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Growth trends and relationships with environmental factors for scots pine [*Pinus sylvestris* (L.)] in Brandemburg

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Abstract

Scots pine growth trends have been determined in Brandenburg (eastern Germany) since the early 1960s. We investigated the interactions between recognized causal factors such temperature, precipitation and foliage nutrient contents in Scots pine and radial and height growth. We performed height stem analysis on 63 Scots pine (*Pinus sylvestris* L.) trees on seven sites from long-term research plots.

Variations in the nutritional condition of the seven stands have been recorded by means of needle analysis.

The relationship between thermal, mean monthly temperature, and pluvial conditions, total monthly precipitation, and tree radial increments was analysed, using methods of correlation, response function and principal components analysis. Temporal trends of height growth changes in relation to levels of foliar nitrogen and phosphorous contents were analysed.

Evapotranspiration index was correlated with height growth deviation values, with indications of different stands behaviour. A distinct rise in N-levels and in the dry weight of needles has become evident. N and P ratio from declining plots was found to have significantly higher values as compared to that from non-declining plots.

Key words: climate, foliar nutrition, productivity, stem analysis.

Resumen

Tendencias en el crecimiento y relaciones con los factores medioambientales para siete lugares de pino silvestre [*Pinus Sylvestris* (L.)] en Brandenburgo

En este estudio se han calculado las tendencias en el crecimiento del pino silvestre (*Pinus sylvestris* L.), desde comienzos de los años 60, en el Estado de Brandenburgo (Este de Alemania). Del mismo modo se han investigado las interacciones entre los factores que causan el crecimiento radial y en altura, como son la temperatura, la precipitación y el contenido foliar en nutrientes. Con el fin de conseguir ésto realizamos análisis de troncos sobre 63 pinos en siete lugares con parcelas permanentes de investigación.

Las variaciones en las condiciones nutricionales de los siete rodales fueron registradas por medio de análisis de acículas.

La relación entre las condiciones térmicas, temperatura mensual media, y pluviales, precipitación mensual total y los incrementos radiales fue analizada, utilizando métodos de correlación, función respuesta y análisis de componentes principales.

Las tendencias temporales de los cambios en el crecimiento en altura en relación con los niveles foliares de nitrógeno y fósforo fueron analizadas.

El índice de evapotranspiración estuvo correlacionado con los valores de los cambios en el crecimiento en altura, indicando un comportamiento diferenciado entre los diferentes rodales. Un incremento diferenciado de los niveles de N y del peso seco de las acículas ha resultado evidente. El ratio de N y P de las parcelas en declive tenía valores significativamente más altos comparado con las parcelas que no presentaban declive.

Palabras clave: clima, nutrición foliar, productividad, análisis de troncos.

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Introduction

Increased plant growth in the northern latitudes during last decades has been detected by different researchers and under different approaches (Myneni *et al.*, 1997; Field *et al.*, 1998). This means that the average annual growing season has lengthened by some days since the early 1960s directly attributed to changes in air temperature (Menzel and Fabian, 1999). Changes in growth (seasonal plant driven by environmental factors) from year to year may be a sensitive and easily observable indicator of changes in the biosphere. The biomass and carbon budget of the European Forests has considerably changed (Kauppi *et al.*, 1992) caused by different drivers like climate change, nitrogen and sulphur deposition, carbon dioxide and land-use change. It is generally considered that there is a consistent and forceful trend of increase of forest resources (Spiecker *et al.*, 1996).

Forest growth is regulated by the availability of light, water, nutrients, and by the duration of the growing season (Linderholm, 2001). Thus, the increment changes reported may be due to different changing or varying growth-limiting factors. Possible mechanisms behind this increased in forest resources include: (i) elevated CO_2 stimulating photosynthesis (Bazzaz *et al.*, 1990; Bazzaz and Williams, 1991), (ii) climate (Spiecker, 1995), and (iii) increased carbon fixation in terms of plant growth resulting from widespread deposition of nitrogen (Townsend *et al.*, 1996). Forests in temperate zones are adapted to the seasonal cycle, having a dormancy period during winter that is triggered mainly by seasonal variation in temperature. Seasonal growing phases can be also influenced by soil, water supply, biotic and abiotic factors, including genes. Plant growth can therefore be used as a biological indicator of changing environmental conditions.

Descending to the tree level, there are many evidences of the effects of recent climatic and environmental change on tree growth (Jacoby and D'Arrigo, 1997; Clark *et al.*, 2003). In some studies enhanced radial and volume increment has taken place explained by climate (Briffa *et al.*, 1990), CO_2 fertilization on land (Field, 2001; Briffa *et al.*, 1998; Briffa and Osborn, 1999) or explained by other causes (snowfall and melt timing) (Vaganov *et al.*, 1999).

The main target of this study is the detection of growth trend anomalies and interaction with climate and nutrition trends. Height and radial increments of Scots pine are used, pretending to describe and model the sites with clear change of site quality but also to find relationships between temporal trajectories in forest growth deviations and potential drivers of these changes.

Material

Environmental data

The combination of individual tree analysis data with permanent research plot and environmental data forms the data base for detecting anomalies in forest growth. Sample and study localities are distributed in Brandenburg (East Germany, Figure 1).

A dataset of mean monthly climate surfaces, interpolated from station data to 0.5 degree lat/long, were used for a range of variables: mean precipitation and mean temperature (New *et al.*, 2000). This dataset was part of the CRU (Climatic Research Unit, University of East Anglia) and was available from the IPCC Data Distribution Centre. Records from the climate measurement stations Lindenberg, Berlin-Schönefeld, Zehdenick and Neuglobsow, were used as they were in the proximity of the study localities.

