SCOTS PINE GROWTH TRENDS IN NORTHWESTERN KOLA PENINSULA AS AN INDICATOR OF POSITIVE CHANGES IN THE CARBON CYCLE

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Abstract. Growth trends of Scots pine (*Pinus sylvestris*) at its northernmost extent may be an indicator of changes in the carbon cycle of terrestrial forest ecosystems. Using a method which removed age trends from the data, a time-series analysis of annual radial increment in wood over the last few decades compared with the period of the last registered warming (maximum around 1930–40), revealed elevated growth of 78% for trees 0–20 years old, 56% for trees 21–40 years old, 21% for trees 41–60 years old, and 10% for trees more than 101 years old. Increments of trees in the 61–80 and 81–100 years old age classes from the two periods were similar. The higher rate of growth in recent times occurred despite a decrease in temperature after about 1940 and significant air pollution. During the last century growth of Scots pine increased for trees in all age groups, except for trees in the 81–100 year old age class for which it was constant. The average rates of growth were estimated at 0.016 mm/year for trees in the 0–20 year age class, 0.012 mm/year for the 21–40 year age class, 0.005 mm/year for the 41–60 year age class, 0.008 mm/year for the 61–80 year age class and 0.006 mm/year for trees in the greater than 101 year age class. The growth trends were unstable over time and took place concurrent with increasing oscillations in radial increment. The most probable reasons for the marked increase in radial increment growth of Scots pine in this region are climate warming and higher levels of carbon dioxide. Together these may produce a synergistic effect on growth.

1. Introduction

Research on the carbon cycle is usually focused on carbon pools and flows. Over the last few decades a number of excellent papers, books and overviews relevant to this topic have been published (Bydiko, 1977; Kondratiev, 1987; Bydiko and Israel (eds.), 1987; Borisenkov and Kondratiev, 1988; Borisenkov (ed.), 1988; Climate Change, 1990; Climate in Crisis, 1990; Kolchugina and Vinson, 1993a, 1993b; Gorshkov, 1994; Vitousek, 1994; Weizsaecker, 1994; Lakida et al., 1996; Mannion, 1998; Alekseyev and Birdsey (eds.), 1998). However, the carbon cycle is not in a steady state and is subject to continuous and significant fluctuations. Therefore, an analysis of the direction and size of current and historical changes in carbon flows is critical to predicting carbon flows and pools into the future. One of the major processes in the carbon cycle of forest ecosystems is accumulation of carbon in wood, changes of which can be inferred from variations in forest tree

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and stand growth. So, understanding trends in forest growth, which may be caused by changes in the forest's environment (such as warming), is important to understanding the carbon cycle especially with regards to the ability of the biosphere to compensate for environmental changes.

Currently forests are also affected by air pollution at local, regional and even global scales, and by a number of other random factors at a local scale, such as temporary changes in weather conditions (e.g., winds, snowfall). The assumption of constant effects of random factors on tree growth seems to be valid for long-term growth trend analysis. The effects of air pollution on growth may mask, in part, changes in forest growth caused by warming and elevated concentrations of greenhouse gases and make it difficult to discern the latter (Innes and Cook, 1989; Alexeyev (ed.), 1990; Norin and Yarmishko (eds.), 1990; Alekseev, 1990, 1991, 1993, 1997; Kozlov et al. (eds.), 1993; Yarmishko, 1997).

Three sources of data are typically used to analyze forest growth trends which include permanent sample plots, inventory data and dendrochronological data (Spiecker et al. (eds.), 1996). We chose the dendrochronological approach because the other two approaches could not provide enough long-term data to meet our objectives. Insufficient data were available from permanent sample plots since there are relatively few plots covering the period 80–100 years ago. Regular forest inventories just began in the first quarter of the last century and the methodology, methods, instructions and routines have varied significantly from one inventory to the next. Therefore, the data from successive inventories are usually not compatible and require special sophisticated pre-treatment.

