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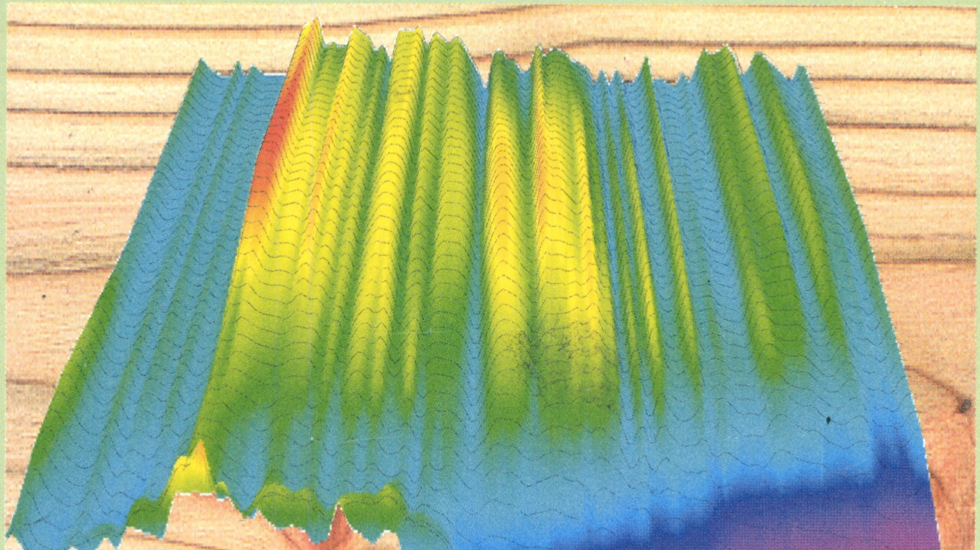

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# Effects of emissions from the nickel–copper smelter in Monchegorsk, northwestern Russia, on the radial growth of Scots pine

Pekka Nöjd

*Academic dissertation*

*To be presented, with the permission of the Faculty of Agriculture and Forestry of the University of Helsinki, for public criticism in Auditorium M II, Metsätalo, Unioninkatu 40 B, Helsinki, on 22 November 1996, at 12 o'clock noon.*

VANTAAN TUTKIMUSKESKUS

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Extensive forest damage exist near Monchegorsk, Kola, where large quantities of sulphur and heavy metals have been emitted for decades from a nickel–copper smelter. The effects of the emissions on the radial growth of Scots pine were studied using the methods of tree-ring analysis. Scots pine stands without silvicultural treatments or major natural disturbances were sampled across a transect starting two kilometers south of Monchegorsk and continuing towards southwest (northern Finland). Options for removing climate-induced variation from the ring-width chronologies with the aid of climate-growth models were evaluated.

Wide-spread growth reductions were discovered south and southwest of Monchegorsk. The initiation of the downward trend could be dated back to mid-1940s at the immediate vicinity of the smelter. The result also suggests that visible forest damage appeared in the region of Monchegorsk soon after the smelting began in 1939. Near the smelter the growth of the sampled Scots pine ceased by the year 1952. Thereafter the damage has gradually expanded. The sampled mature Scots pines no longer form annual rings within 15 km south of Monchegorsk. The area, within which the sampled old Scots pines have ceased forming annual rings, has expanded at a rate of approximately 0.5 km per year. Clear growth reductions were observed within approximately 30 km south of Monchegorsk. The sampled young Scots pines (30–80 rings at breast height) proved to be more resistant against the effects of pollution than old ones (170+ rings at breast height).

As shown by previous dendrochronological studies, the mean temperature of July proved to have a strong effect on the growth variation of Scots pine. Contrary to previous findings from climatically different regions, the climatic signal in tree-rings proved to be insensitive to effects of pollution: a clear dependence between July temperatures and growth was observed decades after the pollution exposure began and also considerably after the actual growth trends had started to decline.

The observed growth trends match well with various indicators of environmental quality. A number of studies have shown that forest ecosystems within 30 km south of Monchegorsk — where obvious growth reductions were observed — have accumulated high quantities of sulphur and heavy metals which clearly exceed background levels. In addition, shortened needle retention and lowered frost hardiness of Scots pine has been observed in the area.

**Keywords:** Scots pine, air pollution, forest damage, tree-ring analysis, time series analysis.

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Vantaa, October 1996
Pekka Nöjd

The following studies are reviewed in the course of this dissertation. They are referred to in the text using Roman numerals:

I **Nöjd, P.** 1990. Detecting forest growth responses to environmental changes — a review of Finnish studies. In: Kauppi, P., Anttila, P. & Kenttämies, K. (eds.). Acidification in Finland. Springer-Verlag. Berlin. p. 507–522.

II **Nöjd, P., Mikkola, K. & Saranpää, P.** 1996. History of forest damage in Monchegorsk, Kola; a retrospective analysis based on tree-rings. Accepted for publication in the Canadian Journal of Forest Research (in press).

