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Modelling the Dynamics of Growth-Climate Relationships of Norway Spruce and Silver Fir in High Elevations of the Black Forest

Hans-Peter Kahle
Institute of Forest Growth, University of Freiburg, D-79085 Freiburg
Germany

1. Introduction

Since the end of the 1970's widespread needle-losses have been observed on Norway spruce (*Picea abies* (L.) Karst.) and silver fir (*Abies alba* Mill.) especially in high elevations of the Black Forest. Research on this "new forest decline" syndrome produced a multitude of hypotheses which have been partially successful in explaining some potential causal aspects for the observed decline symptoms. These hypotheses also gave rise to a number of controversies concerning the underlaying mechanisms of the forest decline syndrome and the question of its unprecedence (Landmann 1989). We realize now that interpretations based on short-term observations remain unreliable, and that deeper insight into the underlying mechanisms cannot be expected until there is a long-term basis for calibrating the findings. In order to represent characteristical time scales of tree growth dynamics, investigations have to consider at least several decades. Instead of monitoring needle-loss status of trees, dendroecological studies are proving to be objective and efficient tools for long-term retrospective analysis of tree vitality and tree growth responses to changing environmental conditions.

2. Objectives

The main research objective of this study is to quantify the relationships between climate, respectively weather and radial growth of Norway spruce and silver fir. Climate related tree growth dynamics are modelled based on time varying coefficient models. Because needle losses have been high in high elevations it was especially interesting to sample trees in the montaneous and upper montaneous zone of the Black Forest. Earlier studies have shown that drought can induce several years of reduced growth in Norway spruce and silver fir, even at elevations where precipitation sums are high and air temperatures are relatively low on average during the vegetative period (Becker 1989; Spiecker 1986, 1987, 1990, 1991, 1995). Besides meteorological factors that cause drought stresses, interactions with site conditions, in particular with available moisture storing capacity of the soil, are taken into account when investigating tree growth responses to drought.

3. Descriptive Background

3.1 Study Area and Sample Trees

To study the effects of drought stress on radial increment with respect to the available moisture storing capacity (AWC) of the soil, we selected study sites with large differences in AWC in high elevations of the Black Forest. Study sites were selected in the southern Black Forest at elevations between 800 and 1160 m above sea level. Underlying geology is composed of periglacial solifluction deposits, predominantly of gneissanatexites. Typical soil type is *inceptisol umprept*. According to Müller and Oberdorfer (1974) the potential natural vegetation type is small-scale mixed *Luzulo-Fagetum* with *Abies alba* and *Abieti-Fagetum*, and in elevations above 1100 m above sea level *Luzulo-Fagetum* with *Picea abies*. Today Norway spruce occupies about 50% of the public forest land in the Black Forest.

In order to minimize variability in growth due to silvicultural treatment and mesoclimate, one study site pair in each of eight ecologically similar forest stands, consisting of one study site with higher AWC (site type hAWC) and one study site with lower AWC (site type lAWC) were selected. On each of these site types, groups of in the average five dominant trees per species were sampled in a next-nearest-neighbour process; in total 75 spruce and 43 fir sample trees were sampled.

AWC was determined in a relative classification scheme using the site mapping method applied in the public forests of Baden-Württemberg on a single tree level. For one site pair (two sample trees from lAWC and two sample trees from hAWC sites) quantitative determination of AWC was conducted based on field methods described in Arbeitskreis Standortskartierung (1980) (Fig. 1). Marked differences between the two strata are indicated, which amount to ca. 100 mm of moisture storing capacity.