Permanent research plots

The sites included in the study are permanent research plots. In all cases, they represent artificial (planted),

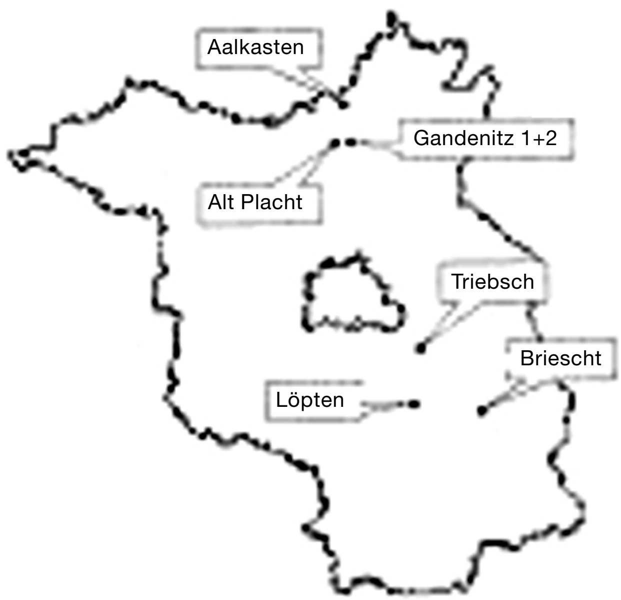

Figure 1. Map showing the locations of the sampled sites in Brandenburg.

established from seed, even aged stands. Altitude, average air temperature, soil types and age of the study sites are summarized in table 1. Regarding site fertility and productivity, the sites were representative of different growing conditions in a relatively small area, fluctuating from less fertile, site index 15.5 (average height of dominant trees at the age 100, stand number 801) to most fertile 30.5 (807). Originally, research plots were established (1960) as long-term fertilizer experiments on old arable land and poorly buffered sandy soils. Data from total of 7 long-term sample sites were provided by Forest Establishment Eberswalde (FFE). Collected data from the plots included values of deposition, foliage nutrition and forest growth.

Foliage samples were repeatedly taken from labelled Scots pine trees per plot between 1960 and 1999 in an annual basis. The methods by which the data has been collected are described elsewhere (Federal Research Centre for Forestry and Forest Products, BFH, 1998). In the laboratory foliage contents of different nutrients were measured and represented the nutritional levels of sampled trees. From all measured parameters we considered in this study the Nitrogen foliage content (**N_fol**, expressed in milligrams per gram of dry matter, mg/g), Nitrogen foliage content in 100 needle pairs weight (**N_fol/w_100**, expressed in mg N/100 needle pairs), Phosphorous foliage content (**P_fol**, expressed in milligrams per gram of dry matter, mg/g), Phosphorous foliage content in 100 needle pairs weight (**P_fol/w_100**, expressed in mg P/100 needle pairs), **N/P** ratio (no dimension) and 100 needle pairs weight (**W100**, expressed in grams) of the seven sites in Brandenburg.

Together with forest growth data, at stand level, FFE made available the Brandenburg forest growth and yield tables (Lembcke, 2000). These yield tables were built based on data of height stem analysis on dominant trees and by using differential equations. The yield tables represent growing conditions before 1960.

Height Stem analysis data

Height stem analysis over 7 sites, 63 trees, were conducted on November 2000. Within each plot nine dominant trees (by DBH, crown development and total height), within no visible evidence of growth anomalies or damage, were felled for stem analysis. A large crown ratio and the occurrence of thick dead branches or large knots in the lower part of the bole have been used as indicators of the dominant crown class status of the tree in the past (Spiecker, 1992).

Total and retrospective annual tree heights were measured in the field after felling by sequentially measuring the distance of each annual height shoot tip or whorl of primary branches to the stem base. Stem discs were then cut at regular intervals (every each two meter by searching up and down the stem axis to the place where no branch disturbs the radial growth pattern on the cross-sectional plane) from the stump to the top. Annual tree ring widths of each individual radius were measured in the laboratory and averaged into one tree ring curve for each tree and at a certain stem height (Figure 2). In the radial increment data quality control, measurement and dating errors are checked by applying standard dendrochronological cross-dating methods

Table 1. Location, elevation, and characteristics of the sites included in the study

Location	Plot number	Lon. (°)	Lat. (°)	Altitude (m)	Average air temperature May-Sept (°C)	Soil type*	Age (years)	N.º trees**
Löpten	801	13.71	52.15	41	15.9	Spodic Podzol	94	9
Brieschst	802	14.10	52.10	44	15.9	Spodo-Gleyic-Cambisol	90	9
Triebsch	803	13.79	52.35	37	16.0	Spodo-Dystric-Cambisol	95	9
Alt Placht	804	13.39	53.17	65	15.6	Cambic Arenosol	85	9
Gandenitz II	805	13.42	53.16	65	15.6	Spodo-Cambic-Arenosol	85	9
Gandenitz I	806	13.42	53.17	68	15.6	Luvic-Arenosol	95	9
Aalkasten	807	13.43	53.25	88	15.2	Cambisol	80	9

* According to FAO/UNESCO (1975) soil types. ** Stem analysis samples. L: Löpten. B: Brieschst. T: Triebsch. Ap: Alt Placht. GII: Gandenitz II. GI: Gandenitz I. Ak: Aalkasten.