III **Nöjd, P. & Reams, G. A.** 1996. Growth variation of Scots pine across a pollution gradient on the Kola Peninsula, Russia. Accepted for publication in the Environmental Pollution (in press).

IV **Nöjd, P. & Hari, P.** The effect of temperature on the radial growth of Scots pine in northernmost Fennoscandia. Submitted for publication.

# Contents

# 1 Introduction

It seems natural to associate air pollution with the modern society. The problem has reached unforeseen dimensions in our time, a side effect of the continuous increase of industrial production. Advances in environmental sciences have also increased our knowledge about the causal mechanisms behind the observed harmful effects. The problem has existed for centuries, however. Even the possibility of pollution-induced detrimental effects on forests was pointed out already in John Evelyn's Silva (1729); the first edition of the classic work was published as early as 1662.

The harmful effects of air pollution on tree growth became evident during the early industrial revolution, when mortality of trees increased around industrial centers in Europe. First studies on the phenomenon were made in Germany in the late nineteenth century (e.g. Schröder and Reuss 1883, Reuss 1893). A review of the early studies on forest growth at the vicinity of point sources of pollution is given by Scurfield (1960a, b). Several cases of regional growth declines have subsequently been reported at industrial locations. Perhaps the most well-known example is in Sudbury, Canada, where Linzon (1958) reported anomalous growth trends of *Pinus strobus* L. within the distance of 40 km on sample plots in line with the prevailing wind. The most well known case in Scandinavia was reported by Wilhelmsson (1983) who studied the growth of Scots pine (*Pinus silvestris* L.) and Norway spruce (*Picea abies* Karst.) at Skellefteå, northern Sweden. Wide-spread growth reductions, caused by long-lasting exposure to sulphur and heavy metal emissions from metallurgical industries, were detected. Norway spruce appeared to be the more sensitive species. Clear reductions of Scots pine growth were observed within 10 km of the smelter. For Norway spruce declining growth was reported within a considerably larger area. Both species showed a growth recovery after the annual emissions decreased during the 1970s.

The detrimental effects of pollutants on forest ecosystems received unforeseen attention during the 1980s, when the phenomenon termed "Waldsteben", later "Neueartige Waldchäden" (Novel forest decline), was reported in many parts of Europe. Similar observations were also made in North America. Strong statements were made about the magnitude of the problem in scientific literature, such as "never before have so many different soil, site, and climatic conditions shown so markedly similar and serious effects" (Schutt and Cowling 1985).

The phenomenon has subsequently been studied intensively. Nevertheless, strong theoretical understanding about the causal factors behind it still seems to be lacking. Up to date no consensus has been reached about the magnitude of the problem. The methods used for assessing the spatial and temporal development of the decline have also been subject to critique (Innes 1988, Skelly and Innes 1994).

The effects of the novel forest decline on forest growth have stimulated much research. Studies in Europe showed a synchronic growth reduction of many coniferous species starting during the late 1970s — more or less coinciding with first observations about the novel forest decline, but also coinciding with a severe drought in 1976 (Kenk 1990). The reduction was followed by a recovery, however. In recent years evidence of increasing growth trends in different parts of Europe has accumulated (Hari and Arovaara 1988, Becker 1989, Kauppi et al. 1992, Eriksson and Johansson 1993, Elfving and Tegnhammar 1996, Spiecker et al. 1996).

In North America a few reported cases of regional forest decline have been studied intensively, especially the downward growth trends of red spruce (*Picea rubens* Sarg.) in northeastern United States. Different hypothesis about the causes of observed growth variation have been brought up, including acid rain, aluminium-induced nutrient deficiency and acid rain-induced reduction in cold tolerance, but also winter injury and natural stand dynamics (Johnson and Siccama 1983, Johnson and McLaughlin 1986, Hamburg and Cogbill 1988, Shortle and Smith 1988, Van Deusen 1990, Wargo et al. 1993). However, up to date no consensus exists about the role of air pollution as one of the causal factors behind the observed growth decline (Johnson et al. 1995, Reams and Van Deusen 1995). Also, the most recent data on red spruce growth in that region shows a marked increase of red spruce growth during the 1980s and 1990s (Reams and Van Deusen 1995).

In Finland the long tradition of national forest inventories has provided a reliable basis for statistics about forest resources since the early 1920s. A steadily increasing trend both in total volume and annual increment has been observed since the early 1960s (Yearbook ... 1995, I). For northern Finland the annual growth has increased from 11.2 million $m^3$ in 1960–1964 to 17.8 million $m^3$ in 1990–1994 (Yearbook ... 1995). Some studies aiming to analyze the causes of the increasing growth trends (reviewed in article I) suggest, that part of the increase is due to factors other than silviculture (Arovaara et al. 1984, Hari and Arovaara 1988). Against that, Mielikäinen and Timonen (1996) did not discover trend-like changes of Scots pine growth in study material, that consisted of untreated stands from conservation areas and old permanent sample plots in Southern Finland.