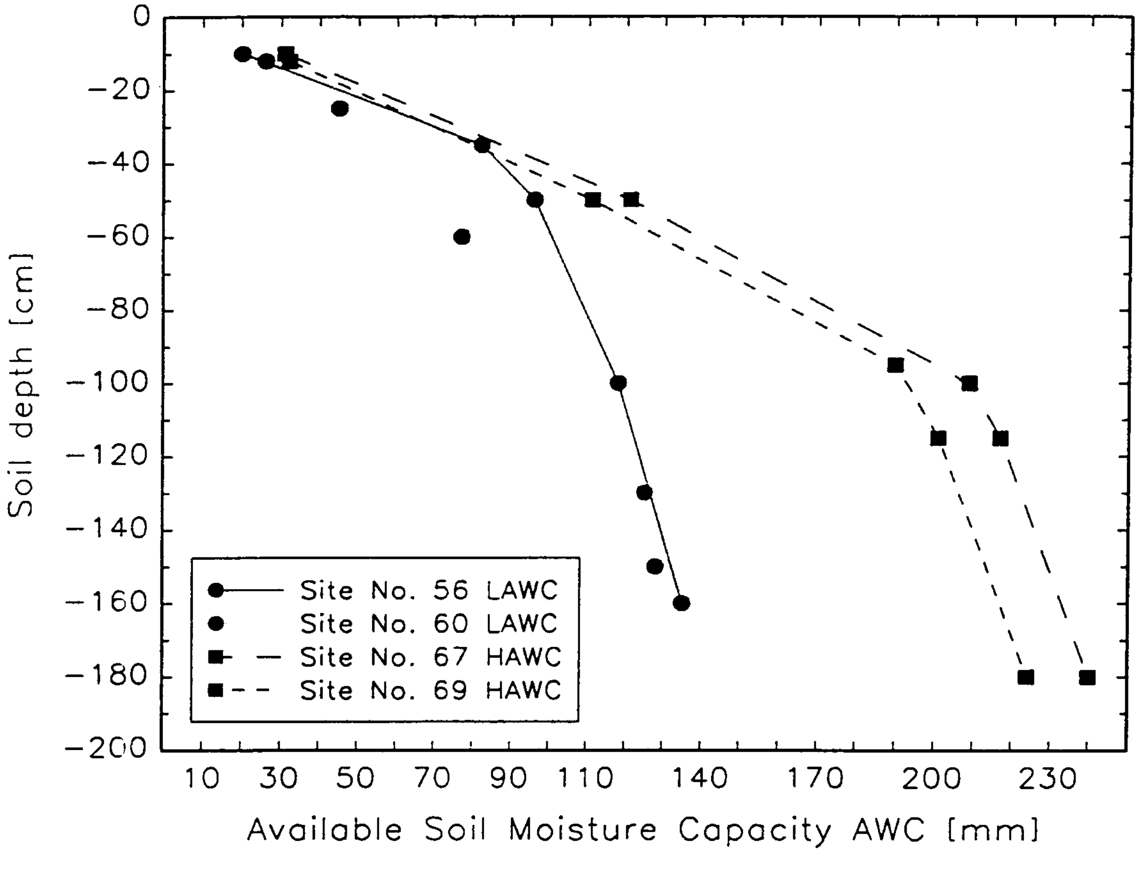

Figure. 1. Available soil moisture storing capacity (*AWC*) in the rooting zone.
Determination of AWC is based on field methods and is presented for four sites, representing the two site strata (lower (*lAWC*) resp. higher (*hAWC*) available moisture storing capacity). Marked differences between the two strata are indicated, which amount to ca. 100 mm of moisture storing capacity.

3.2 Tree Ring Measurement, Crossdating and Standardization

Trees were selected in summer and autumn of 1991. Cross sections of trees were collected at a height of 1.3 m, air-dried and sanded. Tree rings were visually crossdated using marker rings and annual radial increment was measured with a semiautomated device along eight radii. Crossdating was verified by analyzing intra- and intertree cross correlations with lags of ± 2 years of shifted 50 year periods based on first differences of log transformed values (Van Deusen 1987). Some partial missing rings but no totally missing ring were found.

The measurements of the eight radii were averaged to obtain mean radial increment sequences. In order to reduce low- and medium-frequency variations in the radial increment series due to age and dimension related effects on growth, as well as those due to changing competitive status and probably due to changing site conditions, the series were detrended on an individual tree basis prior to the dendroclimatic analysis. The stochastic trend model discussed in Visser and Molenaar (1990) and Van Deusen (1991) has been used. This trend model generates rather flexible trend estimates which may absorb some low frequency climatic signals. Its advantages however lie in its objective and data adaptive control of the flexibility of the estimated trend, being high when common signal is low and *vice versa*. Radial increment indices were calculated by division of the observed and estimated values, and pooled to obtain mean chronologies. The chronologies serve as response variables in the dendroclimatic regression analyses. Chronology sequences were stratified according to the AWC into chronologies consisting of trees from sites with lower (lAWC) and higher (hAWC) available moisture storing capacity. Based on the hypothesis that even after detrending remaining age related differences in growth responses could be detected, an additional stratification was undertaken with regard to tree age at sampling date (Tab. 1).