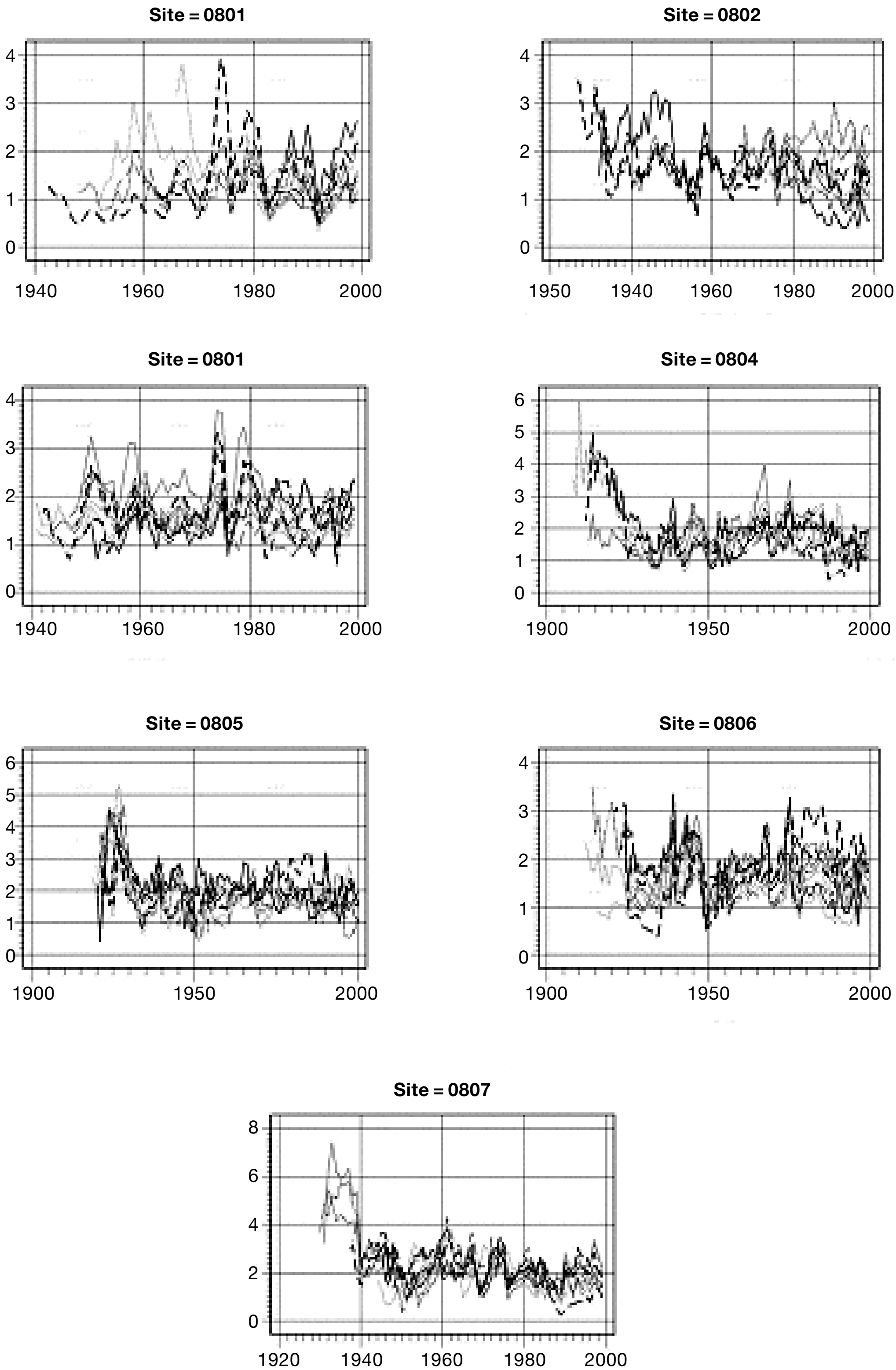

Figure 2. Annual radial increment (mm) for the breast height section (mm, height 1.3 m) from the individual trees sampled at the Brandenburg sites (7 sites with 9 trees per site). Each box represents a site and each line represents a tree. The number of the sites are from table 1.

(Briffa and Cook, 1990). We measured eight radii at the 1.3 meter cross section and 4 at the other sections.

By comparing the number of actual shoots with the number of tree rings at a given stem height (cambial age of the cross-sections from different tree heights), quality of the measurements was controlled (Spiecker, 2002).

Raw height stem analysis data were adjusted and cross-checked using Carmean's algorithm (Dyer and Bailey, 1987) to calculate tree height corresponding to the age at each sectioned disk. The height versus age curves for the nine sampled trees per plot were examined for uniformity and the presence of suppression or damage. Height-age data were averaged by plot in yearly basis up to the youngest sample tree in the plot and according to the chronological-biological age (Kariuki, 2002). Chronological-biological age is considered as the age measured at the stump of the dominant trees.

Methods

Tree chronologies

We use tree-ring data from all the breast height (1.3 m) cross sections derived from stem analysis. Radial increments were statistically cross-dated using COFECHA (Grissino-Mayer *et al.*, 1997), comparing the ring width of one cross section (mean average of eight radii) against the remaining series for the site. If a measurement problem was detected within a cross section it was re-examined and corrected (Holmes *et al.*, 1986). Standardization of radial increment series at breast height was done to eliminate variation due to tree aging and tree-specific growth trends and to maximise high frequency variation. Smoothing spline functions together with a technique to control the stiffness using frequency domain considerations (derived from the matrix theory) were used for our study (Cook and Kairiukstis, 1990). We transformed the series to logarithmic values after standardization to stabilize the tendency of the variance to increase with increasing increment.

During the standardization process we removed the autocorrelation (correlation between the growth of one year and that from previous year) in each series using autoregressive moving average (ARIMA) time series models (Box *et al.*, 1994; Monserud, 1986) to produce «residual» chronologies. The order was selected for the individual series by searching the first minimum of the Akaike Information Criterion. After the ARIMA modelling, we calculated the mean values for each year and site of the individual indexes («residual» chronologies) using the biweight robust mean to reduce bias caused by extreme values of increment indices that do not exist in chronologies of other trees (Cook and Kairiukstis, 1990). These chronologies were created using the program ARSTAN (Holmes *et al.*, 1986). Residual chronologies will be further used in the analysis of climate growth response as they contain a strong common signal (Linderholm, 2001).

The chronologies were carried out in two steps to separate long, medium and short term variation from each other (Mäkinen *et al.*, 2002). In a first detrending, a rigid spline function with a 50% frequency cut-off in 75 % of the length of the series was used (Cook and Kairiukstis, 1990) to remove long term variation caused by tree maturation (Nöjd and Hari, 2001). Increment indexes were computed as the ratio between observed and estimated values. The fitted spline curves are considered as the «long-term, component». In a second step, a flexible spline function with a 50% frequency cut-off in 10% of the length of the series was fitted to the increment indexes of the previous step. Once again increment indexes were computed as ratio, considering them as remaining short term variation. The fitted spline curves in a second step are considered as the «medium-term, component» and the final quotients are classified as «short-term» or «high-frequency component».

Statistical figures of the tree ring data like mean sensitivity (*ms*), standard deviation (*sd*), serial correlation (r_1), mean between-series correlation ($\bar{r}_{bt}$), variance in the first eigenvector and signal to noise ratio (*SNR*) are calculated (Cook *et al.*, 1997). Mean sensitivity is a measurement of the relative intensity of year to year changes in growth. It was calculated as the difference between the increments of the current (ir_t) and preceding year (ir_{t-1}) divided by the mean of these two increments:

$$ms = \frac{1}{s-1}\sum_{t-2}^{s}\left|\frac{2(ir_t - ir_{t-1})}{ir_t + ir_{t-1}}\right| \qquad [1]$$

Standard deviation is a classical statistical measure of variability and measurement of the long-medium term variation. It was calculated as:

$$sd = \sqrt{\frac{1}{n-1}\sum_{t=1}^{n}(x-\bar{x})^2} \qquad [2]$$

in which $\bar{x}$ is the arithmetic mean of the series x. Serial correlation is a measure of the year to year persistence in growth and was calculated:

$$r_1 = \frac{\sum_{t=2}^{n}(x_t - \bar{x})(x_{t-1} - \bar{x})}{\sum_{t=1}^{n}(x_t - \bar{x})^2} \quad [3]$$

Mean between-series correlation is a measure of the strength of the common signal between trees (a measure of the strength of the common climatic-environmental signal contained in the record) and was calculated:

$$\bar{r}_{bt} = \frac{\sum_{i=1}^{m-1}\sum_{j=i+1}^{m} r_{ij}}{m(m-1)/2} \quad [4]$$

in which r_{ij} is the correlation between tree i and j and m is the number of trees.

