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Forest growth response to changing climate between 1961 and 1990 in Austria

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Abstract

Using 30 years of climate records from 20 weather stations, we investigate the magnitude of temperature and precipitation change, and change in the length of the growing season between 1961 and 1990. Special attention is paid to the period between 1981 and 1990, because recent research suggests that, during this time span, forest productivity may have increased in the northern latitudes. In order to understand the importance of changes in climate on forest growth, we use the ecosystem model FOREST-BGC as a diagnostic tool to predict the annual net primary production (NPP). The results of our study indicate: no change in precipitation between 1961 and 1990; a significant ($\alpha = 0.05$) increase in mean annual temperature of 0.72°C, mean annual minimum temperature (0.80°C), winter temperature (2.36°C) as well as an increase in the length of the temperature-controlled growing season by 11 days, resulting in a significant increase in diameter increment obtained from 1179 cores of Norway spruce across Austria. The trends in NPP are consistent with observed increment rates validating the use of biogeochemical modeling as a diagnostic tool to search for possible causes on changing environmental conditions. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Growth trends; Climate change; Growth and yield; Norway spruce; FOREST-BGC model

1. Introduction

During the 1970s many researchers expected a forest growth decline in Europe on account of air pollution (European Commission, 1994). However, recent research suggests that vegetation productivity may have increased in Central and Northern Europe (Kauppi et al., 1992; Spiecker et al., 1996; Myneni et al., 1997). Furthermore, the Austrian National Forest Inventory (Schieler and Schadauer, 1993; Schadauer, 1996) reported an increase in current annual volume increment of 17% in the 1980s. It is important to note that the studies by Kauppi et al. (1992) and Schieler and Schadauer (1993) did not explicitly remove pos-

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sible effects on forest growth due to changing stand age, reforestation of agricultural land resulting in highly productive timber stands, and treatment impacts on forest growth.

Although forests in Austria are managed intensively, the mean stand age as well as the mean stem number per unit area has remained similar over the last 30 years (Schadauer, 1996). This suggests that changes in stand treatments, such as increased thinning intensity or fewer planted trees per unit area, may have influenced the growth on a stand level, but do not explain the observed increment rise throughout Austria. Obviously, other ecological factors, such as increased nitrogen deposition, increased CO_2 concentration, reduced acid deposition and ozone concentration as well as changes in climate (temperature and precipitation), may have caused the recent productivity changes.

Among the three most logical causal factors (nitrogen, CO_2 and climate), CO_2 concentration has continuously increased (Keeling et al., 1995) and nitrogen deposition rates of up to 4 g/m^2/year (Katzensteiner and Glatzel, 1998) have been evident in Austria since the early 1960s. For the 1980s, the NO_x emission has continuously decreased from 230.7 million kg in 1980 to 176.5 million kg in 1990. During this time span (1980–1990), CO_2 emissions remained constant for Austria at ca. 60 million t/year (Statistisches Jahrbuch, 1996). In the 1980s, however, only climate has been reported to have changed for northern latitudes including Austria (Auer and Böhm, 1994). This has resulted in shorter periods of lake ice-cover for high mountain lakes in the Austrian Alps (Sommaruga-Wögrath et al., 1997). Furthermore, the annual snow cover over the northern hemisphere decreased by 10% over the past 20 years due to an increase in surface air temperature (Groisman et al., 1994). Therefore, it seems reasonable that, in an alpine country like Austria with maximum precipitation during the growing season (Auer, 1993; Böhm, 1992), lengthening of growing season as a result of warmer temperatures in combination with changes in environmental conditions could have improved forest productivity.

An important problem in studying productivity changes are the complex ecophysiological interactions which affect carbon uptake and forest growth, respectively. Changes in climate will influence many of these processes, such as transpiration, respiration, etc. and, consequently, affect the transformation and transport of energy, carbon, water and nutrients depending on stand and site conditions. Due to the complex ecophysiological interactions, biogeochemical models are employed to study and quantify the impact of potential climate change on forest growth (VEMAP Members, 1995).

