De Vries et al., 2003). This dataset includes data at a 10 × 10 km<sup>2</sup> grid for temperature, precipitation, cloudiness, wind, etc. at a monthly interval for the period 1900–2000 (Climatic Research Unit (CRU) database). These derived data were thus used in our study.

For precipitation in the period 1993–2000, use was made of the results of bulk deposition monitoring for that period. Apart from the present values in the period 1993–2000, we calculated a 30-year long-term average value for the period, 1961–1990, which gives an impression of the average meteorological circumstances. For the long-term mean, use was made of precipitation data in the 10 × 10 km<sup>2</sup> dataset.

**Table 2**  
Variation of used tree competition variables at the time of first measurement per tree species. SDI is stand density index (Reineke, 1933, Eq. (1)), BAL is basal area of larger trees [m<sup>2</sup> ha<sup>-1</sup>] (Wykoff, 1990).

Tree species	N (plots/trees)	Minimum	Lower quartile	Median	Upper quartile	Maximum
Norway spruce	152/17608					
SDI		151	413	499	625	1593
BAL		0.0	13.8	23.3	34.6	123.9
Scots pine	101/11110					
SDI		118	271	373	504	1299
BAL		0.0	7.9	13.9	23.4	96.3
Common beech	87/7730					
SDI		142	378	446	601	1593
BAL		0.0	13.3	22.5	30.3	123.9
Oak	61/3972					
SDI		135	287	366	417	1040
BAL		0.0	7.0	12.3	18.0	69.7

Potential evapotranspiration (PET) and actual evapotranspiration (AET) were derived from data in the  $10 \times 10$  km grid from monthly temperature, precipitation, cloudiness, wind speed etc (CRU dataset), using the WATBAL (Starr, 1999) model. In this model PET is calculated from the estimated global radiation and based on the relationship between air temperature and the ratio between evaporation and global radiation. The equation used is that by Jensen and Haise (1963); the so-called Alfalfa reference method, and is a further simplification of the Priestly-Taylor equation. It actually calculates the evaporative heat flux density (Ep in WATBAL), which is then converted into mm of PET using the latent heat of vaporization (LH\_Vap in WATBAL). Ep is calculated for the “representative day of the month” (the Julian day in the climate input file) and then multiplied up to monthly values using the number of days in each month. Ep is calculated from global radiation and air temperature, using coefficients found by Jensen and Haise (1963) based on an extensive set of measurements made in the western US on well watered alfalfa fields. A crop factor is used to convert this Ep to an Ep for forests. AET is computed by comparing water supply and -demand, taking into account water available in the soil profile. Both AET and PET were used as 30 year long-term and short time (1993–2000) parameter.

### 2.2.6. Deposition and forest nutrition

Deposition data included total deposition of  $\text{NH}_3$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ , Ca, Mg, K, Na and Cl for the years 1993–2000, with total deposition computed from measured bulk deposition and throughfall at about 300 plots, using a canopy exchange approach described in De Vries et al. (2000). Since use of these total deposition data leads to a serious reduction in the number of plots, additional analysis was carried out using calculated total N deposition by EMEP for all the 382 plots where we have growth data. For comparison we calculated both, the growth model with measured deposition and the growth model with deposition from EMEP data. For this analysis we used only those plots where both datasets were available.

We checked whether there are different results when using modelled EMEP data and measured data for those plots. Since we had the largest number of plots for Norway spruce (152 EMEP and 111 measured) we compared the two datasets for this species first. Starting from this result we used the respective environmental data to find the best models for all species. However, having the best model for a species with EMEP data of all plots, we calculated

the same model with those plots only, where measured data were available and checked for differences of the two datasets (EMEP, measured data) for the given model.

An increase in nitrogen availability is expected to increase forest growth, especially at sites where nitrogen is limiting forest growth. Parameters that give information on the availability are the atmospheric inputs of main nutrients (N, Ca, Mg and K). Apart from this, soil acidification due to excess input of S and N over base cations may have a negative impact on forest growth. We used  $\text{SO}_x$ , Ndep (computed as the deposition of  $\text{NO}_x$  and  $\text{NH}_3$ ) and NetAciddep (computed as the deposition of  $\text{SO}_x + \text{N} - \text{Ca} - \text{Mg} - \text{K} - \text{Na} + \text{Cl}$ ), as deposition variables.

In Table 3 we give an overview of the variation of the finally used site factors and influencing environmental variables on forest growth. Owing to the geographical distribution up to Scandinavia (see Fig. 1), the temperature on plots of both conifers was below that of beech and oak. In a few plots the annual average temperature during the investigation period was even below zero. The higher values of deposition on the broadleaves plots, especially on oak plots, in comparison to the plots of conifers reflect the current deposition patterns caused by emissions from industry, traffic and agriculture, being highest in Central Europe.