Case studies on the vitality and growth of forests in the vicinity of significant point sources of pollution have also been published in Finland (e.g. Koskela 1987, Manninen and Huttunen 1987, Jukola-Sulonen et al. 1989, Manninen et al. 1990). Generally the area affected by pollution has been determined with the aid of various bioindicators, such as the occurrence of especially sensitive plant species. Reduced vitality of trees near the emission source has been reported in a number of cases. However, increased mortality of trees has been observed only in very small areas. Invariably, the reported growth reductions have been of limited economic significance.

The extensive damage areas on the Kola Peninsula, which became common knowledge in Finland during the late 1980s, appeared to present a threat of a different order of magnitude. This is evidenced by the publicity in the media, inter-governmental negotiations aiming to reduce the pollution and even the actions of local forest owners in eastern Lapland, who partially financed some of the pilot studies on the problem.

The areas with severely destroyed vegetation, which according to local scientists cover several hundreds of square kilometers (Kryuchkov 1993), were an unforeseen phenomenon in areas close to Finland. The two main sources of pollutants, Monchegorsk and Nikel, are powerfull polluters. Annual $SO_2$ emissions varying between 200 and 300 Gg $a^{-1}$ during the 1980s have been reported for both smelters (Baklanov et al. 1994). In recent statistics Monchegorsk is ranked as fourth and Nikel as fifth largest sulphur emitter in Europe (Barret and Protheroe 1994). In addition, very large quantities of heavy metals have been emitted, especially from Monchegorsk (Laurila and Tuovinen 1991). The concern about forests was increased by the fact that Scots pines in southern Lapland had suffered from severe needle loss, which began in 1987 (Tikkanen and Raitio 1990). As a result the Lapland Forest Damage Project, funded by the ministry of Agriculture and Forestry, was launched in 1989. The five-year project covered a wide range of topics from measurements of air quality to numerous soil and tree characteristics and also included delimiting the damaged areas using satellite images. The studies on growth variation of Scots pine across a pollution gradient, presented in this thesis, formed one of the 14 subprojects of the Lapland Forest Damage Project.

Prior to the late 1980s the forest damage in the vicinity of the nickel-copper smelters in Monchegorsk and Nikel were known mainly locally in Russia. Lapland was considered to be an area without major local sources of pollution. Relatively low $SO_2$ concentrations of the air were measured by the few air quality measurement stations that existed in northern Finland at the time.

The lack of knowledge can be explained by the strategic importance of the industries at the Kola peninsula and the location of the area at the border of the two major military blocks. Presently the area is extremely militarized (Luzin et al. 1994). Doiban et al. (1992) describe in detail the military base complex on the Kola Peninsula, which includes two strategic nuclear submarine bases.

Intensive monitoring of the environment in the present day scale is not an activity with a long tradition in any part of the world. It is hardly surprising that very little information is available in scientific literature about the gradual development of the forest damage in the region of Monchegorsk. At the time the Lapland Forest Damage

Project was started, even understanding of the current state of the environment on the Kola Peninsula was quite vague.

Since tree-ring analysis is one of the few techniques that produces a retrospective time series closely related to environmental quality, it was a natural choice for an attempt of studying the history of the forest decline in the region of Monchegorsk. Another obvious advantage of the technique is the direct economic value of tree growth. Despite of the unfavorable climate forestry plays an important role in the regional economy in the northwestern part of Russia and especially in northern Finland. If wide-spread growth reductions were observed in northern Finland, it would most likely affect political decisions about pollution control. The main disadvantage of applying tree-ring analysis in environmental sciences is caused by the large natural variation of tree growth, which may hide the pollution-induced signal.

The aim of this research is to analyze the effects of the emissions from the metallurgical industries in Monchegorsk on the growth of Scots pine. Retrospective data on growth variation is used for producing information about the following questions:

1. The initiation of forest damages: When did first signs of a growth depression appear? When did the growth totally cease near the smelter?
2. How quickly did the growth decline expand?
3. How wide-spread is the decline at present?
4. How large quantities of pollutants have caused a growth decline?
5. Are young Scots pines more resistant to pollution effects than old ones?
6. How sensitive indicator of pollution effects is tree growth? Is it possible to use other, more easily measurable indicators for predicting growth effects?
7. Has the response of Scots pine growth to climate been altered in the polluted areas?

# 2 The causes of growth variation

In order to answer the research questions listed above one has to be able to extract the pollution-induced signal from the total variation of growth. There are numerous factors affecting tree growth (I). It can be quite difficult to retrospectively identify the causes of the observed variation — a fact that undoubtedly has limited the use of tree-ring analysis in environmental sciences, despite of the considerable advantages of the method.