The purpose of our study is to analyze the impact of climate on forest productivity between 1961 and 1990 in Austria. The outline of our work is as follows:

1. We evaluate possible trends in climate parameters such as precipitation, temperature and the length of temperature-controlled growing season.
2. We use an ecosystem model, FOREST-BGC (Running and Coughlan, 1988) to predict annual net primary production (NPP), a key terrestrial carbon cycle variable that is related to forest growth. FOREST-BGC combines important interactions among plant growth and climate parameters such as minimum and maximum temperature, precipitation, changes in cloud cover, solar radiation, etc., and possible changes in photosynthesis and the respiration balance of plants. Therefore, the model is used as a diagnostic tool to explain changes in forest growth.
3. Finally, we compare our NPP simulations with observed diameter increment rates using 1179 increment cores of Norway spruce from all over Austria.

2. Methods

2.1. The ecosystem model

The biogeochemical model FOREST-BGC (Running and Coughlan, 1988) is a mechanistic ecosystem model that calculates the cycling of carbon, water, and nitrogen through forest ecosystems. The model requires daily standard meteorological input data, such as minimum and maximum temperatures, precipitation, dew point and incident shortwave radiation. Furthermore, leaf area index (LAI) and the soil water-holding capacity have to be initialized. FOREST-BGC has a mixed time resolution: the hydrologic, photosynthetic, respiration processes are computed daily and the carbon uptake including the tree growth and nitrogen processes are computed yearly. The model calculates canopy interception and evaporation, tran-

spiration, soil outflow of water, photosynthesis, growth and maintenance respiration, allocation, litter decomposition of carbon, deposition, uptake, litterfall and the mineralization of nitrogen.

Daily precipitation is allotted to snowpack or soil depending on the air temperature. A canopy interception fraction based on LAI is subtracted and evaporated. The remaining water goes to soil where it is available for transpiration. Daily transpiration rates are calculated using a Penman–Monteith equation incorporating radiation and vapor pressure deficit. The canopy conductance term is a function of air temperature, vapor pressure deficit, incident radiation and leaf water potential. Air temperature below 0°C reduces canopy conductance to cuticular values, which are important for determining the length of the growing season.

Canopy photosynthesis is calculated daily by multiplying a CO_2 diffusion gradient by a mesophyll CO_2 conductance and the canopy water vapor conductance, both of which are controlled by radiation and temperature. Net photosynthesis (PSN) is computed by subtracting a maintenance respiration term, calculated as an exponent function of air temperature with $Q_{10} = 2.0$ for all stem and root biomass. Subtracting 35% of the remaining PSN for growth respiration gives the final annual net primary production (NPP), which is partitioned into leaf, stem and root compartments as a function of the minimum leaf growth based on the model predictions for carbon, water and nitrogen. The leaf/root partitioning ratio is based on the soil water balance and determines the carbon allocation to roots. The remaining carbon goes to the stem wood. Growth respiration calculated is a function of the carbon allocated to growth for each compartment (leaf, root, and stem).

In this study, we are interested in the response of the carbon balance expressed as NPP. Annual net primary production depends on the hydrologic balance, evapotranspiration and canopy water stress, photosynthesis, and the maintenance and growth respiration of the different compartments. The appropriateness of using this model to describe the carbon, water and nitrogen cycle within forest ecosystems has been tested extensively, as is its applicability in describing the possible carbon balance response of forests resulting from climate change (Running and Nemani, 1991).

3. Data

3.1. Climate data

Daily climate records came from the Austrian National Weather Center in Vienna, Austria. We defined six growth regions according to Killian et al. (1994), representing the major forest eco-climatic conditions in Austria (Fig. 1). The six regions are:

1. the Central and northeastern central Alps;
2. the northern Flysch Alps and the calcareous Alps;
3. the hills and plains between the Alps and the Danube;
4. the Austrian part of the Bohemian Massif;
5. the southeastern edge of the Austrian Alps and the eastern pannonic semiarid region; and
6. the southern calcareous Alps.

We selected 20 weather stations across Austria, at least two stations in each of the six forest growth regions, all with a full climate record of daily minimum and maximum temperatures and precipitation between 1961 and 1990. For five out of the 20 weather stations, we additionally obtained the daily sunshine duration since 1961.