Table 1. Tree Strata.

Stratum			Number of trees	Age (years)		
				Min	Max	Mean
Spruce	lAWC*	young	11	54	80	67
		medium aged	14	82	114	96
		old	10	128	148	137
	hAWC**	young	10	54	76	67
		medium aged	21	85	118	96
		old	9	122	166	143
Fir	lAWC	young	4	71	89	83
		medium aged	14	91	110	99
		old	5	143	151	147
	hAWC	young	4	83	89	86
		medium aged	8	91	117	101
		old	8	133	220	151

* lAWC: lower, ** hAWC: higher available moisture storing capacity.

3.3 Climate Data Preparation

Monthly data of air temperatures and precipitation sums at meteorological stations in the southern Black Forest were obtained from the German Weather Service (18 meteorological stations for air temperature data and 27 stations for precipitation data). The data had to be preprocessed in a two step procedure including homogeneization and spatial interpolation. Test of homogeneity and adjustment of inconsistencies in the data series are based on standard climatological methods (Buishand 1982; Chang and Lee 1974; Craddock 1979).

Single-station climate data may reflect site specific conditions. Therefore spatial interpolation was calculated based on second order polynomial trend surface analysis (Ojansuu and Henttonen 1983) using the stations location data as input data. The monthly climate data were transformed into potential evapotranspiration and climatic water balance, which are calculated based on Thornthwaite's formulae (Thornthwaite and Mather 1955). These variables are used as predictor variables in the dendroclimatic regression analyses.

3.4 Dendroclimatic Analysis and Modelling

Selection of predictor variables

Cross-correlation analysis was used for selection of influential climate variables. Because correlation coefficients are inflated through autocorrelation in the time series, serial correlation has to be taken into consideration appropriately. In order to minimize this effect the individual series of climate as well as tree ring variables were transformed into white noise processes (*prewhitened*) based on autoregressive moving average models (Ans 1976; Box and Jenkins 1970; Guiot 1986; Guiot et al. 1986; Henttonnen 1984; Monserud 1986). The cross-correlation function was calculated with the prewhitened mean residual chronologies and with prewhitened two-monthly-averages of ETP and WBP of the period April to September including lags up to four years. Subsets of the best correlated climate variables were selected for subsequent modelling of the dynamic association of the bivariate time series based on transfer function analysis.

Model specification

The bivariate time series possess a triangular relationship, implying that the radial increment data depend on its own past and on the present and past of the climatic input. The remaining autocorrelation in the indices after detrending is thought to be predominantely controlled by exogeneous driving forces, like delayed responses to climatic inputs. In order to represent growth-climate relationships in the final distributed lag form without using lagged growth data as predictor variables, the contemporaneous and time delayed associations of the *unwhitened* bivariate time series was used to determine the length and the shape of the impulse response function (Bennett and Chorley 1978; Box and Jenkins 1970).

Kalman filter analyses

Regression models with time-varying regression coefficients were calculated using Van Deusen's DYNACLIM software (1992). The Kalman filter is a recursive procedure for calculation of the optimum estimator of the state space vector at time t, using information up to time t. The filtering problem is solved via prediction error decompostition. Once all observations have become available optimal estimates of unobserved components can be made by smoothing, which yields an estimation of the behaviour of the varying paramters through time. Because of the desired discounting of past observations the hyperparameters are modelled as random walk plus noise processes.

4. Results

4.1 Results of Cross-Correlation Analyses

Figure 2 presents results of the cross-correlation analyses of prewhitened series for the spruce strata. The chronology of young trees from sites with lower soil moisture storing capacity is directly correlated with contemporaneous WBP during June and July. Whereas the chronologies of medium aged and old trees are significantely correlated with one year lagged WBP and lagged ETP. The finding that lagged correlations are more pronounced in the older chronologies is confirmed through the results for the other site strata (not shown).