Variation of tree growth can be described as a combined effect of a number of tree specific processes and interactions between the tree and its environment. While there are numerous natural causes for growth variation, human influence can change the course of natural development. The majority of studies on growth variation of trees focus on radial growth, studied by measuring and analyzing ring widths.

## Pollution

The effects of air pollutants on tree growth have stimulated much research (I). The studies represent a wide spectrum of differing time-scales and approaches. Studies in laboratory conditions are useful for identifying harmful substances and threshold concentrations that will lead to acute damage to a tree. However, pollution may also induce changes in forest soil which develop gradually over a period of decades. Such effects are rather more difficult to study using the experimental approach. It is also notoriously difficult to generalize results achieved in strictly controlled laboratory conditions.

The effects of pollutants on tree growth can take several forms (I). Discussion often focuses on growth reductions, but several chemical compounds emitted in the atmosphere may also have the opposite effect. The most obvious examples are $CO_2$ and nitrogen compounds. The main difficulty in using tree-ring analysis for assessing effects of air pollution lies in distinguishing these effects from each other and from other sources of growth variation.

Sulphur dioxide, emitted in large quantities from Monchegorsk, is probably the most studied phytotoxic pollutant that is known to have detrimental effects on forest trees. It affects trees both directly via the above-ground parts of trees and indirectly as a result of changes in chemical and biotic properties of soils. Many comprehensive reviews on the subject exist (e.g. Roberts 1984).

From the beginning ”Novel Forest Decline” was frequently linked to acidic deposition, which is in the main part caused by oxides of sulphur and nitrogen compounds. Particularly well-known was the hypothesis by Ulrich (e.g. 1983) stating that acidification will result in long-term changes in the acid-base status of forest soils. One of the consequences of the process would be a release of aluminium, which has been shown to decrease the growth of conifers in controlled experiments (Arovaara and Ilvesniemi 1990). Subsequent research brought up other factors which may have contributed to the observed damage, such as ozone and ammonium. It also became evident that forest damage in Central Europe cannot be attributed solely to air pollution; a variety of factors like climate, soils and pathogens are involved. The wider perspective is reflected by the term multiple stresses, commonly used by the cognoscenti today.

The other major component of airborne pollution from Monchegorsk, heavy metals, have stimulated less research than sulphur. Presumably the reason for this is that heavy metals are transported lesser distances in the atmosphereand, consequently, environmental problems caused by them tend to be restricted to smaller areas. Their effects on forest trees are most likely connected to changes in soil processes, rather than direct effects on the above-ground parts of trees (Interim report on cause-effect... 1990).

# Competition between trees

As shown by research on distance dependent models describing the growth of individual trees, the competitive status of a tree strongly affects its growth. Removal of trees from a stand decreases the competition between trees; additional light and nutrients are available to the remaining trees (Fritts 1976). As a result, their growth will generally enhance. Such effect can often be diagnosed by studying a ring-width chronology from a stand that has undergone a thinning. Strong disturbances like forest fires or wind damage can be also diagnosed retrospectively from the ring-width chronology (Lorimer 1984, Lorimer and Frelich 1989). Canopy openings may also be exploited by seedlings, which will in due course start competing with the older trees.

# Climate

Identifying climatic parameters which are strongly correlated with growth variation and quantifying some of the most obvious cases of such relationships were among the early achievements of tree-ring research (Fritts 1976). The effect of climate on tree growth varies greatly between different vegetation zones. It was recognized early that strongest correlation between climatic parameters and growth occur in regions where a climatic hazard is present (Fritts 1976). Many classical studies on the subject were carried out near the forest edge between forested land and desert in southwestern United States. In those conditions drought severely restricts the growth processes of plants and consequently the variation in availability of water leaves a strong signal in the ring-width series of trees.

Precipitation is an important factor causing growth variation not only in extremely arid regions. In the temperate conditions of Central Europe the growth of conifers has proved to be strongly dependent of rainfall (Assman 1970, Spiecker 1991); a fact that was frequently overlooked in the debate about the causes of novel forest damage.

Near the polar timber line drought rarely affects tree growth (Mikola 1952). Instead tree-ring research has revealed strong correlation between summer temperatures and growth (Erlandsson 1936, Hustich 1945, Sirén 1961). In the extreme conditions the coefficient of variation of growth is very large compared to more temperate regions Mikola (1952).

The strength of the climatic signal in tree-rings is generally described by the percentage of the total growth variance, that can be explained by climate-growth models. Comparison of such models is problematic, however. Prior to modeling, ring-width series are commonly standardized, i. e. a proportion of the variation is removed. The models describe the fit between the remaining variance and climatic variables. Recent examples of modeling the relationship of climate and tree growth in northern Fennoscandia are given by Lindholm (1995). Historical climate patterns were reconstructed with the aid of tree-ring data. Some of the models were able to explain more than 50 % of the total variance of certain climate variables. Prior to the analysis the ring-width chronologies had been standardized by fitting an exponential or polynomial function.