3.2. Forest growth data

Increment information came from two different data sources (Sample A and B) including 1179 increment cores of dominant Norway spruce (*Picea abies* L. Karst) across all age classes and site conditions (Table 1). Norway spruce is the most important tree species in Austria, representing 61% of the timber growing stock (Schieler et al., 1995) and grows in all major forest areas. Furthermore, the increment cores

Table 1
Distribution of the 1179 increment cores of dominant Norway spruce trees from Austria by age class. Sample A consists of 614 cores, each representing one Norway spruce stand in Austria. Sample B consists of 565 increment cores from 40 different spruce stands

Sample	Number of increment cores by age class (years)					
	20–40	41–60	61–80	81–100	101–120	121–140
A	36	111	154	127	104	82
B	25	25	66	94	90	265

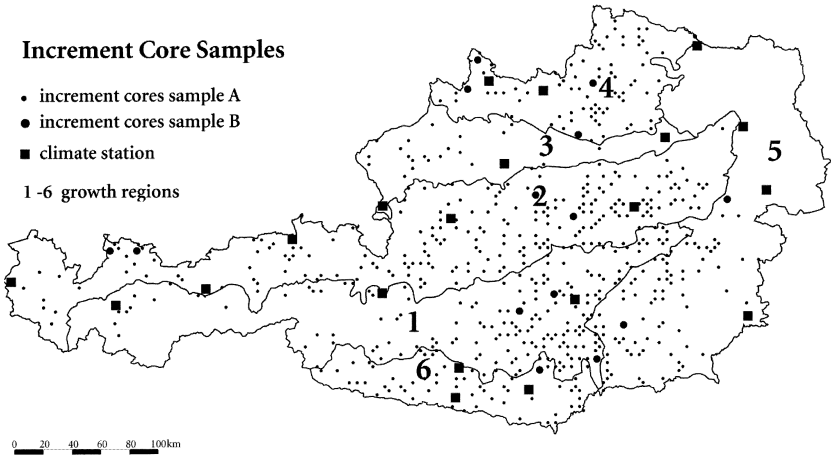

Fig. 1. The six growth study regions including the 20 weather stations with daily climate records between 1961 and 1990, and the 1179 increment cores for Norway spruce. The six growth regions represent a simplification of the nine growth districts of Killian et al. (1994) and characterize the major forest climatic conditions in Austria: Region 1. central Alps, northeastern central Alps (continental and subcontinental zone, high elevations, cold and wet, dominated by Norway spruce); Region 2. northern Flysch Alps and calcareous Alps (subalpine areas, oceanic influence, wet – areas with the highest precipitation rates in Austria – to moderately wet, fir in subalpine areas, Norway spruce and common beech); Region 3. hills and plains between the Alps and the Danube (moderately wet to moderately dry, mixed common beech stands); Region 4. Austrian part of the Bohemian Massif (moderately wet and very cold, in winter but dry and warm during summer, mixed common beech stands); Region 5. Southeastern edge of the Austrian Alps (dry to moderately wet, Norway spruce, fir and common beech) and eastern pannonic semiarid region (dry and warm summer with low winter temperatures, areas with the lowest annual precipitation rates in Austria, dominated by mixed oak stands); and Region 6. southern calcareous Alps (illyric climate, wet to moderately dry with long frost periods in winter in the inner alpine valleys, Norway spruce, fir and common beech).

for this tree species are easily obtained ensuring good data quality.

Sample A was obtained from permanent sample plots established by the National Forest Inventory in Austria (Forstliche Budesversuchsanstalt, 1994). These sample plots were established between 1981 and 1985 and are systematically distributed over Austria every 3.89 km. In a given year, every fifth plot was measured, ensuring an evenly distributed sample of all Austrian forests each year. In the first remeasurement between 1986 and 1990, one increment core of a dominant tree was bored at breast height (1.3 m above the ground). No increment cores were obtained in the second remeasurement between 1991 and 1996. In summary, Sample A consists of 614 increment cores, each representing one typical Norway spruce stand in Austria (Fig. 1).

Sample B came from research plots established by the Institute of Forest Growth Research at the Universität für Bodenkultur in Vienna, Austria, and consists of increment information from 565 cores across 40 different Norway spruce stands distributed over 14 locations (Table 1, Fig. 1). Again, each increment core was bored at breast height (1.3 m above the ground). Because the 1179 increment cores represent growth information from 654 different stands (Sample A = 614 stands, Sample B = 40 stands), the sample size is large and representative, and the data are an excellent source for evaluating forest growth trends in Austria.