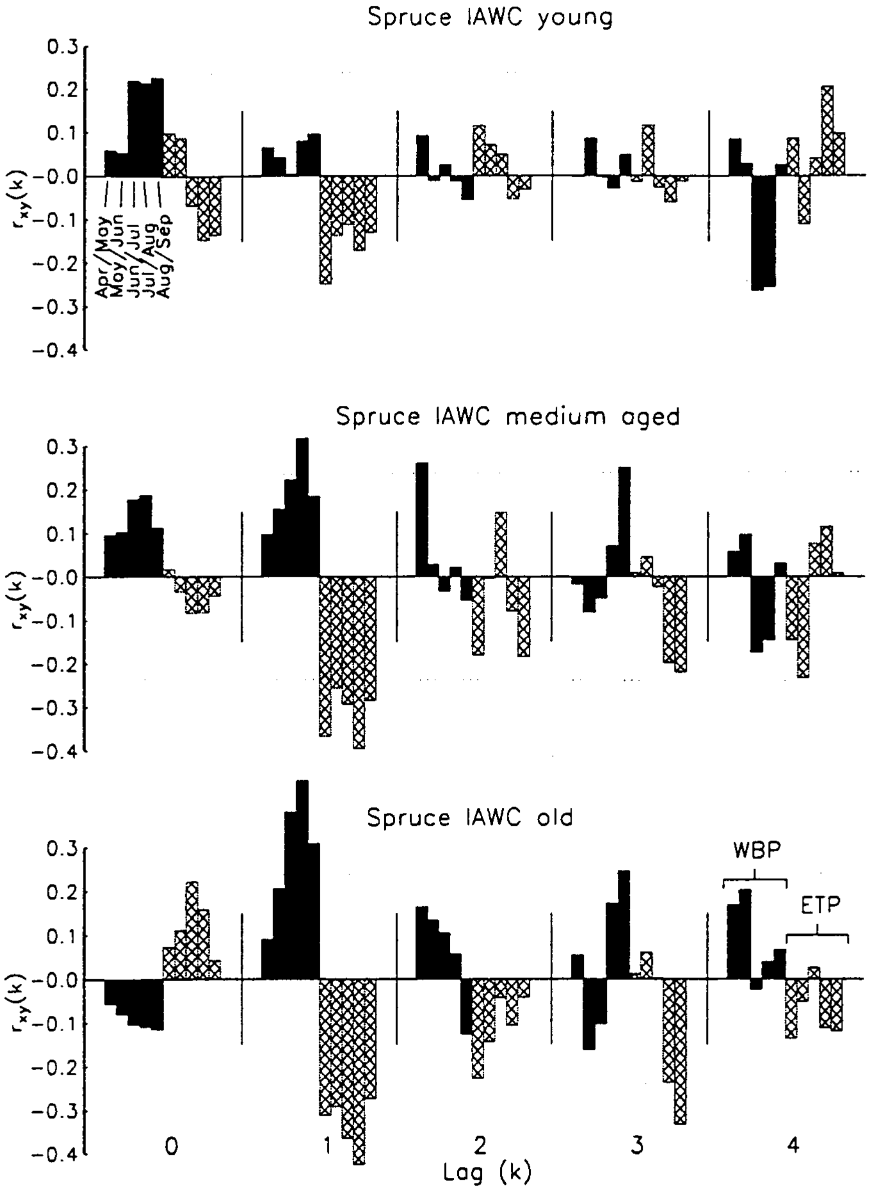

Figure 2. Cross-correlation analyses between climate variables and chronologies of spruce from sites with lower moisture storing capacity.

Cross-correlation coefficients ($r_{xy}(k)$) for lags (k) from $k=0$ to 4 years between prewhitened water balance (*WBP*) and potential evapotranspiration (*ETP*) and prewhitened chronologies, stratified in age classes, are shown related to the period 1915+k to 1990. The dotted lines represent 0.05 significance thresholds.

When comparing the results for the two site strata some aspects deserve mentioning:

- the chronologies of young and old trees from hAWC-sites show significant positive correlations with contemporaneous potential evapotranspiration during April to June respectively May to July, whereas those from the other site type do not.
- significant correlations for both climate variables lagged up to four years can be found.
- the older the trees the higher is the similarity in the cross-correlative structure between the site strata.