The effect of climatic factors on growth can be analyzed using widely varying time-scales. The ultimate example are studies on the gas-exchange of trees which operate on a time-scale of seconds. The diameter variation of trees within a single growing season is also analyzed commonly. In traditional dendroecology the focus has been in relating climatic parameters to tree-ring data sets.

## *Changes in the climate-growth relationship as an indicator of pollution*

The climate-growth relationship has also direct applications in the context of studying air pollution effects on tree growth. It is possible to interpret a change in the response of growth to climate as an indication of pollution effects. Innes and Cook (1989) review several studies (Conkey 1979, Johnson et al. 1986, Cook et al. 1987, McLaughlin et al. 1987) evaluating the growth response of red spruce (*Picea rubens* Sarg.) to climatic variation in northeastern United States. A growth decline took place during the late 1950s — early 1960s. The results suggest that prior to the decline growth was strongly dependent on certain climatic parameters, which since then have become less reliable for predicting growth. As cautioned by Innes and Cook (1989), in addition to pollution such changes may be caused by a range of factors.

## Distinguishing between the potential causes of growth variation

In growth and yield research some sources of growth variation are usually beyond the scope of the study. In such cases researchers seek to rid the ring-width chronologies of the noise created by those factors (I). The retrospective nature of tree-ring research makes it impossible to control such factors experimentally. Selecting the tree-ring material from populations as homogeneous as possible is the most common means of control. In addition a number of mathematical techniques have been developed for removing unwanted variation from ring-width series. Using such methods is rarely an ideal solution, however. In addition to the unwanted noise a considerable share of the studied signal may well be lost in the process as well (Warren 1989, III).

In cases where the effects of sudden reductions of competition are beyond the scope of the study, a common approach for minimizing those effects is to select the material from stands without major disturbances, natural or man-made. Finding such stands is difficult in regions, where mixed and uneven-aged stands are common and forests are managed intensively. At the Kola Peninsula forest management used to be extensive until the latter part of the present century. It is still possible to find pine stands without thinnings or strong natural disturbances. In northern Finland untreated stands are far less common.

Removing the climatic signal from tree-ring series obviously calls for models describing the climate-growth relationship. Most often such models are based on the statistical relationship between the two. An alternative approach, process-based models, have also been applied for the purpose (Hari and Sirén 1972, IV)

Studying the large volume of research papers analyzing growth trends, one can only conclude that it can be quite difficult to identify the primary causes of observed trends. In the debate about the causes of growth reductions of red spruce in United States (cited earlier) all three abovementioned causes — pollution, competition between trees and climate, as well as interactions of them — have been brought up as explanations to the phenomenon. Despite of intensive research no consensus has been reached (e.g. Johnson et al. 1995, Reams and Van Deusen 1995).

Another recent example is a pan-European project aiming to identify and analyze recent growth trends in different parts of Europe (Spiecker et al. 1996). Increasing trends were found in many regions, but the various studies were unable to provide strong evidence about causal factors behind the observed trends.

As the aim of the present study is to analyze pollution-induced changes in tree growth, it is obviously vital to consider the possibilities for analyzing and removing the effects of climate and competition between trees.

# 3 Materials and methods

Since the studies were part of the Lapland Forest Damage Project, the sampling design follows the basic approach of the project. The fact restricted the choices available; the selected design is a compromise between the various subprojects. On the other hand it is a considerable advantage that the results on growth trends can be compared with detailed data describing the soil and trees of each sample plot.

The sampling design adopted by the Lapland Forest Damage Project was to collect data from plots located on

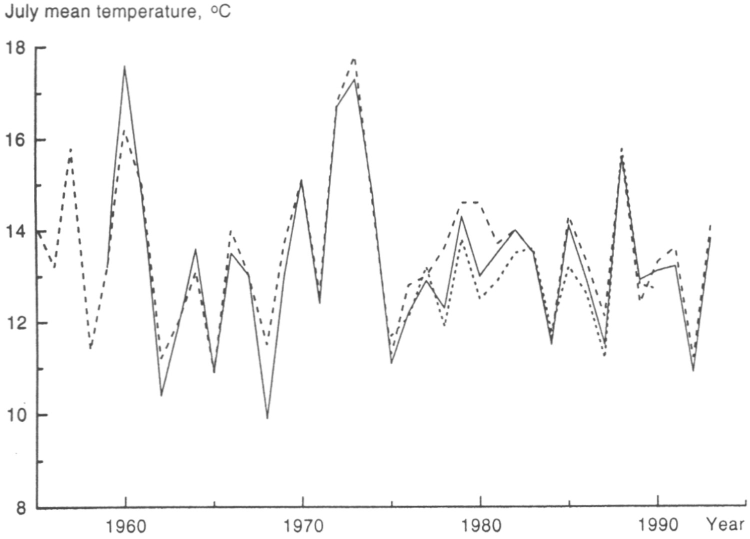

Figure 1. Mean July temperatures at three weather stations representing comparable latitude and altitude, Muonio (67°58'N, 22°41'E, 242 a.s.l.; dashed line), Vuotso (68°05'N, 27°12'E, 246 a.s.l.; solid line) and Naruska (67°22'N, 29°22'E, 261 a.s.l.; dotted line).