The dendrochronological approach has been widely applied in ecology and environmental sciences (Innes, Cook, 1989; Kairiukstis (eds.), 1990; Bartholin et al. (eds.): 1992; Vaganov et al., 1996). Although very attractive, this method has some major limitations including the need to remove age trends from the data and to account for the growth history of individual trees, especially with regard to relationships with close neighbors and competition. These limitations can be addressed by using special methods of data treatment and through the choice of region for forest growth investigations.

We chose to study the growth trends of *Pinus sylvestris* tree stands growing at high latitudes and at their northernmost limits in the northwest region of the Kola Peninsula for the following reasons:

1. A forest growth response to warming in the climate will be noted earliest and most clearly in forests at high latitudes (Bydiko, 1977).
2. A population of trees growing close to its northernmost limit is much more sensitive to variations in limiting factors such as air temperature. Consequently, even a small change in climate may cause an increase in forest growth which can be easily and reliably detected (Beagon et al., 1986).

3. These forests have a well-defined uneven age structure that is important to revealing growth trends with the method we utilized (see Material and Methods Section).
4. Forest stands at high latitudes typically are low density, therefore the influence of competition on tree growth is minimal compared to other areas (Walter, 1979).
5. Forests in this region have been close to a climax or sub-climax state for a long time. Consequently, the influence on tree growth of changes in site productivity due to succession are minimized (Norin and Yarmishko (eds.), 1990).
6. Finally, forests in this region have never been subjected to silviculture and forestry, so their growth has never been influenced by practices such as harvesting, thinning, fertilization etc.

We may conclude then, that Scots pine forests in the Northwest part of the Kola Peninsula are ideally suited to revealing climatically induced growth trends, to analyze the potential influence of forests on the flows and pools of the carbon cycle. and to evaluate it's significance as an indicator of change to the whole biosphere.

The main objective of this paper is to reveal long-term changes in growth of Scots pine trees in the study area and discuss the possible reasons for those changes.

2. Material and Methods

The study area is in the forest-tundra zone, which is relatively homogeneous with respect to edaphic features such as relief, geology, soils, climate and geo-botany. Sample plots were located along the border between Norway, Russia and Finland (Figure 1).

The air pollutants produced by smelter mills located in the settlement Nikel and the town Zapoliarny are easily removed from the landscape by an excess of mobile air (a small number of windless days) and water masses. The climate is characterized by high precipitation and low evaporation which results in a substantial surplus of water on the landscape. Shallow soils, hilly relief, and a high number of streams all contribute to a highly mobile hydrologic system. Under these circumstances, damage to forest plants from pollution depends mainly on the frequency and direction of winds during the growing season.

The growing season begins at the end of May and continues through to the beginning of September. Average values for mean annual temperature and precipitation for the last century are +0.5 °C and 422 mm respectively, and for the growing season +11.7 °C and 586 mm respectively.

The health status of sampled trees was described by the damage classes commonly used in different programmes for forest health monitoring (Manual, 1998). The six classes are described as follows; 1 – healthy tree, 2 – slightly damaged, 3 – moderately damaged, 4 – severely damaged, 5 – trees that died during the last year,