Transfer function analysis of the spruce data revealed, that potential evapotranspiartion from April to June (*ETP46*) and climatic water balance during July and August (*WBP78*) of the preceding 1 to 5 years, perform best, and show the most consistent associations among the strata. The persitence intervals for the fir data are considerably shorter than for the spruce data. Significant correlations are given for potential evapotranspiration during April to June of the contemporaneous year, and with opposite sign of the preceding year (not shown). As with the spruce chonologies no marked differences between the site strata can be found.

4.2 Dendroclimatic regression analyses

From the results of the cross-correlation analyses it was assumed that

1. the strong lagged associations may reflect adaptive behaviour in the tree's responses to climatic inputs. Since prewhitening implies filtering out the dynamic structure of the chronologies, modelling of adaptive behaviour has to be based on unwhitened series.
2. the growth-climate models basically can be built upon two candidate variables
   - for spruce: one covering the early, and the other covering conditions in the late vegetative periods of the five preceding years.
   - for fir: one covering the contemporaneous, the other covering the one year lagged relations.

The variables *ETP46* and *WBP78* were selected for the specification of the impulse response functions based on *unwhitened* spruce chronologies (not shown). High values of cross-correlation coefficients could be found for both climate variables in the lag range from 1 to 5 years. The association between the bivariate series decreases with increasing time delay. This is mainly due to autocorrelation in the chronology series, and the shape of exponentially decreasing correlation coefficients is in fact expected in the presence of a positive *AR(1)* process. This finding is consistent with the assumption of adaptive behaviour of the system under consideration.

For the subsequent dendroclimatic regression analyses of spruce, distributed lag models of order five with similar geometric lag structures for both input variables (*ETP46* and *WBP78*) and for all site- and age-strata were formulated. Results of the Kalman filter analyses are shown in Figure 3 for spruce. For fir only *ETP46* with Lag 0 and 1 were used (Figure 4). The model values not only follow major growth depressions but also increase, when growth accelerates. For spruce the analyses indicate that temporal variation is present for the climate variable *WBP78* but not for the variable *ETP46* (not shown). The time-varying coefficients corresponding to *WBP78* show synchronously increasing trends, with the longer series since the beginning of the century. Some goodness of fit statistics for the time-varying growth-climate models fit to the spruce tree ring data are given in Table 2.

Table 2. Goodness of fit statistics for the time-varying growth-climate models fit to the spruce tree ring data.

Data set *		MVNR**	MVNR 95% interval		C^* †	$P(C)$	R^2 ‡	DF§
lAWC	young	1.606	1.525	2.475	0.986	0.328	0.65	70
	medium aged	1.690	1.574	2.426	0.496	0.621	0.71	87
	old	1.824	1.574	2.426	0.664	0.508	0.73	87
hAWC	young	1.385	1.525	2.475	0.537	0.593	0.29	70
	medium aged	1.801	1.574	2.426	0.134	0.893	0.69	87
	old	2.047	1.574	2.426	1.105	0.272	0.55	87

* lAWC resp. hAWC: chronologies of trees from sites with lower resp. higher available moisture storing capacity.

** MVNR: Modified Von Neumann Ratio (Harvey 1989; Van Deusen 1990). The 95% MVNR confidence interval gives the limits within which model fit is acceptable.

† The C^* test is based on the sum of the standardized prediction errors and indicates misspecification of the model if the probability of a greater absolute value of C^*, $P(C^*)$, is small.

‡ The R^2 statistic is an analogy to the usual OLS value (Harvey 1989 p. 268; Van Deusen 1991), but it is possible that adding a variable will reduce R^2.

§ Degrees of freedom.