4. Analyses

For each of the 20 weather stations, we apply simple linear regression to explore possible trends in the following climate parameters:

1. total precipitation;
2. mean annual temperature ((max + min)/2);
3. mean annual minimum temperature;
4. maximum temperature;
5. winter temperature;
6. summer temperature;

Table 2
Trends in precipitation, average, wintere and summer temperatures and the number of growing days in Austria for the growth period between 1961 and 1990. The results show the magnitude of the detected change given by the calculated trend lines. The given climate parameters represent the arithmetic mean obtained from the 20 weather stations available for this study

Trend in	Growth period					
	1961–1990		1961–1980		1981–1990	
	change	SE	change	SE	change	SE
Mean annual precipitation (mm)	−47	114.7	−62	131	62	80
Mean annual temperature (°C)	0.72 *	0.50	0.21	0.51	0.68	0.50
Mean annual minimum temperature (°C)	0.80 **	0.45	0.42	0.47	0.60	0.43
Mean annual maximum temperature (°C)	0.66 +	0.60	−0.01	0.59	0.74	0.62
Winter temperature (°C) [a]	2.36 *	1.40	2.80 *	1.41	1.57	1.34
Summer temperature (°C) [b]	0.39	0.53	−0.33	0.54	0.44	0.47
Growing season length (days) [c]	11 *	10	−1	10	20 +	9
Sunshine duration of the growing season (h)	−21.8	112.1	−134.2	98.5	145.0	127.1
Net primary production – NPP (%) [d]	3.5	4.0	−1.0	3.6	6.3	4.5
Mean annual increment index (%) [e] Sample A	9.5 *	5.9	1.9	6.4	8.0	5.4
Mean annual increment index (%) [e] Sample B	10.8 *	5.7	−0.9	5.4	6.8	5.0

[a]Defined as the mean annual temperature development of those months which exhibited an average monthly temperature <0°C in 1961.
[b]Temperature development of those months with an average monthly temperature >0°C in 1961.
[c]Sum of the days with an average temperature >5°C.
[d]Based on the NPP production in 1961 and 1981, respectively.
[e]Based on the mean annual increment index in 1961 and 1981, respectively.
+Significant, $\alpha = 0.10$.
*Significant, $\alpha = 0.05$.
**Significant, $\alpha = 0.01$.

7. length of the growing season; and
8. the sunshine duration of the growing season.

Using 1961 as the base year, winter temperature for each year was computed as the average temperature of the months which exhibit a monthly mean temperature of <0°C. All months with a mean temperature of >0°C in 1961 are considered as summer months. The length of the growing season is defined as the number of days with a mean daily temperature >5°C and represents days where photosynthesis and carbon fixation may have taken place. The results are given in Table 2.

The ecosystem model FOREST-BGC (Running and Coughlan, 1988) is run for each of the 20 sites to determine the annual NPP between 1961 and 1990. Climate data for the year 1960 are used as an adjustment run. FOREST-BGC requires minimum and maximum temperatures, precipitation, humidity and incident solar radiation. Humidity, as well as incoming solar radiation, are derived using MT-CLIM, a microclimate simulation model developed for mountainous terrain (Running et al., 1987). Besides daily climate records, FOREST-BGC also requires the LAI, and soil water-holding capacity as additional data inputs. LAI is important for predicting canopy interception and evaporation, transpiration, canopy light attenuation, photosynthesis, and canopy nitrogen content. For our analyses, we assume a double-sided LAI of 10 m^2/m^2 (closed timber stand) and a soil water-holding capacity of 15 cm across all locations. As we wish to investigate only climate trends to our growth data, leaf nitrogen, stem nitrogen, soil nitrogen, etc. are assumed to be constant across all locations and throughout the simulation period. Thus, differences in the annual NPP predictions can result only from varying daily climate records over time.

Tree age as well as annual tree ring widths of the 1179 cores are measured with the digital positiometer (Johann, 1977). The last measurement of each increment core is removed because radial increments were obtained during the summer months when the growing season of this year was not yet completed.