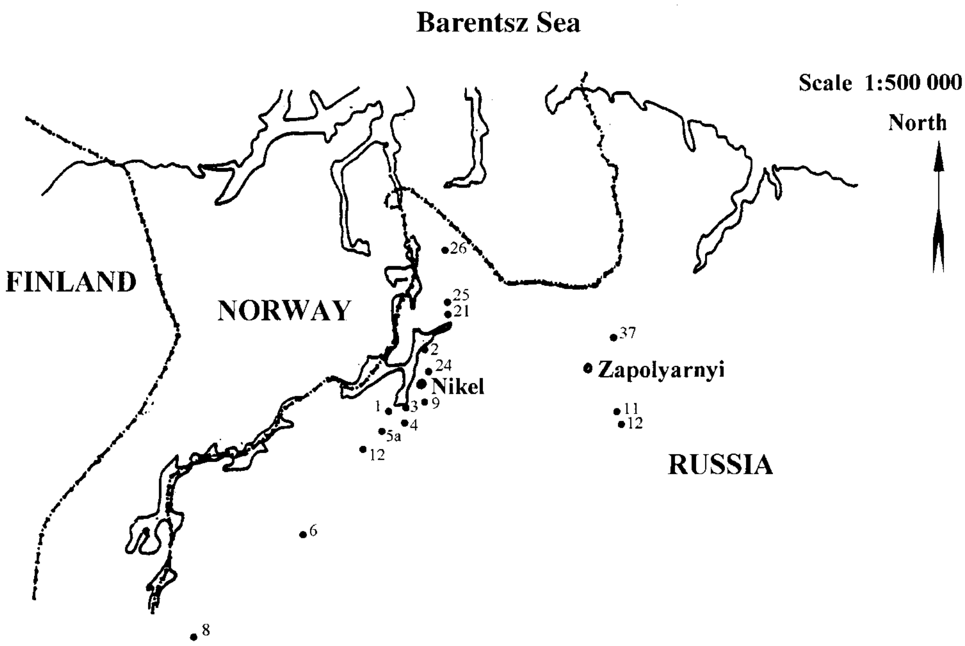


Figure 1. Map of the study area with locations of sample plots.

6 – trees that died a few years ago. The health status of a sample stand is estimated as the numerical average of its trees damage classes.

Wood cores were taken from 175 Scots pine trees located on 17 sample plots using a Pressler borer (Table I). To avoid sampling bias, sample trees were selected to represent the uneven age structure of the Scots pine forest studied. 63 trees were sampled from the 21–40 year age class, 20 from the 41–60 year age class, 18 from the 61–80 year age class, 11 from the 81–100 year age class, 41 from the 101–200 year age class and 22 trees from the older than 201 year age class.

Radial increment was measured with an accuracy of 0.015 mm. The widths of 16 954 tree rings that appeared between 1660 and 1992 were measured. The tree rings data were distributed between 6 age classes. Data for 3 523 tree rings were place in the 0–20 year age class, 2 920 tree rings in the 21–40 year age class, 2 052 tree rings in the 41–60 year age class, 1 664 tree rings in the 61–80 year age class, 1 373 tree rings in the 81–100 year age class and 5 422 tree rings in the older than 101 year age class.

In order to reveal growth trends in our time series data, we needed to remove the influence of age bias. For this purpose a method of forest growth reconstruction was used that randomizes the growth process by splitting tree ring time series into single rings with subsequent regrouping. Each ring width is assigned a tree age and a calendar year. Subsequently, individual tree rings of the same age class (the 6 age groups mentioned above) and calendar year class (1660–1850; 1851–1950; 1951–1992) were grouped together allowing for comparison of tree ring widths of

Table I

Description of sample plots in Scots pine tree stands located in the Northwest part of Kola Peninsula close to the town Zapoliarny and settlement of Nikel

Town or settlement, direction	Reference number of sample plot	Distance km	Mean			Tree stand density [b]	Average damage class	Number of cores
			Height, m	Diameter [a] cm	Age, years			
Nikel, south-west	3	5.0	12	16	100	0.4	3.08	11
	1	7.0	10	18	120	0.5	3.70	14
	4	7.0	19	18	120	0.3	3.53	12
	5a	9.0	18	20	120	0.4	2.53	12
	12	12.0	12	14	100	0.5	2.19	11
	6	28.0	16	22	160	0.6	1.65	4
	8	50.0	12	14	60	0.6	1.50	13
	7	78.0	20	18	170	0.5	1.96	11
Nikel, south	9	3.0	16	22	120	0.1	3.65	6
Nikel, north	2	8.0	12	36	140	0.2	2.82	10
Nikel, north-north-east	24	2.0	14	18	120	0.6	4.19	4
	21	12.5	16	26	150	0.4	3.24	6
	25	15.0	10	10	60	0.4	1.93	14
	26	22.5	12	14	80	0.5	1.37	11
Zapoliarny, south-east	11	10.0	14	18	180	0.1	2.51	4
	12	12.0	9	10	50	0.7	1.45	19
Zapoliarny, north-east	37	8.0	8	13	30	0.5	1.35	13