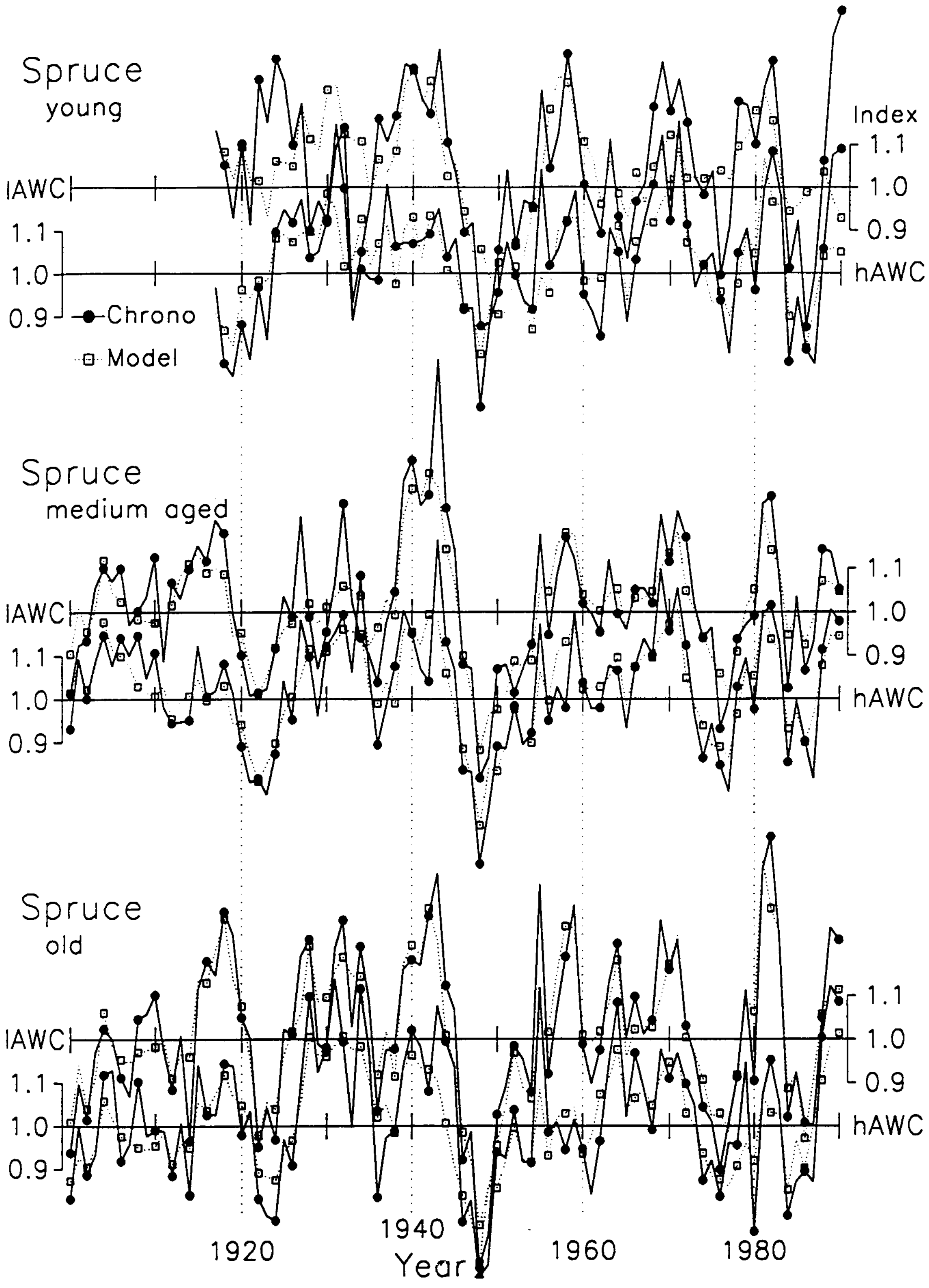

Figure 3. Chronologies and growth-climate models - Spruce.
The two-variable growth-climate models (dashed, for explanation see text) are shown together with the chronologies (solid lines; *LAWC* resp. *HAWC*: chronologies of trees from sites with lower resp. higher moisture storing capacity). Data are standardized to a mean of 0 and a standard deviation of 1.