An important concern in evaluating dendrochronological data is that age trends have to be removed

without eliminating possible growth trends. We chose the method proposed by Becker (1989) based on the relationship between cambial tree age and the mean annual radial growth increment for all age classes and sites. After cross-dating the increment cores to detect single missing values, we calculate the mean annual radial increment according to the ring age for the whole data set.

Next, we calculate the deviations from the standard as growth indices, in percent, for each individual radial growth series. Essentially, we compare the relative change (increase/decrease) of a given increment core by dividing the actual ring width with the corresponding standard value of this age to eliminate the age trend. For example, indices >100 indicate higher increments than expected from the age trend. Again, simple linear regression is applied for both, the mean annual NPP predictions as well as for increment indices to predict the corresponding regression trend lines between 1961 and 1990 (Table 2, Fig. 4).

Note that in Table 2 all trend changes presented refer to changes in regression values rather than actual values to avoid unreasonable findings caused by randomly high starting or ending values. The slope parameters of the linear regression runs indicate the direction (increasing or decreasing) as well as the

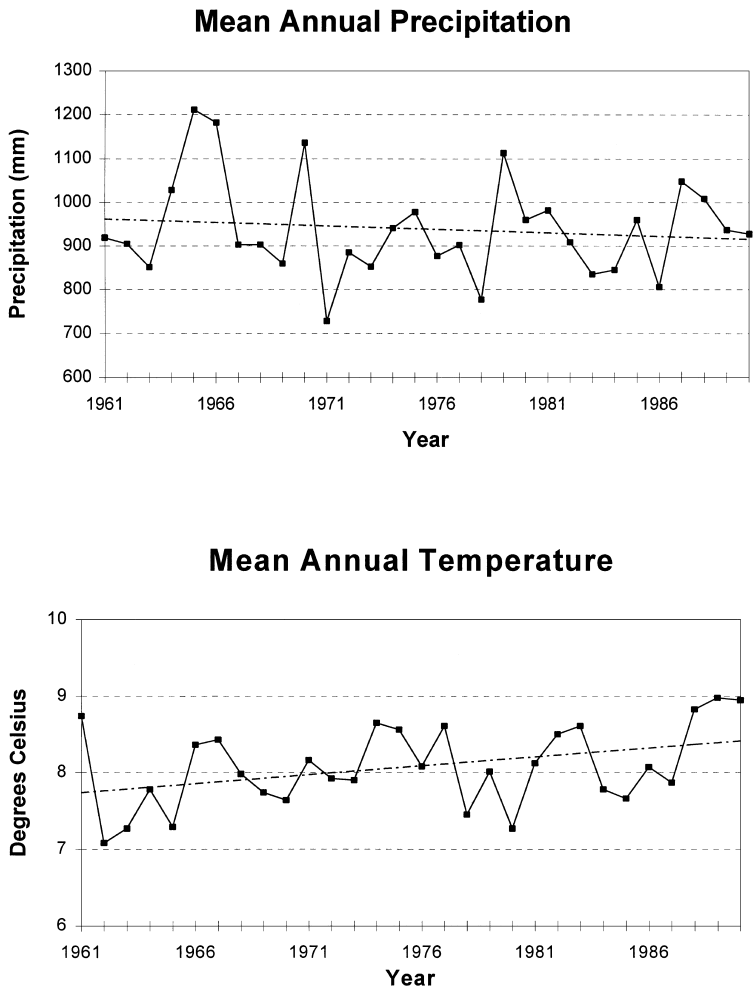

Fig. 2. Mean annual precipitation and temperature development, including the corresponding trend lines for the time spans 1961–1980 and 1981–1990. The numbers represent the mean annual development of the 20 weather stations.