[a] Diameter is measured at breast height.
[b] Tree stand density is measured relative to a fully stocked stand.

the same age but from different calendar year classes. The uneven age structure of the Scots pine stands also contributed to removal of age bias. Because tree growth is affected by many random factors operating on a local scale, this procedure of randomization permits accounting for the influence of stochastic factors averaged over the long-term.

For trend analysis of the mean and variance of annual radial increment of Scots pine trees over the last century (1900–1992) the data was fit to a non linear function that is the sum of a linear trend and harmonic oscillations (Kairiukstis, 1981):

$$p(t) = (x * t + y) + \sum_i \left[(z_i * t) * \cos\left(\frac{2\pi * t}{T_i} - v_i \right) \right],$$

where, $p(t)$ – radial increment of year t, mm; x, y – parameters of the linear trend; x – rate of radial increment growth, mm/year; y – estimate of the radial increment at the first year, mm; z_i – rate of growth in oscillation amplitude of the ith harmonic component, mm/year; T_i , v_i – period and phase of the ith harmonic component.

The data on tree ring width was used to develop diameter growth curves for the three calendar year classes.

Standard versions of one-way analysis of variance and linear regression analysis were used to compare tree ring width data and temperature data (Shmidt, 1984).

3. Results and Discussion

Results of the analysis of long-term trends in mean radial increment by 20 year periods for six age groups provide evidence of an increase in mean radial increment of Scots pine trees (Figures 2 and 3). Coefficients of determination for linear trends are higher for the first three younger age groups, 0–20 years (71%), 21–40 years (81%) and 41–60 years (68%) than for the older ones, 61–80 years (39%), 81–100 years, and greater than 101 years old (30%). Trends for the last age groups are statistically reliable.

Results for the analysis of long-term trends in variance of radial increment by 20 year periods for six age groups are shown in Figures 2 and 3. These results indicate that variability in the radial increment of Scots pine trees increased over time. Coefficients of determination for the linear trends vary from 38% for the 81–100 year age class to 76% for the 21–40 year age class without the regularity evident for trends in mean radial increment.

It is of interest to interpret our data on long-term dynamics of radial increment of Scots pine trees grouped according to well known climatic periods of the past (Borisenkov, 1982; Losev, 1985; Cannell, 1995). For this purpose radial increment data for three periods of time were considered. The first time interval, from 1660–1850, coincides with the end of the Little Ice Age; the second, from 1851–1950, is the period of the last registered climate warming, the maximum of which occurred in 1930–1940; and the third, from 1951–1992, covers the last five decades. The results of the comparison of mean radial increment and its variance for the three periods of time are shown in Table II.

All differences between radial increment means and variances within age classes are statistically significant at the 95% confidence level, with the exceptions of mean radial increment for the 61–80 and 81–100 year age groups in the last five