The signal-to-noise ratio is an expression of the strength of the observed common signal among trees in the ensemble and is defined:

$$SNR = \frac{N\,\bar{r}_{bt}}{(1-\bar{r}_{bt})} \quad [5]$$

where $\bar{r}_{bt}$ is mean between-series correlation and N is the number of trees in the ensemble of standardized tree-ring indices.

Principal component analysis was used to identify common patterns of inter-annual growth variability among the chronologies (variance in the first eigenvector is obtained from here).

Climate relationship

Relationship between climate and tree radial increment was evaluated by the use of response functions and correlations (Briffa and Cook, 1990). Indices of residual chronologies were compared to mean monthly temperature and total monthly precipitation (Borgaonkar *et al.*, 1996). A 14-month period extending from previous July to August of the growth year was analysed. The analysed period was 1900-1998 for which climate data was available from CRU. Bootstrapped response function analysis was computed with software PRECON (Fritts, 1999). The bootstrap procedure provides a way to test the significance of the regression coefficients and the stability of the estimates in the response function generated by regression on principal components (Guiot, 1991; Efron, 1979). Using the bootstrapping method we could determine the value of a particular growth-climate model by simultaneously testing the regression model and individual coefficients in an independent data set (Cullen *et al.*, 2001). From hundred re-samples used in this study, the mean regression coefficient for each month was calculated.

Height growth anomalies

We first transform the absolute non stationary height increment growth raw series into a new series of stationary, relative height increment that have a defined mean of 0 and a relatively constant variance (Cook and Kairiukstis, 1990). This is accomplished using the following expression:

$$Ih\_dev_t = 100 * (Ih\_obs_t - Ih\_\exp_t / Ih\_\exp_t) \quad [6]$$

where Ih_dev_t (%) is the height increment deviation expressed in percentages for the time t, Ih_obs_t, $Ih\_\exp_t$, are the absolute observed (directly from stem analysis) and expected (according with yield tables) height increments for the time t (expressed in meters). For example values exceeding 0 indicate higher increments than expected from the age trend. Therefore the age trend was removed without eliminating possible growth trends (Becker, 1989). Expected height increments are the ones from the yield tables of Lembcke (2000).

Nutrition trends

Trend estimation methods are discussed by several authors (Van Deusen, 1991; Cook and Kairiukstis, 1990). Time trend in foliar nutrition showing the magnitude of the detected change is given by the calculation of trend lines (simple linear regression) and for the stand i, equations of the form:

$$Foliar_{i,t} = a + b * Date \quad [7]$$

where the coefficient b (slope) indicates the direction (increasing or decreasing) as well as the magnitude of changing nutrition parameters within a given span (Hasenauer *et al.*, 1999; Moonen *et al.*, 2002); the coefficient a (intercept) characterizes the starting level of foliar content. $Foliar_{i,t}$ represents different nutritional levels of the stand i at a sampling *date t*.

We performed pairwise t tests (LSD-test), equivalent to Fisher's least-significant-difference test, for all main effect means, to indicate significant differences of nutrient concentrations among stands.

Mixed model

Time series of the potential evapotranspiration (ETP) were calculated from climatic parameters as average monthly air temperature and precipitation records (Thornthwaite and Mather, 1955). The difference between the precipitation and potential evapotranspiration was used as drought index (ETP-index). According with Spiecker (1990), the air temperature and precipitation during the vegetation period (May-September) had an effect that last up to several years. For this reason, we included previous five years periods (last five years including the actual period), as the basis of the calculations. Deviations of these values from the long-term average expressed the ETP-index in percentages (Figure 3).

Linear regression lines and Pearson correlation coefficients were calculated between nutritional levels, ETPindex and height growth deviation values. Data were evaluated with multiple regression analysis using a mixed model to take into account the clustered structure of the data in the seven sampling plots (SAS statistical software, release 8.02). The mixed model was developed by adding a random parameter, referred to the site, and acting over the constant of the model. Relationships between height growth deviations and N/P ratios are presented graphically as partial correlation plots which consider the multivariate approach and averaged for each plot. Because of the multivariate data evaluation, no r^2 can be given for single parameters (Flückiger and Braun, 1999).

Results

Tree chronologies and climate relationship

We analysed changes in radial growth of the sampled trees from the seven sites describing their development during the last century. Figure 4 showed the tree-ring