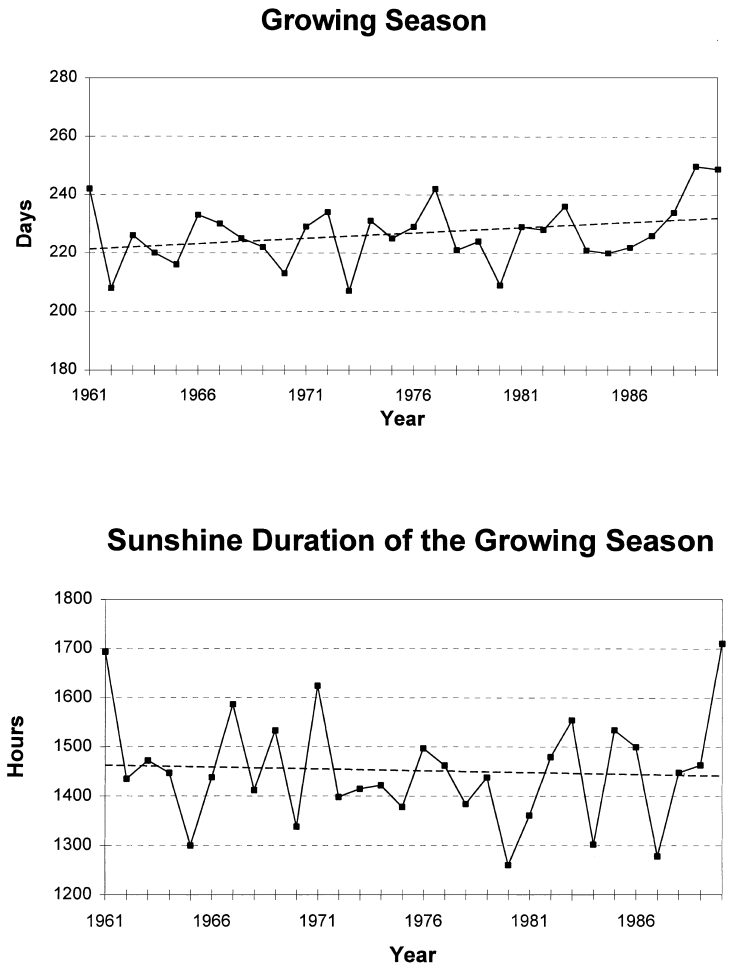

Fig. 3. Development of the growing season length and the sum in sunshine duration of the growing season since 1961. The length of the growing season is defined as the number of days with a mean daily temperature >5°C, indicating days on which photosynthesis and carbon fixation may have taken place.

magnitude of changing climate and growth parameters within a given time span.

5. Results

Between 1961 and 1990, the length of growing season has significantly ($\alpha = 0.05$) increased by 11 days associated with a mean annual temperature increase of 0.72°C (Table 2, Figs. 2 and 3). Furthermore, a significant ($\alpha = 0.05$) increase in winter temperature (2.36°C) and a highly significant increase ($\alpha = 0.01$) in the mean annual minimum temperature (0.80°C), both important indicators of the growing season length, are evident since 1961 (see Table 2). While maximum temperature has increased by 0.66°C ($\alpha = 0.10$, Table 2), summer temperature as well as mean annual sunshine duration of the growing season (Fig. 3) have remained constant during the whole time span.

The simulation runs with FOREST-BGC indicate an increase in NPP of ca. 3.5% which is not significant. Table 2 gives the mean relative change in NPP in Austria and Fig. 4 presents the mean annual NPP predictions plus the corresponding regression line for the time period from 1961 to 1990. The forest