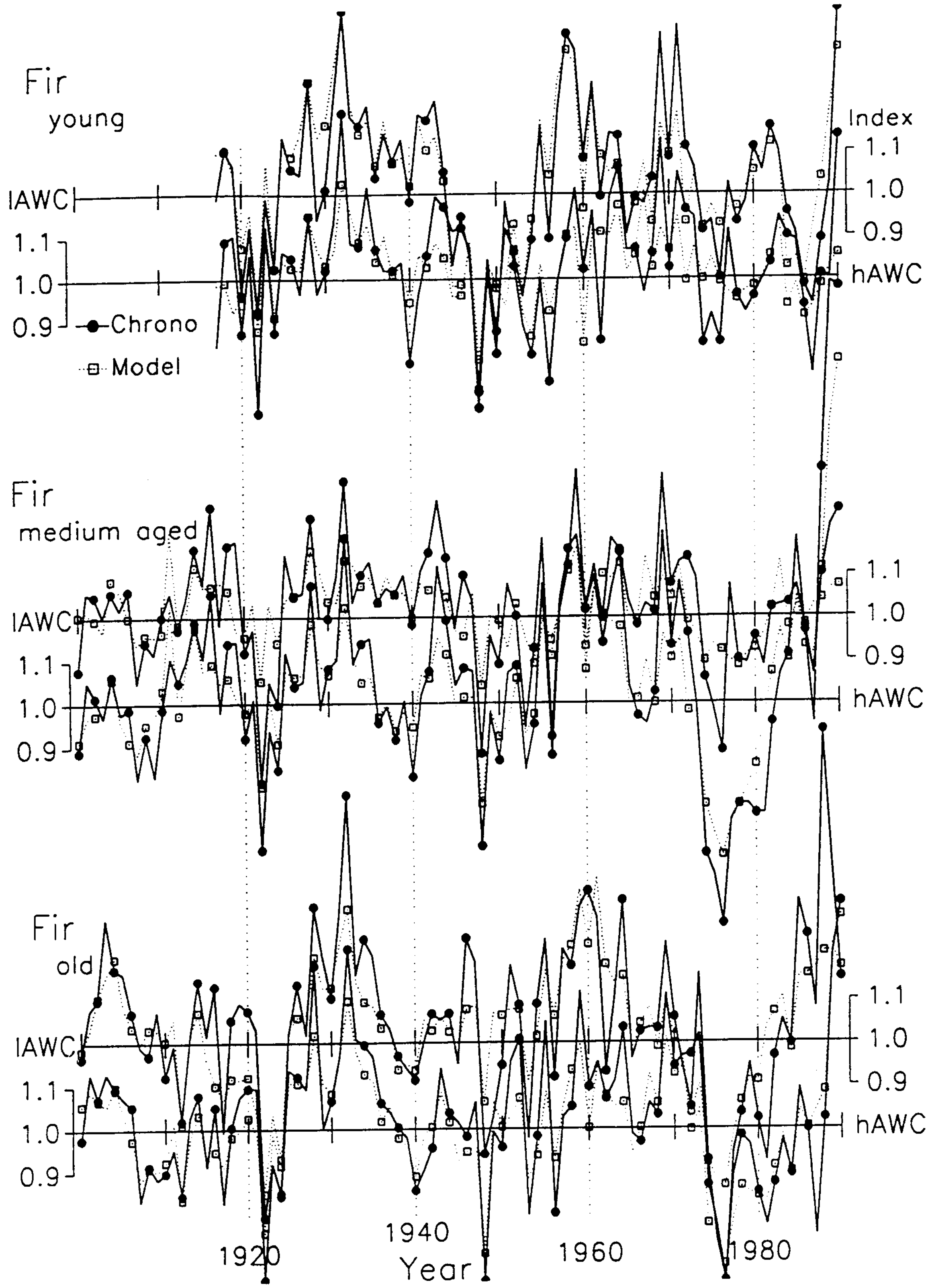

Figure 4. Chronologies and growth-climate models - Fir.
The two-variable growth-climate models (dashed lines, for explanation see text) are shown together with the chronologies (solid; *LAWC* resp. *HAWC*: chronologies of trees from sites with lower resp. higher moisture storing capacity). Data are standardized to a mean of 0 and a standard deviation of 1.

The modified Von Neumann Ratio is only in one case slightly below the 95% limit (hAWC-young trees), which suggests positive correlation in the prediction errors (Harvey 1989; Van Deusen 1990). The C^* test shows no significant trend as judged by $P(C^*)$, which gives the probability of obtaining a larger absolute value of C^* under the null hypothesis of no trend. The R^2 values are all highly significant. Beside the exception mentioned above the fit statistics don't indicate any particular lack-of-fit problem of the growth-climate models. The same is true for the fir models. The R^2 values with fir are between 0.39 and 0.78.