### 2.3. Validation, correction and supplementation of data

To parameterize the model we used only measured increment data. The dependent variable, basal area increment was the result of two dbh measurements, one at the beginning and one at the end of the investigation period. The competition measures were those at the beginning of the investigation period, not already containing the resulting increment.

Unfortunately several trees seemed to have been measured only once, some at the end and others only at the beginning of the investigation period. Supposing that this was a numbering error, we tried to find out which tree at the second measurement could have been which tree at the first measurement. For every species and every plot separately, we calculated the theoretical first dbh of trees with only a second dbh, by subtracting the mean diameter increment from the second dbh. We set limits of  $\pm 0.5$  cm of the theoretical first dbh and sought for a tree which was only measured the first time with a dbh within this range. The final assignment of all fitting trees was done manually. The limits of  $\pm 0.5$  cm were chosen to

**Table 3**

Variation of all site factors and influencing environmental factors (climate and deposition) per tree species used in the final growth models (Eq. (6)). Temp\_9300\_YrMean is average annual temperature between 1993 and 2000 [ $^{\circ}\text{C}$ ], CNRat\_020 is C/N ratio in the upper 20 cm of soil, Ndep\_9300\_emep is average yearly deposition of nitrogen from EMEP between 1993 and 2000 [kg/ha/yr].

Tree species	N (plots/trees)	Minimum	Lower quartile	Median	Upper quartile	Maximum
Norway spruce	152/17608					
Temp_9300_YrMean		-1.8	3.9	6.2	7.5	10.3
CNRat_020		10.4	16.8	20.0	24.5	42.7
Ndep_9300_emep		1.5	6.9	16.5	24.0	33.8
Scots pine	101/11110					
Temp_9300_YrMean		-1.9	2.3	6.1	9.7	12.3
CNRat_020		9.1	17.9	21.0	25.9	36.3
Ndep_9300_emep		1.1	3.8	12.1	21.8	60.1
Common beech	87/7730					
Temp_9300_YrMean		4.6	7.2	8.5	9.4	14.3
CNRat_020		10.2	14.3	17.4	22.2	35.0
Ndep_9300_emep		11.1	18.7	23.1	27.9	60.0
Oak	61/3972					
Temp_9300_YrMean		6.7	9.0	10.4	11.7	14.9
CNRat_020		8.5	14.7	18.5	20.6	39.6
Ndep_9300_emep		12.7	17.4	22.5	32.7	60.0

avoid a negative increment of a tree because the lowest mean of diameter increment was 0.6 cm. Trees for which no matching diameters were found were not used in the final parameter estimation procedure.

Nevertheless, in order to describe the competition at the beginning of the investigation period correctly, we needed to calculate the first dbh of the remaining trees, when only the dbh of the second measurement was recorded. We thus derived a dbh-increment regression function based on the trees with two measurements with the dbh increment as the dependent variable and the dbh of the second measurement as independent variable. For trees which had only dbh-measurements at the second observation we inserted that dbh in the regression function, calculated the respective increment and then derived the first dbh by subtracting the increment from the second dbh. If for a species and the given diameter only a small growth could be expected, we set the first dbh to the second dbh. If there were not sufficient trees of a species in the plot with two dbh-measurements, we used similar species in the plot. We excluded trees with a dbh < 5 cm at the first observation, to avoid the problem of calculating a non-existing first dbh of an ingrown tree. All calculations were made plot and species specific.

### 3. Methods

#### 3.1. The growth model

Since Kopecky (1899) the relationship between volume increment and basal area increment is well documented. Owing to many missing height data we first checked whether this relationship holds for our data too, in order to use basal area increment as response variable for the individual tree growth model. We plotted volume increment of those trees, where dbh and height measurements were available for both observations over basal area increment (Fig. 2). The  $R^2$  of the linear regressions for the two conifers and oak were about 0.7 and for beech just 0.5. The dispersion was mainly reasoned by the methodical inaccuracy of height measurement. For example, Fig. 2 shows the correlation