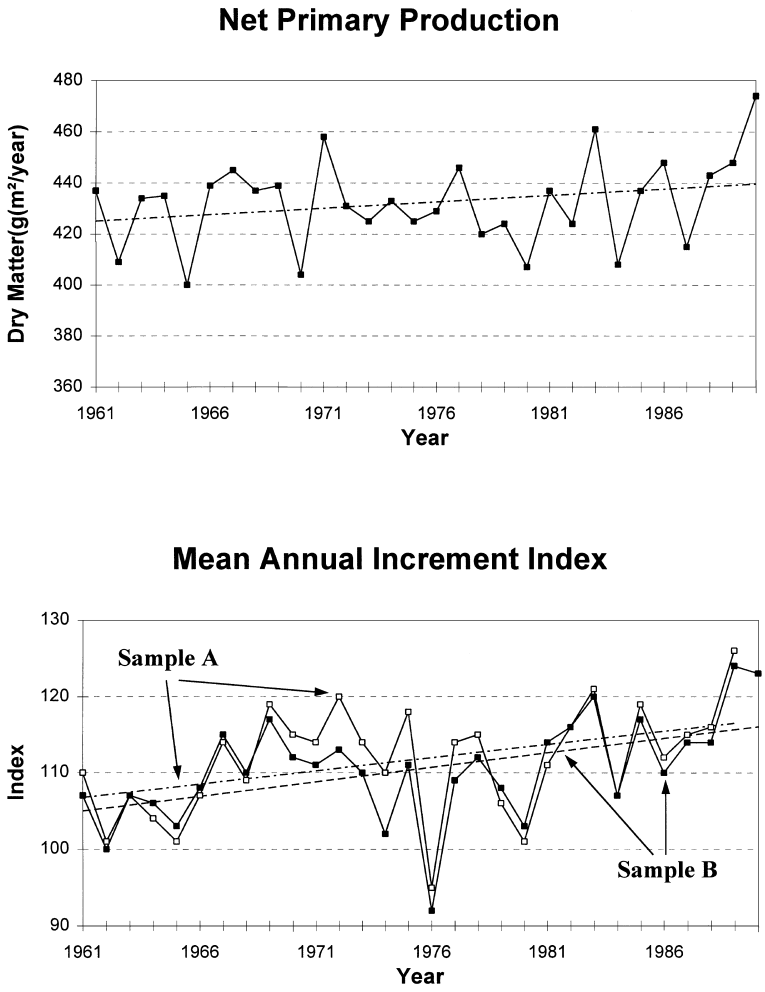

Fig. 4. Mean annual net primary production (NPP) vs. the increment index development for Norway spruce plus the calculated regression line for the time span 1961–1990. The NPP represents the average mean annual development simulated for the 20 weather stations. Sample A gives the mean annual increment index from the 614 systematically distributed permanent plots of the National Forest Inventory. Sample B summarizes 565 increment cores from 40 different spruce stands.

growth-trend analyses has resulted in a significant increase ($\alpha = 0.05$) of the mean annual increment index of 9.5% (Sample A) and 10.8% (Sample B) since 1961, mainly because of the increasing trend during the late 1980s (Table 2, Fig. 4).

It is difficult to estimate how much of the NPP is allocated to stem wood as it depends on a number of biotic and abiotic factors (Running and Coughlan, 1988). Therefore, we restricted our analyses to see how well the NPP predictions relate to the tree measurements using a large and representative sample of increment data from all over Austria. The analyses of variance showed a significant ($\alpha = 0.05$) relationship for Sample A (F-value $= 7.4$, $n = 29$) as well as for Sample B (F-value $= 10.5$, $n = 30$) between the mean annual NPP predictions and the increment indices given in Fig. 4.

Most of the growth indices in Fig. 4 are above the 100 level. Although we are only interested in the development since 1961, the data available would allow for a growth trend analysis since 1870 (see Neumann and Schadauer, 1995; Schadauer, 1996). Similar to tree-ring width development in Mongolian forests (Jacoby et al., 1996), our data show a slight

increase in the mean annual increment index of ca. 1% for the 10-year period before 1961. Thus, most of the growth indices since 1961 are >100.

Because recent research suggests that during the 1980s forest productivity may have increased (Myneni et al., 1997), we additionally split our data in two different time spans: 1961–1980 and 1981–1990. Essentially, we are interested in noting whether the findings of Myneni et al. (1997), based on the normalized difference vegetation index (NDVI) derived from satellite data, are consistent with those of our study. For both the time spans, again, a simple linear regression has been applied to our climate, simulated NPP and growth data to explore if the slope parameters between the two time periods may have changed, an indication of changing trends. The results are given in Table 2. Please note that the numbers presented are the regression lines of the two different time periods. Thus, summarizing the changes between 1961–1980 and 1981–1990 may be different from the numbers presented over the whole time span.

A first regional trend analysis of the data shows that growth regions 1, 2, 3, and 4 of Austria (see Fig. 1) tend to exhibit a higher increase in average temperature, number of growing days as well as NPP in the 1980s vs. the time span 1961–1980. The highest increase in NPP is evident in growth Region 4 (23% increase in NPP). This region of Austria is part of the Bohemian Massif (700–900 m) and is characterized by moderately wet and very cold winter months and warm, dry summer months. The alpine parts of the country (growth regions 1 and 2) show the highest increase in the number of growing days (25 days), but the lowest improvement in NPP (ca. 5–10%).