transects starting from Monchegorsk and continuing towards west. Climatic differences are relatively small in Lapland between regions on the same latitude and altitude. Fig. 1 illustrates July mean temperatures, crucial for tree growth in Lapland, for three meteorological stations representing approximately the same latitude and altitude: one in western Lapland (Muonio), the second in central Lapland (Vuotso) and the third in eastern Lapland (Naruska). It is evident that variation between those locations is rather small compared to variation between years. Thereagainst differences between locations on different latitudes are comparatively large. The design of the Lapland Forest Damage Project is therefore well suited for growth analysis; the data is collected from relatively comparable locations.

The sample plots were established on infertile mineral soils dominated by mature Scots pine. A target location for each plot was selected before field inspection; the nearest pine stand that fulfilled the criteria was then selected. Forest management data acquired from the National Board of Forestry was used in selecting the sampling sites.

A considerable share of the sample plots established by the Lapland Damage Project had been treated with intermediate cuttings. As cuttings invariably cause an enhancement of growth of the remaining trees, thinned stands are difficult to use for studying growth trends. Because of this, only a subsample consisting of the untreated sample plots of the Lapland Forest Damage Project was used for the purposes of this study. In northern Fennoscandia it is fairly easy to judge whether the stand has undergone disturbances like storm damage; decomposition of wood is very slow, due to the cold climate. Also intermediate cuttings can be diagnosed as stumps of felled trees remain recognizable for roughly a century. Prior to the present century the volume of annual cuttings in Lapland was rather small. Main difficulties in selecting undisturbed stands were encountered close to the smelter in Monchegorsk. The total destruction of forest ecosystems made conclusions about stand history less certain.

Since the original network of sample plots consisted of only 11 plots on the Kola Peninsula, the study material was supplemented by selecting additional sample plots. The need for this was evident especially in the dieback area near Monchegorsk, where only two original plots are located. The sampling locations for the growth trend studies (II, III) are shown in Fig. 2. Additional tree-ring data, not shown in Fig. 2, was collected near the northern forest limit for testing the climate-growth models in article IV. Statistics about sample sizes, tree ages and distances from Monchegorsk for the different sample tree categories are given in Tab. 1.

In the forest damage area near Monchegorsk where all old conifers are presently dead, few standing conifers remain; the majority of trees have been removed. Close to the smelter the standing dead trees were invariably strongly decomposed. Since decomposed wood is difficult to process for the purposes of tree-ring analysis, the least decomposed individuals had to be selected for studying the history of damage near the smelter (II).

Within each sample plot only dominant and co-dominant trees were selected for the analysis. One core at breast height was taken from each tree. The ring widths were measured to within 1/100 mm.

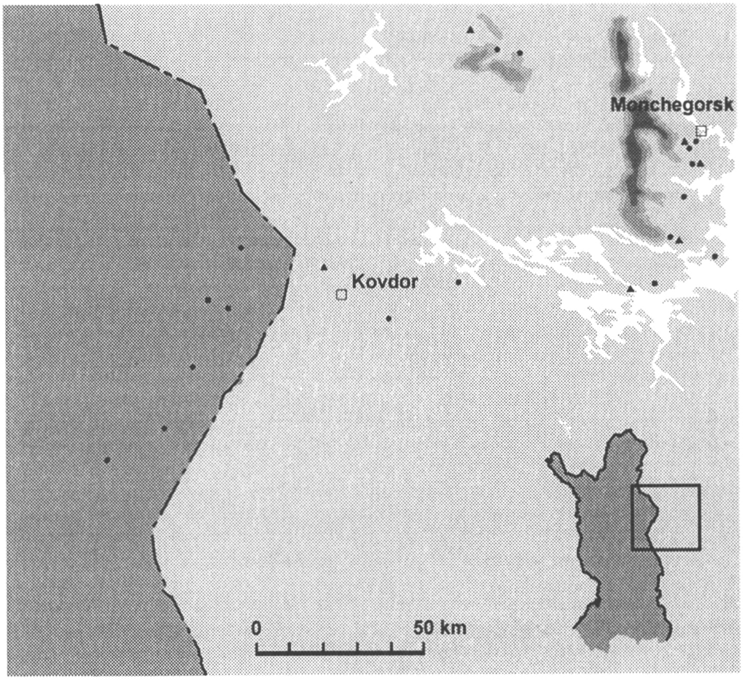

Figure 2. The sampling locations used for collecting tree-ring data for articles II and III.