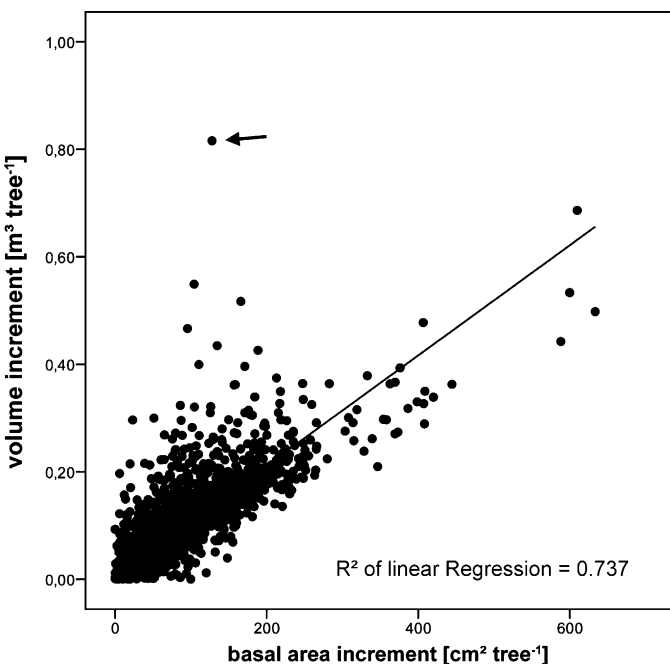


Fig. 2. Correlation between basal area increment per tree and volume increment per tree of Scots pine calculated for such trees only, where dbh and height were measured twice, at the beginning and the end of the investigation period.

for Scots pine. The arrow-marked outlier had two plausible dbh values but an unbelievable average height increment of 1.625 m per year. In general breast height diameter is a more reliable measurement than tree height, which is an additional reason to use basal area increment instead of volume increment in the analyses. Despite the uncertain tree height values (causing an  $R^2 = 0.737$ ), the intercept of the respective regression is near zero (0.006), showing that volume increment is approximately proportional to basal area increment. This implies that percental changes in basal area increment in response to influencing parameters can be related to percental changes in volume increment. Admitting that carbon sequestration per stem volume growth varies considerably depending on growing conditions and stand treatment, for a rough conversion of volume growth to carbon sequestration we refer to Liski et al. (2002), who assume a constant percentage of carbon for a study on European scale.

To parameterize the model we only used trees, where breast height diameters have been measured in both the first and second measurement year. As concept we used the model idea of Wykoff (1990) as it is written in Monserud and Sterba (1996):

$$\ln \text{BAI} = a + \mathbf{b}^T \cdot \text{SIZE} + \mathbf{c}^T \cdot \text{COMP} + \mathbf{d}^T \cdot \text{SITE} + e \quad (2)$$

where BAI is the 5-year basal area increment per tree, SIZE a vector of variables describing tree size, i.e. the natural logarithm of the dbh and dbh<sup>2</sup>, COMP a vector describing tree competition, i.e. basal area of larger trees per hectare (BAL), number of trees per hectare and stand density index (SDI), and SITE a vector of different site descriptors, i.e. available water capacity, pH (CaCl<sub>2</sub>), base saturation and C/N ratio, latitude, longitude, altitude, orientation, a the intercept, **b**, **c** and **d** are the vectors of the respective coefficients and *e* are the residuals. To take into account the hierarchical structure of our data (stand/site variables on plot level, size and competition variables on tree level) we used a mixed model approach with “plot” as the random effect. Hence, we extended Wykoff’s (1990) model to a multilevel-mixed model, as it was used with similar structured data for example by Lappi and Bailey (1988) and Hökkä et al. (1997). Further we added a site change (SITEC) vector and its coefficients *f* for describing environmental change in our model, including climatic variables (temperature, precipitation, potential evapotranspiration and actual evapotranspiration) and atmospheric deposition (SO<sub>x</sub>, N and acidity) and their interactions with size- and competition variables. Thus, the final mixed model is:

$$\ln \text{BAI} = a + \mathbf{b}^T \cdot \text{SIZE} + \mathbf{c}^T \cdot \text{COMP} + \mathbf{d}^T \cdot \text{SITE} + \mathbf{f}^T \cdot \text{SITEC} + u + e \quad (3)$$

with **b**, the vector of the coefficients for the size-variables, **c**, the vector of coefficients for the competition-variables, **d** the vector of coefficients for the site-variables, and **f** the vector of coefficients of the environmental change variables; *u* and *e* are the random effects of the plots and the trees, respectively.

#### 3.2. Parameter estimation

For estimating the coefficients in the vectors **b**, **c**, **d** and **f** of Eq. (3) we at first used multiple regression analysis with ln(BAI) as dependent variable. Starting with the size and competition parameters as independent variables we added and again deleted the SITE and SITEC parameters in order to finally have only parameters in the model, which behaved biologically reasonable and exhibited significant ( $p \leq 0.05$ ) coefficients and variance inflation factors (VIF) < 10, indicating tolerable collinearity between the independent variables (Montgomery and Peck, 1992). Then we used the restricted maximum likelihood (REML)

method produced by the MIXED procedure in SPSS 12.0 with the plots as random effects. Since this procedure is not a least square method, the goodness of fit criterion is the  $-2 \log$  likelihood ( $-2LL$ ). In this procedure we started with those independent variables, which were in the final model of the multiple regression analysis and among them again deleted and added those which finally exhibited significant ( $p \leq 0.05$ ) coefficients, while collinearity was already tested in the multiple regression analysis. Due to the hierarchic structure of the data (tree within plots), these estimates are the most appropriate ones. In order to get an idea of the impact of the random plot effect, we used the same procedure with the same variables to estimate the coefficients without a random plot effect, i.e. only with the fixed effects of the independent variables.