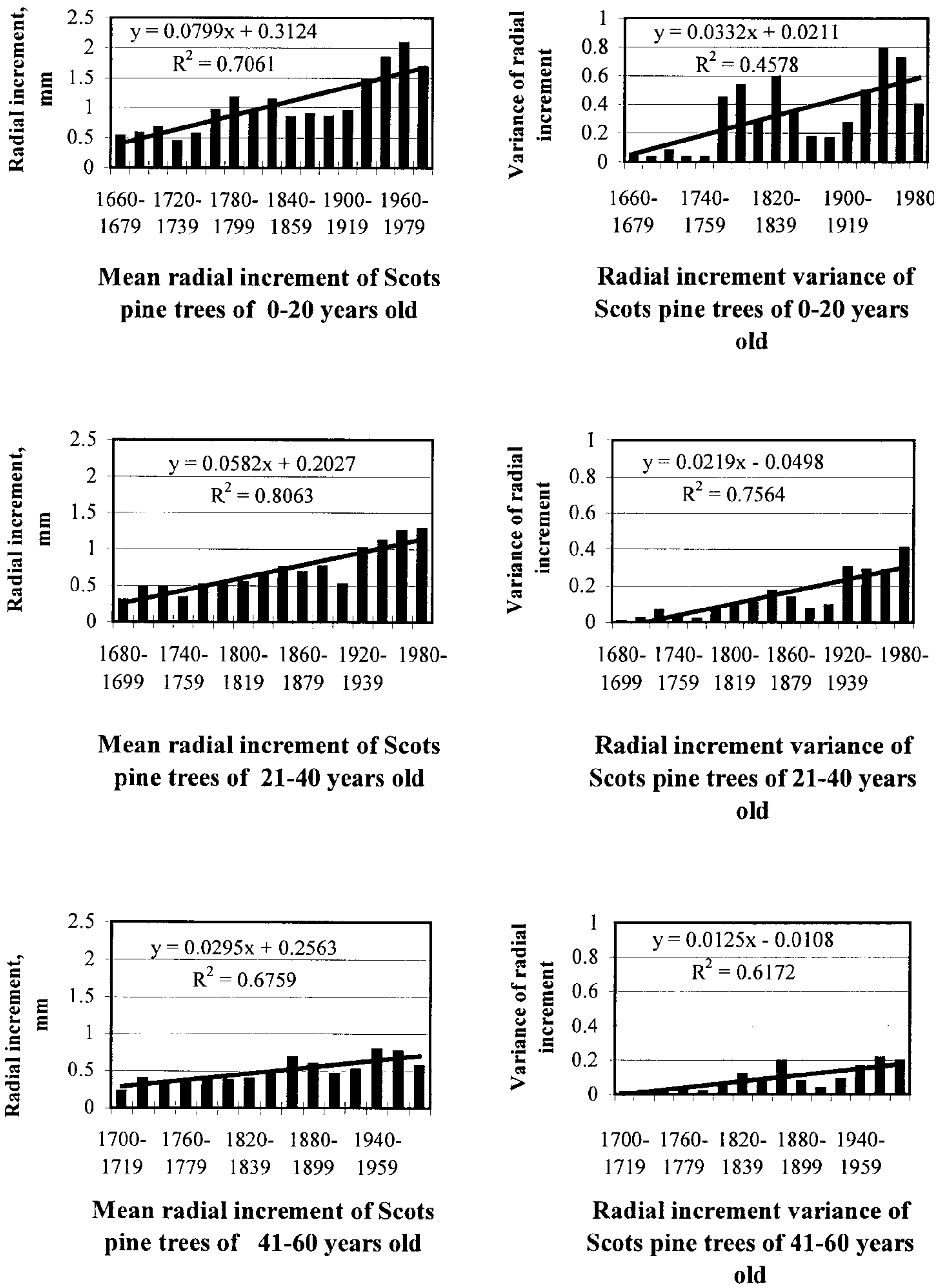
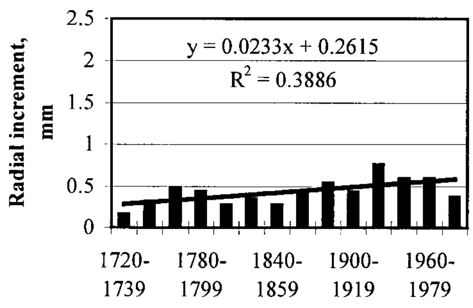
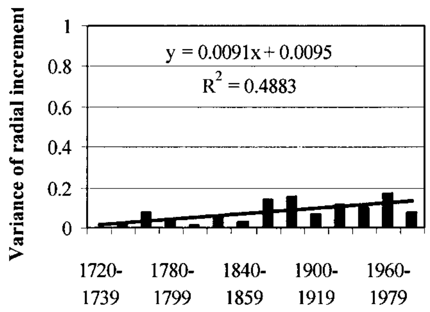