Table 1. Statistics about the sampled Scots pines: number of sample trees, range for the number of annual rings at breast height and the range for distance from Monchegorsk.

| | N | Annual rings at breast height | Distance from Monchegorsk km |
|---|---|---|---|
| Dead, standing; near Monchegorsk (analyzed in article II) | 55 | 105–370 | 1.5–16 |
| Young; across the pollution gradient (III) | 191 | 35–73 | 8–300 |
| Old; living; across the pollution gradient (II, III) | 308 | 170–356 | 15–190 |
| Old; living ”unpolluted” area (IV) | 271 | 135–437 | 275–310 |

Standardization of the ring-width series is a commonly used procedure in tree-ring research. The purpose is to remove those components of ring-width variation that are of no interest for the study in question. The risk of the procedure lies in the possibility that a considerable share of the studied signal will be lost as well. Because of this, standardization was not used in studying growth trends (II, III). The growth models (IV) were tested using a method of standardization that aims to remove the effect of tree age on the ring widths without removing components of the low-frequency growth trends; the difference of the indices and actual growth is in fact very slight.

Studies aiming to analyze whether the climatic signal in tree rings has been altered by pollution generally use standardization methods which intentionally remove low-frequency variation from the ring-width chronologies before relating the chronology to climatic variables (Johnson et al. 1995). The approach was tested in article III. Therefore a standardization method removing all but the high-frequency variation of growth was adopted for that particular purpose. A simple regression model was used for testing whether the climatic signal in the detrended growth indices has been altered in areas severely affected by pollution.

Growth trends were compared simply by calculating arithmetic means of individual ring-width chronologies over regions (II, III). Variability within the regional ring-width chronologies was analyzed using cluster analysis (III).

Regional chronologies were presented in a three-dimensional graph, which allows one to compare both the low- and high-frequency variation of growth across the sampling gradient (II). The three-dimensional surface was prepared using the ARC-INFO geographic information analysis package (ESRI 1992).

Various models describing the growth-climate relationship were constructed and tested in articles III and IV. A dynamic growth model was constructed in an attempt to utilize information about the seasonal changes in $CO_2$ uptake capacity. The model was tested together with a traditional regression model as well as a dynamic model constructed by Hari and Sirén (1972) (IV).

# 4 Results and discussion

## Recent growth trends at varying distances from Monchegorsk

Growth trends of Scots pines in certain age categories (breast height age 30–80 and 170+) were described at varying distances from Monchegorsk (II, III). The main findings are summarized in Fig. 3 (page 38). The three-dimensional graph illustrates the spatial and temporal development of the growth reductions. The growth variation follows a markedly similar pattern for the period 1800–1939 across the gradient. Thereafter the trends clearly diverge.

Tree-ring material collected within 2.5 km from the smelter showed a rapid growth decrease starting during the mid-1940s already (II). As the smelter was put into operation in 1939 and had not been in constant production during the war, the time lag between the onset of smelting and the initiation of the decline has been rather short. The growth of the nearest sample trees ceased by the year 1952 (II).

The growth decline of the sample trees 4.5 km south of the smelter had been slightly less abrupt (II). At the distance of 8.5 km the growth of the sample trees also started to decline during the 1940s, but the rate of the decline has been slower (II). Six of the eleven sample trees continued to form annual rings during the 1960s.

The growth reductions have gradually expanded along the gradient. At the distance of 15.5 km from the smelter strongly reduced growth was observed during the 1960s (II). The sample trees ceased forming annual rings by the year 1988.

Obvious growth reductions were observed as far as 30 km from the source of pollution; at that distance growth has steadily decreased for 1960–1990, while growth has clearly increased at the western end of the study gradient during that period (II, III). Slight signs of a growth decline during the 1980s were observed 40–45 km south of the smelter (III).

Virtually no documentation exists about the initiation and early development of forest damage in the region Monchegorsk, evidently because of the strategic importance of the industries. An abrupt and severe growth decline, such as the one observed during the 1940s near the smelter, most likely coincides with a general deterioration of forest ecosystems. It seems highly probable that first signs of visible forest damage appeared in less than a decade after the smelter in Monchegorsk started operation.

The available emission history is inadequate for judging the validity of the conclusions about initiation of the damage. A time series of the sulphur emissions that covers the years 1970–1990 has been published by Baklanov et al. (1994) (Fig. 4). The increase in the early 1970s is evidently connected to the fact, that gradually increasing amounts of raw material with an especially high sulphur content has been transported from Norilsk in the Ural mountains since 1964 (Luzin et al. 1994). For the same reason the sulphur emissions prior to 1970 were most likely smaller than during the period 1970–1990. The increase of emissions during recent decades may partly explain the fact that the forest damage near Monchegorsk has been continuously expanding, instead of reaching a steady state.