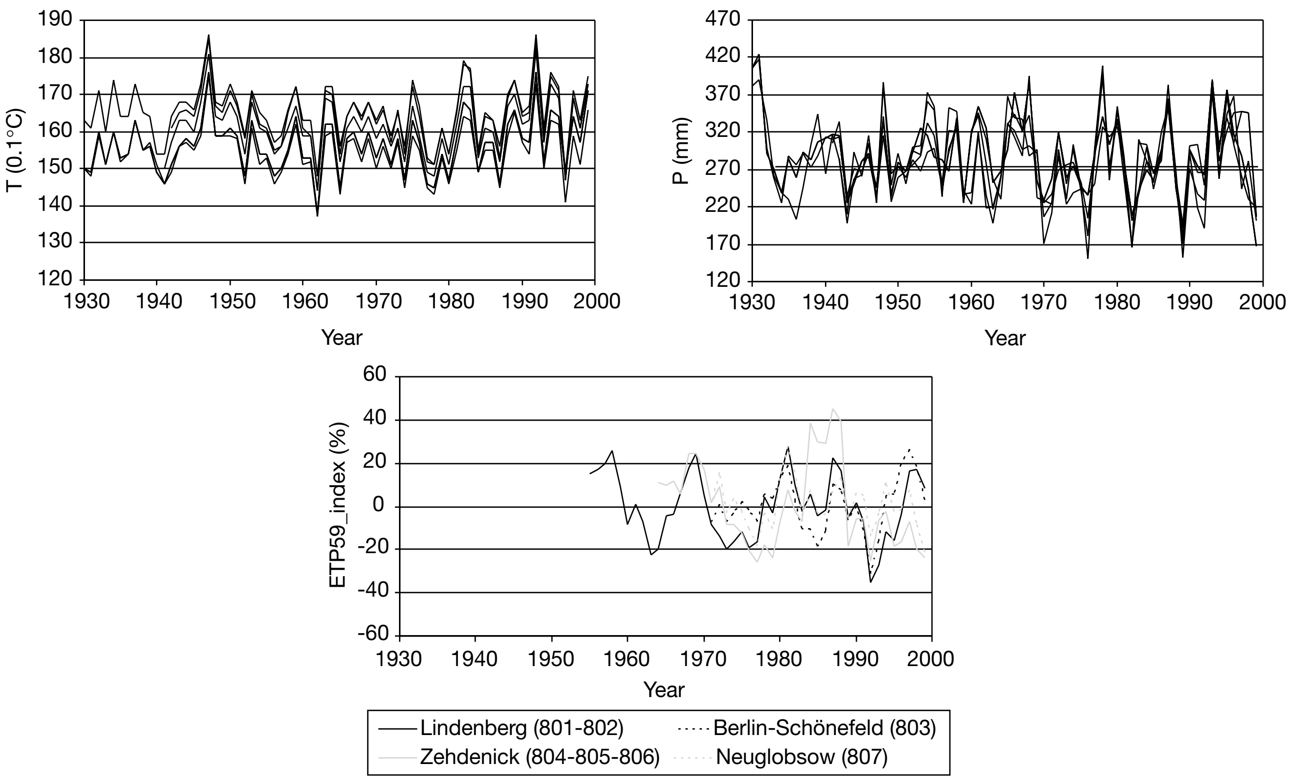

Figure 3. Air temperatures (upper left graph) and precipitations (upper right graph) from the selected sites. The solid horizontal line is the average value for this seventy year period. Temperatures are monthly averages and precipitations are monthly sums for the vegetation period (May to September). Drought severity index (lower graph, ETP-index) using records from the climate station located in Lindenberg (stands 801, 802), Berlin-Schönefeld (803), Zehdenick (804, 805, 806), Neuglobsow (807).

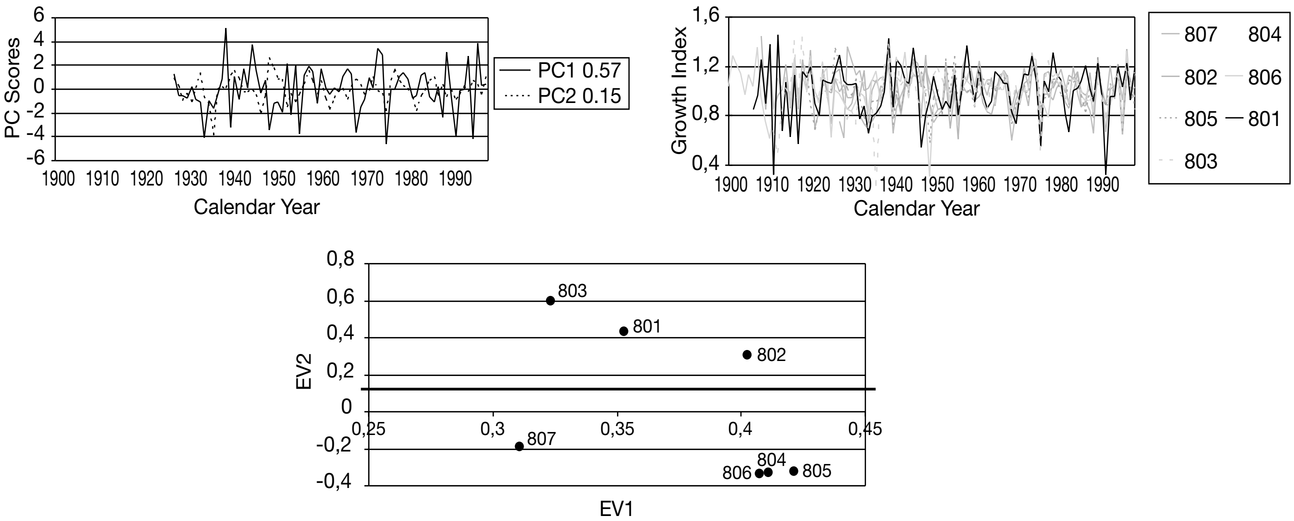

Figure 4. Principal component analysis of short term variation in radial increments on plots from Brandenburg. Upper left graph represents the component scores of PC1 and PC2. Tree-ring index residual chronologies for each stand (upper right graph). Lower graph shows the scattering of the value of the first (EV1) and second (EV2) eigenvector for indexed chronologies of the seven sites. See methods for more details. The number of the sites are from table 1.

index residual chronologies. The principal component analysis distilled two groups out of the seven site chronologies studied. One homogeneous group included the chronologies from the stands 804, 805, 806 and 807. The other group was composed of the site chronologies from the stands 801, 802 and 803. The first eigenvector accounts for 57% of the variance among all the chronologies. The second eigenvector accounts for 15% of the variance among all the chronologies. In table 2 statistical figures of the tree ring data like mean sensitivity, standard deviation, serial correlation, mean between-series correlation, variance in the first eigenvector and signal to noise ratio are shown characterizing the variability in these increment series. Cross-correlation coefficients (r_{xy}) and corresponding *p-values* ($p < 0.01$) among ring width residual chronologies along Brandenburg are shown in table 3.

There are four strong and consistent patterns in the relationship of the indices of the regional chronologies (final quotients determining the short term variation) to climatic variation (Figure 5). First, growth is positively correlated with February temperature for the seven Scots pine chronologies. Secondly, growth is negatively correlated with June temperature of the current vegetation period for the first three chronologies as well as negatively correlated to July temperature of the year preceding the increment for the 802, 803 and 804 chronologies. Concerning precipitation patterns the responses are as consistent as the two previous relationships. First six chrono-

Table 2. Statistics of the tree ring data of the Brandenburg sites based on a total of 63 individual tree series (9 trees per plot). Averages of mean sensitivity (*ms*), standard deviation (*sd*), first order serial autocorrelation (r_1), signal to noise ratio (*SNR*), variance of first eigenvector (*V*), mean correlation between trees ($\bar{r}_{bt}$)

Plot *number*	***ms***	***sd***	r_1	***SNR***	***V***	$\bar{r}_{bt}$
801	0.23	0.23	0.27	10.76	0.68	0.64
802	0.16	0.17	0.24	5.59	0.64	0.58
803	0.19	0.21	0.45	5.02	0.70	0.63
804	0.15	0.16	0.30	4.39	0.60	0.52
805	0.15	0.16	0.36	3.01	0.61	0.50
806	0.16	0.19	0.45	7.82	0.69	0.66
807	0.16	0.18	0.38	8.20	0.60	0.54

Table 3. Cross-correlation coefficients (r_{xy}) and corresponding *p-values* among ring width residual chronologies. Calculations based on maximum common pair wise overlap period. Only significant correlations are shown ($p < 0.01$)

Plot-x	Plot-y	N	Correlation	p-values
802	801	84	0.6075	< 0.0001
803	801	89	0.4829	< 0.0001
803	802	84	0.6677	< 0.0001
804	801	92	0.4559	< 0.0001
804	802	84	0.582	< 0.0001
804	803	89	0.3895	0.0002
806	801	94	0.3646	0.0003
806	802	84	0.5058	< 0.0001
806	803	89	0.3721	0.0003
806	804	92	0.5999	< 0.0001
807	801	73	0.3547	0.0021
807	802	73	0.4546	< 0.0001
807	804	73	0.4519	< 0.0001
807	806	73	0.4564	< 0.0001
p < 0.01				

logies showed a strong positive correlation with late spring precipitation (June precipitation) and with late autumn precipitation (December precipitation of the year preceding the increment).