Finally, because the dependent variable in Eq. (3) is the natural logarithm of the basal area increment, the estimates of the basal area increment itself are biased (Bradu and Mundlak, 1970). In order to correct for this bias, the multiplier,  $\lambda$  according to Condes and Sterba (2005) was used.

$$\lambda = \frac{\sum \text{BAI}_{\text{observed}}}{\sum \text{BAI}_{\text{predicted}}} \quad (4)$$

### 3.3. Data selection—EMEP or measured environmental data

We started with the model for Norway spruce to check whether there are differences between environmental data based on EMEP and measured data. We started with the largest dataset (EMEP data) and finished with following equation for Norway spruce:

$$\ln \text{BAI} = a + b_1 \cdot \ln_{\text{dbh}} + c_1 \cdot \text{BALrel} + c_2 \cdot \text{SDI} + d_1 \cdot \text{CNRat}_{020} + f_1 \cdot \text{Ndep}_{9300} \quad (5)$$

The descriptions of the variables are given in Tables 2 and 3. We calculated three models for comparison: (I) with measured deposition data on plots where measured deposition data were available; (II) with EMEP data on plots where measured deposition data were available and (III) with EMEP data on all plots (larger data set, see Table 4).

All parameters were significant in all three models. The coefficients of the variables exhibited the same order of magnitude in all three models too. The quality of the models I and II with less plots and trees was equal and better than the quality of model III (see AIC-Akaike Information criteria, Table 4). Owing to the similarity of models I and II and in order to have more plots, we decided to take the EMEP data and finished with the model III for Norway spruce. For the other species, we also used EMEP data only. Thus, we were able to use a larger dataset, because we were not restricted to only those plots where deposition data were measured.

## 4. Results

### 4.1. The model

The following variables were influential on basal area increment (Eq. (3)): In the vector SIZE, it was only the logarithm of the

dbh and  $\text{dbh}^2$ . Regarding tree competition, both Reineke's (1933) stand density index (SDI) and the relative basal area of larger trees (BALrel), i.e. the ratio between the basal area of larger trees and the total basal area of a plot, appeared to be influential. As site parameter the C/N ratio in the upper 20 cm of the soil (CNRat\_020), and the yearly mean temperature in the investigation period (Temp\_9300\_YrMean) showed an influence on growth.

To describe environmental change (SITEC vector) we added the differences in temperature between the long time measurements of the time span 1961–1990 and the investigation period 1993–2000 (Temp\_change). It was computed as Temp\_9300 – Temp\_6190. The deposition of  $\text{SO}_x$  and Ndep in the investigation time is also part of the SITEC vector. To get more insights into the influence of nitrogen or sulphur deposition on growth we computed interactions of all factors with nitrogen or sulphur deposition. Only for Scots pine an interesting interaction between nitrogen deposition and competition became significant: Ndep·BALrel, which is the product of Ndep and BALrel. Finally, based on Eq. (3) we developed the general model Eq. (6) with all these variables.

$$\ln \text{BAI} = a + b_1 \cdot \ln_{\text{dbh}} + b_2 \cdot \text{dbh}^2 + c_1 \cdot \text{BALrel} + c_2 \cdot \text{SDI} + d_1 \cdot \text{CNRat}_{020} + d_2 \cdot \text{Temp}_{9300\_YrMean} + f_1 \cdot \text{Temp\_change} + f_2 \cdot \text{Ndep}_{9300} + f_3 \cdot \text{Ndep\_BALrel} \quad (6)$$

We parameterized four different models, one for each species, with different selections of parameters, depending on which of them proved to contribute significantly ( $p \leq 0.05$ ) to the model and having a VIF < 10. When there is no coefficient recorded, the respective variable was not significant and thus not used in the respective model (see Table 5).

All the mentioned coefficients were significant at the 5% level in the mixed model approach, except  $f_2$  for beech. However this coefficient was nearly significant ( $p = 0.077$ ). Only two out of ten variables ( $\ln_{\text{dbh}}$ , BALrel) showed significant influence on growth in all models.