5. Discussion

Time delayed responses of radial growth of Norway spruce to climatic inputs have been observed frequently, especially following severe droughts (e.g., Krauß 1948; Wiedemann 1925). Quantitative assessment of drought induced growth depressions with regard to delayed effects was investigated early (Weck 1948), but has virtually been neglected for several years. Bernhart (1963) and Spiecker (1986) referred to Weck's work and confirmed his findings (see also Henttonnen 1984; Münster-Swendsen 1984). The phenomenon of lagged growth responses has gained much interest in the dendroecological literature (e.g., Fritts 1976 pp.193). Most tree ring series exhibit significant autocorrelation, even after major sources of serial correlation have been removed through detrending (e.g., Monserud 1986). Different strategies have been suggested to handle its statistical implications (for more extensive discussions see Cook 1985, 1987; Blasing et al. 1984; Briffa et al. 1987; Fritts et al. 1971; Guiot 1986; Guiot et al. 1982). With the models described in this study we mainly tried to reduce this subject to its main determinants based on well developed methods in econometric literature. However, the method described here is also affected by some weak points e.g.,

- the cross-correlation analysis reduces the selection of influential variables to the bivariate case without temporal variation, which is a strong simplification of the real underlying mechanisms.
- the relationships between climate variables and growth responses are handled as if they were linear, but it is more likely that they are nonlinear.

The persistence in tree ring data has been interpreted extensively by Fritts (1976 e.g., p.186, p.188, pp.193), and some of its causes may be summarized under *physiological preconditioning* which is defined by Fritts (1976 p.541) as: "The induction of internal metabolic conditions which can influence the biochemical reactions and other processes of a plant during later stages in its life cycle". The external forces inducing these metabolic alterations may either serve as energy sources for the induced processes or may function as signals which trigger certain metabolic mechanisms without being matter or energy source. Both aspects can well be integrated in an interpretation based on adaptive mechanisms. Therefore the lagged growth responses to variations in air temperature and precipitation regimes may be interpreted as modificative phenological adaptations to changing environmental conditions. Inertia of tree growth response to climatic inputs only allows for partial adjustment to new environmental conditions and therefore results in the long memory behaviour of the spruce chronologies as indicated in the presented study.

The time-varying coefficients of the climatic water balance during July and August of the five preceding years show synchronously increasing trends since the beginning of the century. The following aspects should be considered when explanation of this phenomenon is assessed. Possible causes for the indicated structural changes may be (1) general or partial misspecification of the growth-climate model, e.g. due to omitted variables (2) structural changes in the selected input variables themselves, or in their interactions and interrelations (3) changes in sensitivity of radial growth to variations in climate.

Diagnostic checking of the models revealed that general misspecification is unlikely to be the cause for the observed structural change. However, it remains possible that new exogeneous variables, especially increased CO_2 levels in the amtosphere and increased atmospheric nitrogen input may cause altered sensitivity of radial growth to moisture deficits in late summer (Spiecker 1987). In addition it cannot be excluded that part of the increase in the model coefficients is due to ageing effects which are probably not completely filtered out through the standardization process. The unprecedented high frequency of years with extremely warm and dry late summer months during the recent decades seems to be the most likely cause for the observed structural changes.

6. Summary

The effects of climate variations on radial growth of Norway spruces (*Picea abies* (L.) KARST.) and silver fir (*Abies alba* Mill.) and interactions between growth and site conditions are quantified. Radial growth data are derived from cross-section analysis. The sampling sites were selected pairwise to compare extremes in the available moisture storing capacity of the soil. A network of long-term synoptic meteorological data has been assembled from meteorological stations of the German Weather Service. Cross-correlation analysis of unwhitened and prewhitened chronologies is used for selection of influential variables and for identification of transfer function models. The general transfer function model is incorporated into time-varying coefficient models which are calculated with Van Deusen's DYNACLIM (1992) software.

Material from all sites shows close inverse correlations with potential evapotranspiration from April to June and close direct correlations with the climatic water balance during July and August of preceding years. This was unexpected because, on average, precipitation is high and air temperature is relatively low in the study sites. Persistence in growth responses is more pronounced in spruce than in fir, and more pronounced in chronologies of older than of younger trees. The lagged growth response to climatic inputs is interpreted in terms of phenological adaptation by successive partial adjustment of tree vitality to changing environmental conditions.

7. References

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