Using the increment data of Sample A, which covers 614 spruce stands in Austria (Fig. 1), the mean annual increment index across different elevation groups exhibit an increase within the 1980s of ca. 20% for plots below 900 m ($n = 200$), 7% between 900–1300 m ($n = 285$) and an ≈2% increase in the mean annual increment index for all cores from plots ($n = 129$) above the 1300-m altitude. Similar findings of diminishing growth in higher altitudes have been reported for Austria (Schadauer, 1997) and for the Bavarian mountains in southern Germany (Pretzsch, 1996).

6. Discussion

Austrian forests have responded to the warmer climatic conditions. The mean annual, minimum and winter temperatures have increased continuously which has resulted in a significant change in the number of growing days and increased increment indices for Norway spruce between 1961 and 1990.

The trends between the observed growth rates and the simulated NPP are quite similar over the simulation period and predicted annual NPP was related to the increment indices of our two growth samples, validating the use of FOREST-BGC as a diagnostic tool to search for possible causes of changing growth trends. Although CO_2 and nitrogen is kept constant, physiological-based models allow us to integrate and better interpret the complex ecophysiological processes which have promoted forest growth.

Our results confirm that the carbon cycle has responded to an increase in the length of the growing season from warmer temperatures. These findings are strongly supported by a recent phenology study (Menzel, 1997) which shows that bud burst tend to take place earlier in spring across Europe (ca. 0.5–1 day/year) mainly due to increasing temperatures during the last 20 to 30 years. The climate data show that the largest changes in air temperature and growing season length occurred between 1987 and 1990. Forest growth also responded strongly to these changes, evident from both NPP estimates as well as increment data (Fig. 4).

Our results suggest that the number of days with snow cover, one of the main limiting factors for plant growth in Austria, has decreased. This is consistent with a study by Koch and Rudel (1990), which reports a strong correlation between the number of days with snow cover and the average winter temperature. These authors conclude that a temperature increase of 1°C leads to a decrease of 25 days with snow cover. In our study, we have found an increase in the mean annual temperature of 0.72°C, which has resulted in 11 additional growing days since 1961. For the late 1980s, similar tendencies of decreasing numbers of days with snow cover have been reported for the Alpine areas of Austria (Mohnl, 1991) resulting in shorter lake ice-cover (Sommaruga-Wögrath et al., 1997). No changes in precipitation are evident (Fig. 2, Table 2).

Between 1961 and 1980, only winter temperatures have improved significantly ($\alpha = 0.05$), by 2.8°C. While precipitation, maximum and summer temperatures, sunshine duration as well as NPP and the increment index of Sample B has decreased slightly, temperature, minimum temperature, growing season length and the increment index of Sample A has increased (see Table 2). In the 1980s, however, all investigated climate and growth parameters increased. Although most of the trends are not significant, the numbers in Table 2 suggest that most of the detected significant trends between 1961 and 1990 are due to improved climatic conditions, particularly in the late 1980s. The only exception is the temperature-controlled growing season length which has improved by 20 days ($\alpha = 0.10$, see Table 2). The covariance analysis exhibited an increase in the slope parameter for the 1980s vs. the time span 1961–1980.

NPP estimates show an increase of 6.3% between 1981 and 1990 vs. −1.0% between 1961 and 1980. The mean annual increment index, calculated from 1179 increment cores, increased by 8.0% (Sample A) and 6.8% (Sample B) during 1981–1990 vs. only 1.9% (Sample A) and −0.9% (Sample B) during 1961–1980, respectively. The results are consistent with the previous findings of Myneni et al. (1997), who estimated an 11% increase in plant growth for the northern latitudes (45°–70°N) during this time span.

7. Conclusion

Significant changes in growing season length found in this study may have profound effects on the functional aspects of ecosystems. In our analysis, we used FOREST-BGC to search for possible causes of the growth trends detected since 1961. Although no change in nitrogen deposition as well as CO_2 concentration were considered, the resulting NPP predictions were related to tree measurements. This suggests that biogeochemical modeling is an appropriate tool to investigate the complex interactions among plant growth and climate parameters under changing environmental conditions.

While trees can respond by vigorous growth to climatic changes discussed in this study, the long-term effects of such stimuli are unknown. A comprehensive understanding is required to project the state of ecosystems into the future in response to changes in climate and biogeochemistry. Simulation models, when coupled with carefully planned field experiments, could assist in understanding the future course of ecosystems.

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