Although the C/N ratio of the humus layer is a better predictor for N availability than the C/N ratio of the mineral topsoil, only the latter one was significant in the model for Norway spruce. The temperature in the investigation period was significant for Scots pine and oak. While Ndep deposition was significantly influential in the models of Norway spruce, Scots pine and oak as well as nearly significant in the common beech model,  $\text{SO}_x$  deposition was not significant for any species. As a climate change parameter the difference between long-term temperature and the temperature in the investigation period showed a significant effect on growth of common beech. For Scots pine the model exhibited a significant interaction between competition and deposition (Ndep·BALrel = Ndep·BALrel).

### 4.2. Model validation

In absence of an independent data set, the validity of a model is usually described by different goodness of fit statistics and calculations, testing the reasonability of the model behaviour. In our case we used the Akaike Information Criterion (AIC), which is

**Table 4**

Comparison of EMEP and measured data—results of mixed models: AIC is the Akaike information criterion, N-trees is the number of trees, N-plots, the number of plots, and  $a$  to  $f$  estimated coefficients of the model.

Models	AIC	N (trees)	N (plots)	$a$	$b_1$	$c_1$	$c_2$	$d_1$	$f_1$
I	24245	13620	111	−0.873	1.737	−0.498	−0.00066	−0.0212	0.0141
II	24245	13620	111	−0.950	1.734	−0.502	−0.00068	−0.0198	0.0174
III	30693	17608	152	−0.875	1.720	−0.494	−0.00056	−0.0227	0.0126

**Table 5**The estimated coefficients for the influencing factors that appeared to be significant ( $p \leq 0.05$ ) in the models.

Species	$a$	$b_1$	$b_2$	$c_1$	$c_2$	$d_1$	$d_2$
Norway spruce	-0.87521	1.72013	-	-0.49441	-0.00056	-0.02274	-
Scots pine	-1.17577 <sup>a</sup>	1.30008	-0.00031	-0.34301	-0.00066	-	0.05208
Common beech	-3.82025	2.35728	-0.00012	-0.18252	-	-	-
Oak	-2.77615	1.98750	-0.00024	-0.48240	-0.00062	-	0.07681
Species	$f_1$	$f_2$	$f_3$				
Norway spruce	-	0.01256	-				
Scots pine	-	0.01480	-0.00836				
Common beech	0.06184	0.01197 <sup>b</sup>	-				
Oak	-	0.01332	-				

<sup>a</sup> This intercept is not significant  $p = 0.380$ .<sup>b</sup> This coefficient is nearly significant at  $p = 0.05$  ( $p = 0.077$ ).

recommended for mixed models (Demidenko, 2004), and additionally the usual  $R^2$  of the linear multiple regression and McFadden's (1979) Pseudo- $R^2$ , which is calculated from the log-likelihood criterion, which results from the maximum likelihood parameter estimation procedure (see Section 3.2).

$$\text{Pseudo-}R^2 = 1 - \left( \frac{\log L_{MA}}{\log L_{Mo}} \right) \quad (7)$$

where  $\log L$  is the  $-2 \log$  likelihood, once for the model with the significant independent variables (MA) and once without any independent variable, i.e. assuming the dependent variable being sufficiently described by its mean (Mo). For comparison of our models the  $R^2$  of the multiple regression, the Pseudo- $R^2$  of the model calculated with the mixed procedure with no random effects, and the Pseudo- $R^2$  of the final mixed model with random and fixed effects are shown in Table 6.

The McFadden's (1979) Pseudo- $R^2$  is in general smaller than the  $R^2$  of a multiple regression. Values between 0.2 and 0.4 already represent good fit (McFadden, 1979). To get an idea of the real meaning of the Pseudo- $R^2$  it is possible to compare the  $R^2$  of the multiple regression and the Pseudo- $R^2$  of the mixed model with fixed effects. Through all species models, adding the random plot variable led to an increase in Pseudo- $R^2$  which supports the use of the mixed model approach.

Although the derived models are individual tree models, it is important to see how well the average growth per plot may be predicted. This is done in Fig. 3, where the observed means of basal area increment per plot are plotted against the predictions for the four selected tree species. All models show very good predictions.

## 5. Discussion

### 5.1. Model quality

Overall, our models showed good quality. The  $R^2$  values of our models (Table 6) were quite similar in magnitude with comparable BAI-models of Monserud and Sterba (1996) for Austrian forests, Andreassen and Tomter (2003) for Norwegian forests, as well as

**Table 6**Quality of the models. AIC – Akaike Information criterion;  $R^2$  – from multiple regression; Mf – mixed model with only fixed effects; Mm – mixed model with random and fixed effects;  $\lambda$  – bias correction.