Radial increment growth trends (long-term variation), separately plotted for the seven sampling sites (801-807 from top to the bottom) are shown in Figure 3. There is not a general trend towards increased growth during recent decades. In sites 803-804, forest stands have been increasing ring widths during last decades. However at sites 801, 802 a general negative trend of radial growth after 1950 is prominent. Sites 805-807 showed no trend for this period, confirming no evidence of generally improved growth conditions during the last decades.

Nutrition trends and relationships with height anomalies

Temporal trends in Nitrogen content in leaves as well as Phosphorous content and N:P ratios are presented in table 4. Specially, stands 801, 802, 803 and 804 showed slopes of the linear regression models significantly different from zero and for all studied parameters. Element concentration (N, P), ratio and weight of 100 needle pairs are represented in table 5. Stands 803, 804, 805 and 806 showed similar means for all studied parameters. Stands 802 and 807 had higher values of the N:P ratio, showing nutrient imbalances.

Relationships between height growth deviation, nutrition levels and ETP-index, showing the linear regression line and displaying correlation coefficients, are presented in figure 7 (for the common overlapping period between plots). There is a significant correlation between height growth deviation and levels of Nitrogen and Phosphorous content on leaves (highly correlated between them). Inter-annual variability of nitrogen and phosphorous needle concentration is not explained by variation in levels of ETP (i.e. drought periods are not correlated with relative low nutrient concentration values). Height growth deviation values were correlated with values of water balance. There was a significant correlation between N:P ratio and height growth deviation.

A good fitness of a linear mixed model ($F_{7,243} = 36.04$, RMSE = 1.26, RSQ = 0.51) showed a strong statistical

Table 4. R-Squares of the regression lines of Nitrogen foliage content expressed in 100 needle pairs weight (mg N/100 needle pairs), Phosphorous foliage content in 100 needle pairs weight (mg P/100 needle pairs), N/P ratio and 100 needle pairs weight (g) *versus* sampling date of seven sites in Brandenburg for the period 1960-1999. Regression lines were fitted by simple linear regression following equation seven; in some cases the slope of the linear regression models is significantly different from zero (*** p < 0.001, ** p < 0.01, * p < 0.05)

Plot	R-Square N/P	N_fol/W_100	P_fol/W_100	W_100
801	0.10**	0.26***	0.15***	0.22***
802	0.18***	0.27***	0.11**	0.18***
803	0.11***	0.35***	0.13**	0.29***
804	0.23***	0.26***	0.11**	0.24***
805	0.04*	0.01	0.06	0.03
806	0.03	0.13**	0.09**	0.10**
807	0.01	0.00	0.01	0.00