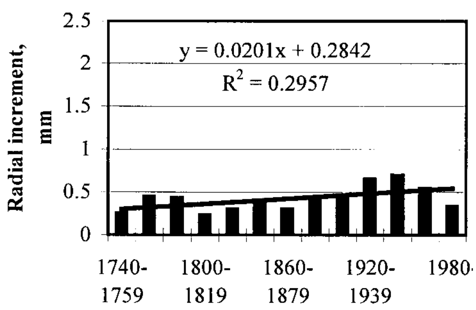
Figure 2. Rise in mean radial increment and radial increment variance of Scots pine trees from North-West part of Kola Peninsula for age classes of 0–20, 21–40 and 41–60 years old.



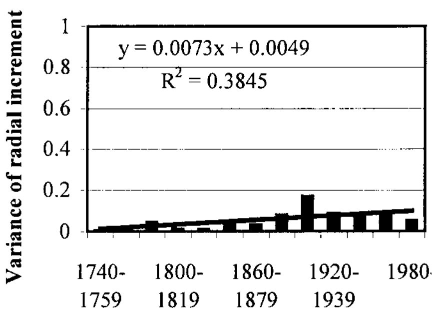
Mean radial increment of Scots pine trees of 61-80 years old



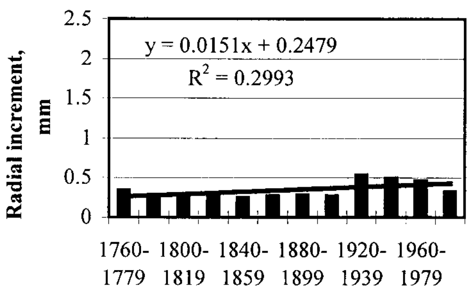
Radial increment variance of Scots pine trees 61-80 years old



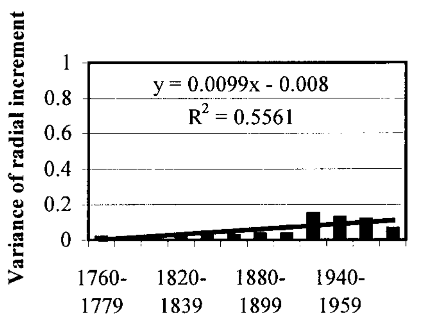
Mean radial increment of Scots pine trees of 81-100 years old



Radial increment variance of Scots pine trees of 81-100 years old



Mean radial increment of Scots pine trees older than 101 years



Radial increment variance of Scots pine trees older than 101 years old

Figure 3. Dynamics in mean radial increment and radial increment variance of Scots pine trees from North-West part of Kola Peninsula for age classes of 61–80, 81–100 and older then 100 years old.

Table II

Comparison of mean radial increment and variance of radial increment for three periods of time 'Small Ice Period' 1660–1850, 'Last Warming' 1851–1950, 'Last Decades' 1951–1992 (in each data cell the top numbers are the real values of mean radial increment and variance and the bottom number is the ratio to the previous period of time)

Age classes, years	Mean radial increment, mm			Variance of radial increment, mm^2		
	1660–1850	1851–1950	1951–1992	1660–1850	1851–1950	1951–1992
0–20	0.87	1.16	2.06	0.38	0.44	0.70
	1.00	1.33	1.78	1.00	1.16	1.59
21–40	0.53	0.81	1.26	0.08	0.21	0.35
	1.00	1.53	1.56	1.00	2.65	1.67
41–60	0.37	0.58	0.70	0.06	0.11	0.21
	1.00	1.57	1.21	1.00	1.83	1.91
61–80	0.37	0.54	0.53	0.05	0.13	0.15
	1.00	1.46	0.98	1.00	2.60	1.15
81–100	0.35	0.51	0.50	0.03	0.11	0.08
	1.00	1.46	0.98	1.00	3.67	0.73
>100	0.27	0.39	0.43	0.02	0.09	0.11
	1.00	1.44	1.10	1.00	4.50	1.22