Species	AIC	$R^2$	Pseudo- $R^2_{Mf}$	Pseudo- $R^2_{Mm}$	$\lambda$
Norway spruce	30693.90	0.579	0.262	0.368	1.136
Scots pine	20972.85	0.369	0.173	0.333	1.150
Common beech	14612.36	0.700	0.338	0.422	1.114
Oak	6430.40	0.678	0.382	0.424	1.096

those of Wykoff (personal communication, 1994, cited in Monserud and Sterba, 1996) for forests in the northern Rocky Mountains. Compared with Monserud and Sterba (1996) even the ranking of the  $R^2$  between the species was the same, highest in common beech and lowest in Scots pine.

Monserud and Sterba (1996) worked with eight species and resulted in  $R^2$  ranges of 0.33–0.63. The  $R^2$  of the models of Andreassen and Tomter (2003) ranges from 0.26 to 0.55 and the  $R^2$  for Norway spruce and for Scots pine were 0.55 and 0.48, respectively. Although Wykoff (1990) worked with different species and in a quite different region the comparison is important due to the similarity of methods. The  $R^2$  of his models ranged from 0.44 to 0.69 for 11 species. Although the goodness of fit of the common beech model was quite good (Pseudo- $R^2_{Mm} = 0.422$ ), the predictions against the observed data showed the highest variance (Fig. 3c). This reflects high variance in the dataset. The model for Scots pine is the opposite example. Despite the Scots pine model was the most complex one, with seven variables included in the equation (Table 5), the smallest part of the variance could be explained by the model. Nevertheless, it showed the best prediction, having small variance in the dataset. The addition of the random plot variable to the models showed a smaller increase of goodness of fit of the two broadleaves which is maybe due to their narrower geographical distribution.

### 5.2. Impacts of stand and site characteristics and climate

The structure of all four models was considerably different. Only two out of ten variables (ln\_d, BALrel) influence growth significantly over all tree species. These two variables and Ndep which was significant in three models and nearly significant for common beech were most influential for increment of the investigated tree species in Europe. For site and competition factors this is similar to findings of Monserud and Sterba (1996). The positive coefficient  $b_1$  for the logarithmic dbh and the negative coefficient  $b_2$  for  $\text{dbh}^2$  reflect an increasing basal area of increment per tree (BAI) with increasing age in young trees and a decrease in BAI with further increasing dbh (age) after a species specific culmination point. This is an expected behaviour of most growth models (Assmann, 1970). An increase in competition led to a decrease in increment which can be seen by the negative sign of BALrel and SDI in Table 5, which seems to be logic and is also well known from silvicultural experience (Assmann, 1970).

Among the soil factors only the C/N ratio in the model of Norway spruce showed a significant effect on growth. The lower the C/N-ratio, the higher the nutrient status of the soil and this led to a significantly better growth of Norway spruce. The positive effect of the temperature increase in the investigation period (1993–2000), as compared to the long-term period (1961–1990),