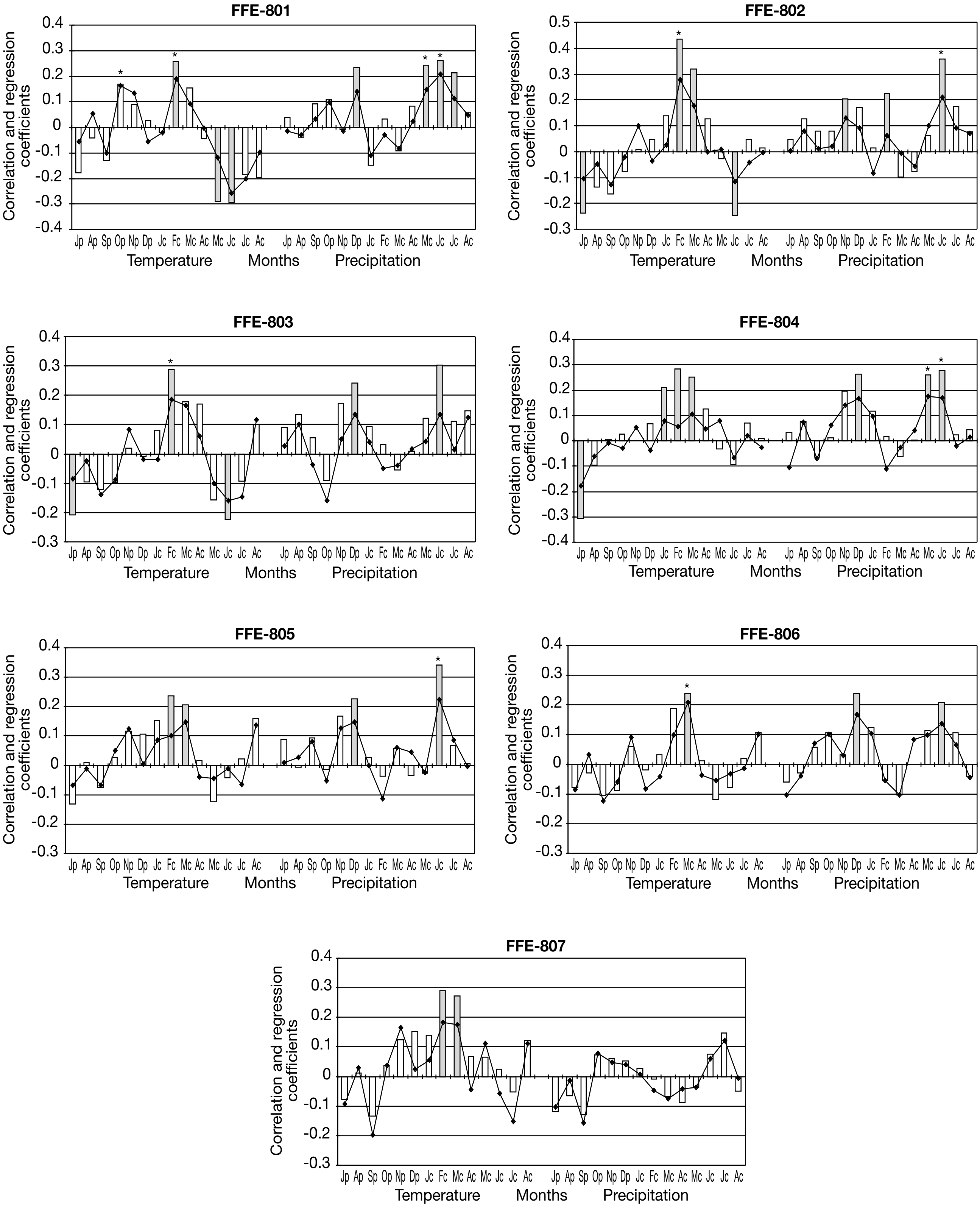

Figure 5. Bootstrapped response functions (lines) and cross correlation coefficients (bars) between tree ring-index residual chronologies and temperature and precipitation for the pines of the Brandenburg 7 sites from July (Jp) of the year preceding the increment to August (Ac) of the current vegetation period. Grey bars and asterisks show significant correlation coefficients at $\alpha = 0.05$ level.

Table 5. Element concentration (N, P) per 100 needle pairs, ratio and weight of 100 needle pairs in 1-year-old needles*

Plot	N/P	N_fol/W_100 (mg N/100 needle pairs)	P_fol/W_100 (mg P/100 needle pairs)	W_100 (g)
801	9.52 ± 1.07 b	58.55 ± 18.69 a	6.20 ± 1.83 a	4.45 ± 1.36 a
802	10.12 ± 1.14 a	87.63 ± 23.14 b	8.73 ± 2.08 b	5.57 ± 1.20 b
803	9.92 ± 1.11 b	74.31 ± 17.95 b	7.53 ± 1.80 a	4.69 ± 0.99 a
804	9.63 ± 1.07 b	66.35 ± 18.93 b	6.99 ± 1.82 a	4.70 ± 1.19 a
805	9.65 ± 1.09 b	70.59 ± 21.90 b	7.33 ± 1.98 a	4.74 ± 1.10 a
806	9.85 ± 0.92 b	73.81 ± 18.33 b	7.62 ± 1.88 a	4.99 ± 0.96 a
807	10.42 ± 0.95 a	80.20 ± 17.64 b	7.78 ± 1.81 a	4.88 ± 1.01 a

* Values are the mean of n = 108 repetitions ± SD for the ratio and n = 75 repetitions ± SD for the other parameters. Small letters indicate significant differences of nutrient concentrations among the stands (LSD-test, $P < 0.05$). All the parameters showed homogeneity of variance.

evidence that the explanatory variables in the model are related to the expected value; a transformation of type square root of the response variable was suggested by a maximum likelihood analysis in order to keep a constant variance of the residuals (Figure 8). There correlation between N:P ratio and height growth deviation, was modified when the stands indicated nutrient imbalances (stands 802, 807). Within stands 801, 803, 805 height growth deviation values was positively correlated with the N:P ratio. Stands 802 804, 806 and 807 showed a different pattern.

Discussion and Conclusion

To obtain a detailed description about the sensitivity, vitality and resistance of Scots pine in terms of growth trends, 7 stands were collected throughout Brandenburg (Eastern Germany). Although their geographical proximity, these stands differed not much on regards climatic and environmental conditions but in soil fertility and growing conditions. As bio-indicators for sensitivity, vitality and resistance in the past, tree radial and height increments from stem analysis were chosen and analysed by means of dendroecological and statistical methods. The variation in tree radial and height increments were found to be significant parameters reflecting the signal of exogenous influences such climate.

Radial growth is a clear indicator of environmental effects on growth acting on short to medium-term time

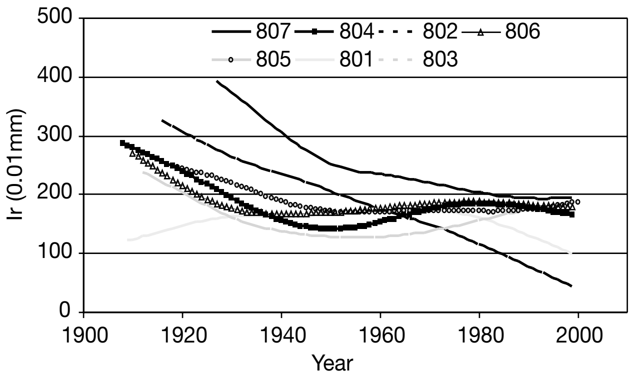

Figure 6. Radial increment (0.01 mm, breast height) growth trends of Scots pine stands in Brandenburg. Trends are rigid spline with 50% frequency cut-off in 75 % of the series length.

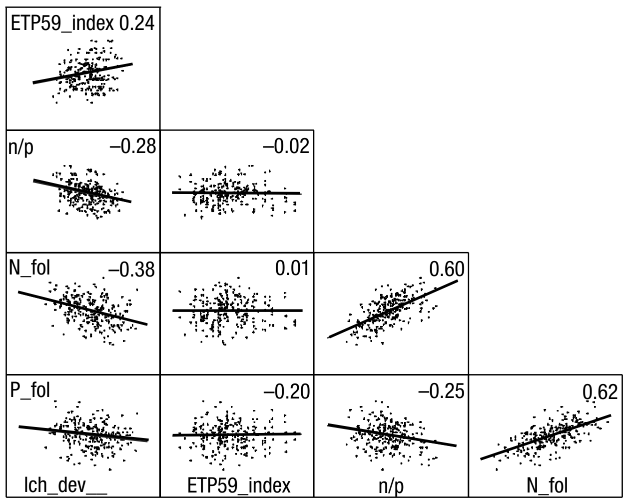

Figure 7. Scatter plot matrix showing linear regression lines and displaying correlation coefficients of the seven sites in Brandenburg plotted together and for the overlapping period 1964-1999. Ich_dev: height growth deviation (%), N_fol: Nitrogen foliage content (mg N/g dm), P_fol: Phosphorous foliage content (mg P/g dm), N/P ratio and ETP59_index: drought severity index (%). Significance level: 1% for all correlations but the ones between foliar parameters and ETP.