decades compared with the period of the last registered climate warming, which are not significantly different (Table II). Mean radial increment is significantly higher for four age groups in the period of the last five decades compared with the period of the last registered warming and remained the same for the other two age groups. The magnitude of the increase in radial increment is highest for the younger age classes and varies from 10% for the older than 100 years age class to 78% for the 0 to 21 year age class (Table II). A comparison of the variances for the same data produced similar results where the increase in variance for the growth increment ranged from 15–91% for five age groups. A statistically significant lower value for variance was observed only for the 81–100 years old age class where it decreased by 27% in the last five decades compared with the period 1851–1950.

Mean diameter growth curves for the Scots pine forest were developed using radial increment data for three periods of time (1660–1799, 1800–1899 and 1900–1992). Results indicate that diameter growth for the last period (1900–1992) is greater than for both of the previous two periods (Figure 4).

Results of linear trend and oscillation analysis for the mean and variance of annual radial increment of Scots pine trees over the last century are shown in

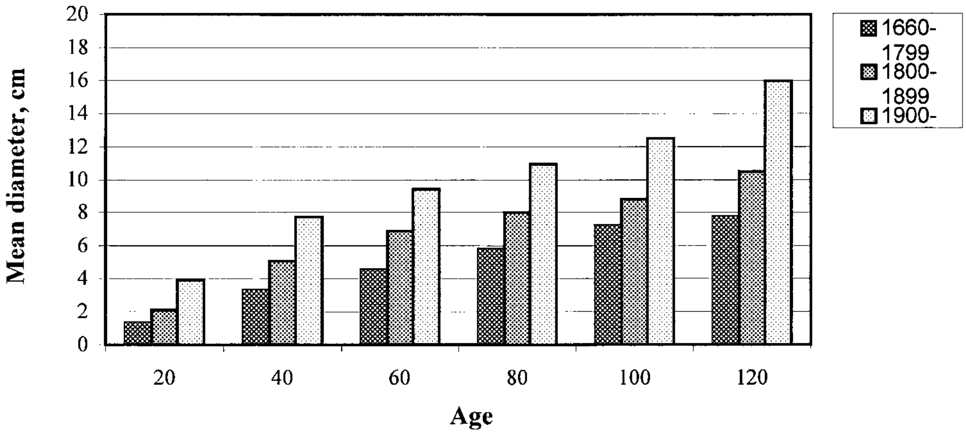


Figure 4. Mean diameter growth curves for three time periods: 1660–1799, 1800–1899 and 1900–1992.

Table III

Results of mixed linear trend and oscillation analysis of dynamics in mean annual radial increment of Scots pine trees during 1900–1992

Age class	Parameters of linear trend		Parameters of oscillations				R^2, %
	x, mm/ year	y, mm	z, mm/ year	T, years	v	Number of harmonics	
0–20	0.016	0.89	–0.007	1.0	–	1	74.5
21–40	0.012	0.49	–0.002	1.4	–	1	72.7
41–60	0.005	0.44	0.003	1.0	–	1	76.6
61–80	0.008	0.34	0.007	3.4	–	2	61.7
81–100	0.000	0.61	0.159 [a]	1.1	259.0	1	38.7
>101	0.006	0.20	0.006	3.7	–	1	69.6

[a] In this case z is independent of time amplitude of oscillations and has mm as dimension.

Table III. Over the last century there was an increase in growth of Scots pine annual radial increment for the trees in all age groups, except in the 81–100 year age class for which it remained constant. The average annual rate of radial increment growth was 0.016 mm/year for the 0–20 year age class, 0.012 mm/year for the 21–40 year age class, 0.005 mm/year for the 41–60 year age class, 0.008 mm/year for the 61–80 year age class and 0.006 mm/year for trees in the more than 101 year old age class.