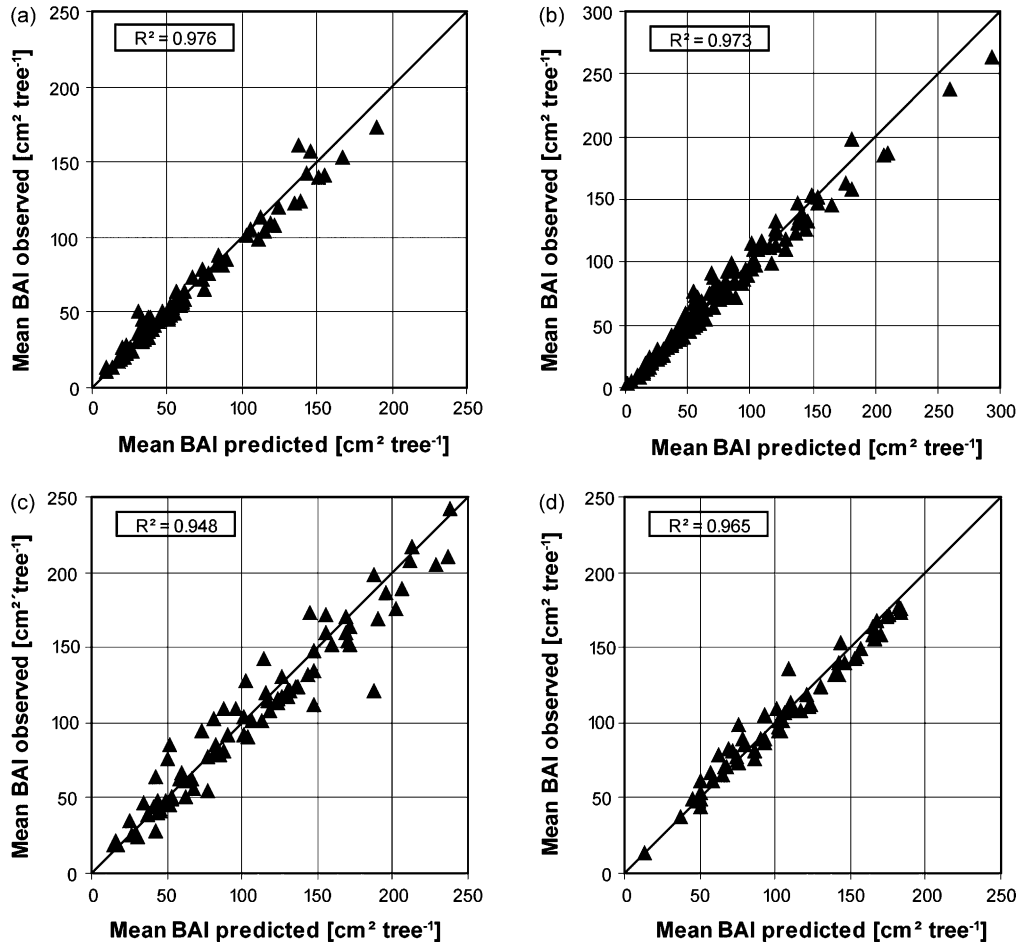


Fig. 3. Mean basal area increment of all sample trees on a plot, observed vs. bias-corrected predictions: (a) Scots pine; (b) Norway spruce; (c) common beech; (d) oak.

on growth as a direct variable of climate change was only significant for common beech. No other computed direct variable of climate change between these two periods (e.g. precipitation change) was significant in any model. However for Scots pine and oak, at least the mean annual temperature of the investigation period showed a significant and positive influence on the basal area increment. Surprisingly for Norway spruce we could not detect any influence of the climate variables. Reasons could be (i) that many of the plots used for the spruce model are located in lower altitudes (around 550 m), where temperature is not a growth limiting factor and (ii) that the influence of temperature on growth is already explained by the significant variable C/N ratio which is naturally influenced by temperature. The drought stress as it is defined by Solberg et al. (2009), showed no significant effect in any model.

### 5.3. Impact of nitrogen deposition

The positive influence of N deposition on growth for all four species is a key finding in this study and is in line with previous model studies (Rehfuss et al., 1999; Milne and van Oijen, 2005) and experimental studies (Kahle et al., 2005; Kahle et al., 2008). But investigations from Kennel and Wehrmann (1967) or Magnani et al. (2007) showed that there is an optimum input of nitrogen, after which increment decreases again. In order to test, if in the data an optimum of nitrogen deposition can be detected, the interaction between N in the soil and nitrogen deposition was introduced into our model but turned out to be not significant. In Fig. 4 all predictor variables except Ndep, were set to their mean, and basal area increment per tree was calculated with the models described in Table 5. An almost equal increase of growth with

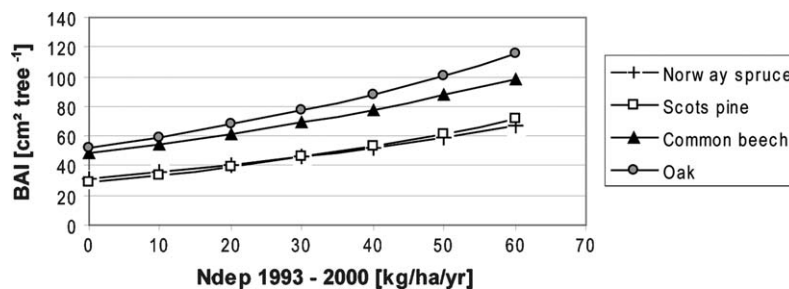


Fig. 4. Basal area increment per tree vs. average annual N deposition between the years 1993 and 2000, by species.

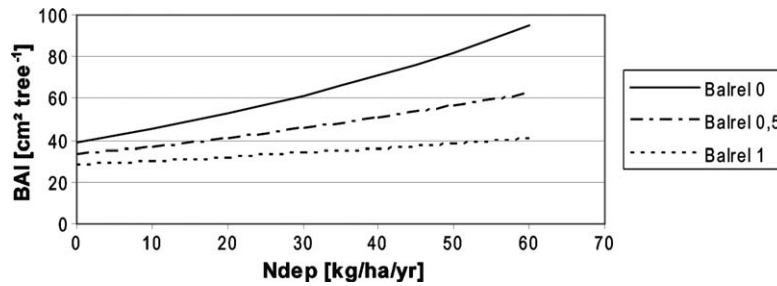


Fig. 5. Interaction between competition and deposition for Scots pine. BAI is the basal area increment per tree, Ndep is average annual N deposition between the years 1993 and 2000, Balrel is the ratio between the basal are of larger trees and the total basal area of a plot.

increasing nitrogen deposition could be seen for all four tree species.