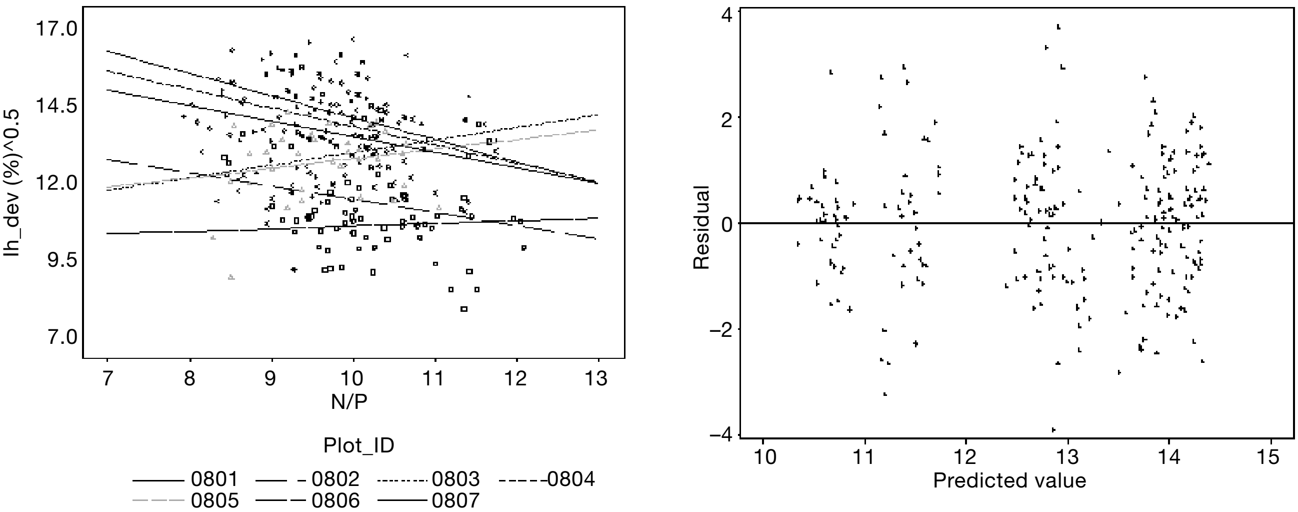

Figure 8. Growth trends and nutrition of seven sites in Brandenburg. Square root of height growth deviation over N:P ratio of each site (upper graph) and residual plot (lower graph). Deviations of growth respect Scots pine yield table of Brandenburg (Lembcke, 2000). Height growth deviation was transformed to the power of 0.5 to ensure normal distribution of the residuals.

scales (Kahle and Spiecker, 1996; Mäkinen, 1998). Variation in radial growth can also be regarded as a sensitive measure of tree vitality (van den Brakel and Visser, 1996) and an indicator of the occurrence of extreme events. The high-frequency variations of the annual radial increment time series are significantly synchronized suggesting a strong climatic control over radial growth of sample trees (on time-scales of one to several years) (Kahle *et al.,* 2003).

The examination of long-term variations in tree radial increments by the used of rigid spline functions demonstrated site dependent radial growth trends. Slightly decreasing growth trends during last decades were found at two sites (801, 807) reflecting reduced growth potential and strong disturbances between 1960 and 1999. The selection of dominant and co-dominant individuals as sampled trees for the whole dataset minimized the competition effects within the stands on the explanation of the growth trend. Several environmental changes in the recent past like atmospheric deposition of nitrogen, fertilization due to increased atmospheric CO_2 content, higher temperatures and subsequent extended vegetation period, could improve growing conditions at some locations (Heinsdorf, 1993; Spiecker *et al.,* 1996).

The climate-growth relationships, established by dendroecological methods, demonstrated distinct growth limiting factors. At some sites (801, 802, and 803) drought and water stress reduces radial growth for 1 to rarely 2 years (negative correlation with June temperature of the current vegetation period and induced drought). At the other sites most growth limiting factors could be warmth and radiation (i.e. late frosts, cool, wet and cloudy weather conditions during the vegetation period could be responsible for poor ring growths). The poor correlation with late spring precipitation (June precipitation) of site 807 was most probable due to induced drought caused by coupled high temperatures (any beneficial influences of increased soil moisture are outweighed by negative influence associated with late spring temperature events and the benefit of precipitation is masked). The negative response of Scots pine to increasing temperature in late spring-late summer is a typical pattern which reflects the negative influence of temperature on physiological processes related to tree growth under these sites with limited water and/or soil water holding capacity. The fact that February temperature positively correlates with radial growth, pattern repeated in all chronologies, is difficult to explain. To be considered is the strong positive correlation with late autumn precipitation of the year preceding the increment (December precipitation). Special attention required site 807 with the poorest responses of growth to climate conditions. Stronger reactions to influences and growth disturbances in the recent decades (1960-1999) indicated an increased sensitivity or reduced ecological fitness of Scots pine under this special rich site.

The sensitivity of this centre European example of tree growth to temperature has declined in recent decades: non climatic factors or factors other than temperature (e.g., moisture stress) may thus have become increasingly important limits on tree growth in high latitude forests (Briffa *et al.*, 1998).

The findings of inverse temperature responses to climate among trees with a positive temperature response suggest that assumptions that centre European productivity will continue to increase as temperature rise may be unwarranted, specially in those sites where the forest growth stagnation or decline could be attributed to temperature-induced drought stress (Lloyd and Fastie, 2002).

Foliar mineral concentration may provide a basis for monitoring the consequences of long-term environmental changes, such as eutrophication and acidification of soils, or increased atmospheric CO_2 concentration (Duquesnay *et al.*, 2000). The foliar N:P ratio below 10 indicated optimal P nutrition if we are using critical and marginal foliar levels for *Pinus sylvestris* to determine nutritional status of these stands. The supply of P in relation to N suggests a separation of the stands in two groups. The stands that showed a stronger deviation respect the yield table (801,803,804,805,806) showed a P high supply in relation to N. The stands 802, 807 clearly suffered from an imbalance between P and N (10.12-10.42), confirming the fact that nitrogen nutrition appears to dominate the regulation of stem growth.

This study reflects, that even in a small area, growing conditions could affect growth in a different way for each stand. Some of the stands showed an increasing growth potential during last decades but we could not conclude of an existing overall trend. The fact that we could not confirm a general increasing growth trend in a reduced area underlined negative environmental influences predominating in the last decades under certain conditions (i.e. drought induced by temperature). The mixed model stressed the statement, where the explanatory variable referred to the site, added significance to the model.

Forest growth trends are influenced by several factors under different conditions. A varying spatial and temporal combination of site specific factors might be responsible for the observed phenomenon. This together with additional potential effects or more punctual factors like differences in management (stand dynamics) or/and land use history, and genetics (use of improved material) might explain the large amount of variation in the data of growth changes, and the large extent of confounding effects in the multivariate analysis.

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