The growth trends were unstable over time and exhibit growing oscillations in radial increment. Increase in the amplitude of oscillations was detected for five age groups and oscillations varied from 0.002 to 0.007 mm per year. For the 81–100 year age group the amplitude of the oscillations was constant. The results

Table IV
The influence of growth period air temperature variations on Scots pine trees growth for the period 1901–1992

Age class, years	Parameter a, mm/°C	R^2, %
0–20	0.0149	94.5
21–40	0.0095	95.9
41–60	0.0057	93.7
61–80	0.0052	93.1
81–100	0.0051	95.4
≥101	0.0040	96.4

shown in Table III confirm that for the last century, a shorter period of time than was analyzed in this study, the same trends as demonstrated in Figures 2 and 3.

Air pollution did not appear to significantly influence Scots pine tree growth. Air pollution has become significant only over the last few decades, so it would not strongly affect long-term growth trends. In addition, the special comparison of diameter growth for trees of different health status did not reveal any significant differences. Significant differences may not have been revealed because a low number of severely damaged trees, which are most susceptible to growth suppression by pollution, were sampled.

Data on temperature dynamics were used to investigate one of the possible reasons why Scots pine trees grow faster now than during the period of the last registered warming. This data covers the period from 1901–1992 and represents the mean air temperature for the growing season. We related meteorological and increment data using the simple proportion function:

$$y = a * x ,$$

where, y – mean annual radial increment, mm; x – mean air temperature for the growing season, °C; a – parameter which shows an increase in radial increment as the result of elevation in air temperature, mm/°C. Results are shown in Table IV.

Variation in mean annual air temperature explains 93% to 96% of the variability in mean annual radial increment of Scots pine trees, even in the absence of a statistically reliable increase in air temperature from 1901–1992 (Table IV). The younger the Scots pine trees are, the more sensitive they are to warming (Table IV).

Our results are consistent with the conclusions of some other authors, who have revealed elevated growth in forests at northernmost latitudes (Myneni et al., 1997) and predicted the magnitude of the increase in forest growth under the influence of possible climate warming (Beuker et al., 1996).

The most probable reasons for a marked increase in radial increment of Scots pine in this region are small, statistically insignificant climate warming effects and higher levels of carbon dioxide. Together these may produce a synergistic effect on growth. In addition, elevated growth of Scots pine trees may also result from other causes such as an increase in the length of the growing season, the ameliorative effect of mild air pollution, or changes in forest fire frequencies.

From a general theoretical analysis of the carbon cycle it is known that carbon is transferred from the atmosphere, in the form of carbon dioxide fixed by plant photosynthesis, first to the soils and bottoms of water reservoirs and then to different kinds of sedimentary deposits such as natural gas, oil, coal etc. (Kostitsyn, 1984). Theoretically, an increase in the average radial increment of Scots pine trees at their northernmost extent indicates the beginning of positive changes in the carbon cycle resulting in a higher rate of carbon accumulation in the forest biomass. In general, this may be considered an indicator of a response by the biosphere to counteract greenhouse effects and global environmental changes.

4. Conclusions

Our results provide evidence that the growth rate of Scots pine trees, at their northernmost extent in the Northwest region of the Kola Peninsula, has increased over the long-term. Generally, the younger the trees, the greater the increase in growth. Increases in growth are estimated as high as 78% in the period of the last five decades when compared with the period of the last registered warming. The growth trends are unstable over time and exhibit growing oscillations of radial increment.

The most probable reason for the marked increase in radial increment of Scots pine in this region is a synergism of mild climate warming and higher levels of carbon dioxide. Other reasons may include an increase in growth season longevity, the ameliorative effect of mild air pollution and changes in forest fire frequencies.

The elevated growth rate of Scots pine trees is a response of these forests to regional or global environmental changes and may be considered an indicator of a self-regulating mechanism of the biosphere to increase its stability, including the stability of the climate.

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