From the coefficient  $f_2$  in our model (Eq. (6)), the relative increase in growth by 1 kg nitrogen deposition  $\text{yr}^{-1} \text{ha}^{-1}$  can be calculated from

$$\frac{\text{BAI}_{N+1}}{\text{BAI}_N} = \exp(f_2) \quad (7)$$

with  $\text{BAI}_N$ , basal area increment per tree with nitrogen deposition of N kg,  $\text{BAI}_{N+1}$ , basal area increment per tree with nitrogen deposition being 1 kg higher, and  $f_2$ , the coefficient of our model as given in Table 5.

An increase in growth of 1.26%, 1.49%, 1.20% and 1.34% for Norway spruce, Scots pine, common beech, and oak, respectively results for an increase in N deposition by 1 kg. Because volume increment is approximately proportional to basal area increment (Fig. 2), these percentages also hold for volume increment. Given a proportional relationship between the amount of carbon uptake and volume growth as roughly assumed for European forests by Liski et al. (2002), the relative carbon gain per kg N deposition follows the same percentages. Our values are quite similar to the result of Solberg et al. (2009), who found an equal increase of about 1% for the conifers.

Referring to the total carbon uptake for European forests, given with 1729 kg carbon per hectare and year in De Vries et al. (2006), the increase of carbon per kilogram nitrogen deposition can be estimated between 20.7 and 25.8 kg carbon per hectare and year, depending on tree species composition. This compares well with the 25 kg C per kg N deposition as calculated by Nadelhoffer et al. (1999) based on  $^{15}\text{N}$  labelled tracer experiments in nine temperate forests indicating an average N retention fraction in stem wood of 0.05 and an average C/N ratio in stem wood of 500. The value is somewhat below the 33 kg as found by De Vries et al. (2006), using a similar approach. It is also in line with results of simulations with three ecosystem models (Century, BGC and Hybrid), which estimated the average change in total carbon content of the ecosystem with the cumulative change in nitrogen deposition over 100 years at 20.1 kg C/kg N), with a standard deviation of 13.8 kg C/kg N (Levy et al., 2004). Similar results were also found in long-term (15–30 year) nitrogen-fertilizer trials in Sweden and Finland at rates of nitrogen addition below 50 kgN/ha/yr, indicating that this ratio seems rather robust (Högberg et al., 2006; Hyvönen et al., 2007b) Given the data, we could not prove a significant influence of  $\text{SO}_x$  on basal area increment during the investigation period.

Additionally, for Scots pine we were able to show a changing effect of deposition on BAI per tree depending on competition (Fig. 5). Trees with less competition (small BALrel) gain more from N deposition than highly competed trees. This unequal effect on growth will possibly lead to an increasing suppression of small trees in a given stand with increasing N deposition.

## 6. Conclusions

To develop an individual growth model based on data on the plot level (e.g. temperature, soil) as well as on the individual tree level (e.g. dbh) a mixed model approach is necessary to take these different levels into account. Although many different variables were available, only three factors namely dbh as size factor, the competition factor BALrel and the nitrogen deposition seemed to have crucial influence on the increment of all investigated tree species. Apart from these factors, the models differed notably in structure. Out of all site factors only one soil factor, the C/N ratio and yearly mean temperature in the investigation period were significant for different species. The C/N ratio was only influential in the model for Norway spruce. Mean annual temperature was positively related to the growth of oak and Scots pine. This positive relation of temperature with growth can be seen as an indirect sign of response to climate change. For common beech, the difference between the long-term yearly mean temperature and the yearly mean temperature in the investigation period was significant in the model. The basal area increment of Norway spruce showed no response to temperature.

With the model for Scots pine it was possible to show an interesting interaction between competition, nitrogen deposition and basal area increment. Heavily competed trees gain less from nitrogen deposition than trees which are less strongly competed. Thus, nitrogen deposition will increase the competition within Scots pine stands.

Referring to the verbalised hypotheses we conclude that a strong relationship between basal area growth on the one side and tree size and competition on the other side was found in all investigated tree species. The only environmental-change factor affecting growth of all species was nitrogen deposition, while the role of other site factors differed by species. Evidence of an adverse effect of  $\text{SO}_x$  deposition on growth could not be proved by these data, while a positive effect of increasing temperature on growth could be proved for all species except Norway spruce. Keeping all other influential factors constant, the increase in growth by one additional kg nitrogen deposition varied between 1.2% and 1.5% depending on tree species, corresponding to a range of approximately 20–25 kg carbon sequestration per kg N deposition.

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