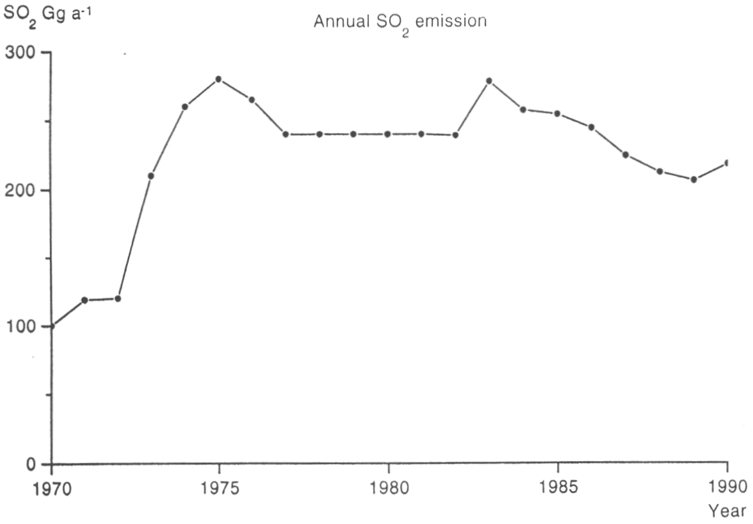

Figure 4. Sulphur dioxide emissions from Monchegorsk for 1970–1990 (reproduced from Baklanov et al. 1994).

In 1952 none of the nearest sample trees any longer formed annual rings. All pines sampled at the distance of 15.5 km had ceased growing by the year 1988. The rate of damage expansion has evidently been fairly stable (Fig. 3, p. 38). The distance, within which old Scots pines south of the smelter no longer form annual rings, has therefore extended to 15.5 km in 36 years — somewhat less than 0.5 km per year (II).

Clear growth reductions were observed near the smelter during the 1940s. At the distance of 30 km reductions have been observed since 1961 (II). The 1960s were a climatically unfavorable period (e.g. Pohtila 1980, Hari and Arovaara 1988, IV), which to a great extent explains the reduced growth during the decade. The fact that growth continued to decrease during the 1970s and 1980s is clearly an anomalous feature, most likely connected to pollution. Therefore anomalous growth reductions have expanded 30 km between the mid 1940s and early 1970s, equaling to approximately 1 km per year.

The results presented above describe old Scots pines (170+ annual rings at breast height). Young Scots pines (30–80 annual rings at breast height) appear to be clearly more resistant against the effects of pollution than older ones (III). Unlike old pines, the young sample trees approximately 30 km south of Monchegorsk failed to show growth reductions. A proportion of the sampled young pines continued to grow within 10 km south of the smelter, while the growth of all old sample trees had ceased within the distance of 15.5 km. It is also significant that young Scots pines with green foliage are quite common at the distance of 4–5 km south of the smelter, where the old pines are invariably dead.

The fact that the growth of younger Scots pines has been less affected by pollutants is noteworthy and might have practical value for silviculture and reforestation efforts in existing forest decline areas. However, contradicting results were reported by Wilhelsson (1983), who studied the effects of emissions from metallurgical industries on the growth of Scots pine and Norway Spruce (*Picea abies* Karst.) (and Scots pine) at Skellefteå, northern Sweden. Greater growth reductions were observed for young trees than for old ones. Evidently further research on the subject is called for.

A disadvantage of averaging ring-width series is the fact that the average may hide considerable variation within the data set. To guard against this possibility the regional data sets were tested using cluster analysis (III). The method has proved to be useful for detecting synchronous changes in radial growth among individual trees (Reams and Van Deusen 1993). In the present application each ring-width series was described by fitting a third degree orthogonal polynomial to the last 30 years (1961–1990) of ring widths of individual trees. The coefficients of the polynomial were then used as input variables for the cluster analysis. The results of the cluster analysis did not show large variability within any of the regional data sets (III). Growth trends had been either increasing or stable for the period 1961–1990 at the western end of the study gradient. Decreasing trends are typical — in varying degree — at the distance of 30 km south of the smelter.

Averaging of raw ring widths is probably the most common method of producing mean chronologies of unstandardized data, presumably because such results are easy to interpret. When considerable variation within the data set exists, the alternative of taking logarithms before calculating the average is worth considering (e.g. Wilhelmsson 1983). The method gives more weight to observations with below average values. The differences of arithmetic means and the means of logarithms are compared in Fig. 5 using a data set consisting of old Scots pines at varying distances from Monchegorsk, also used in article III. In this instance taking a logarithm of individual ring widths could not be used, because zero is a legitimate value for ring-width which also does exist in the data. Because of it, the value 1 has been added to each observed ring with before taking the natural logarithm. It is evident from Fig. 5, that taking natural logarithms prior to averaging the regional chronologies has not changed the growth trends significantly. The most likely reason for this is that the data, consisting of extensively managed old pine stands in northern Fennoscandia, is quite homogeneous.

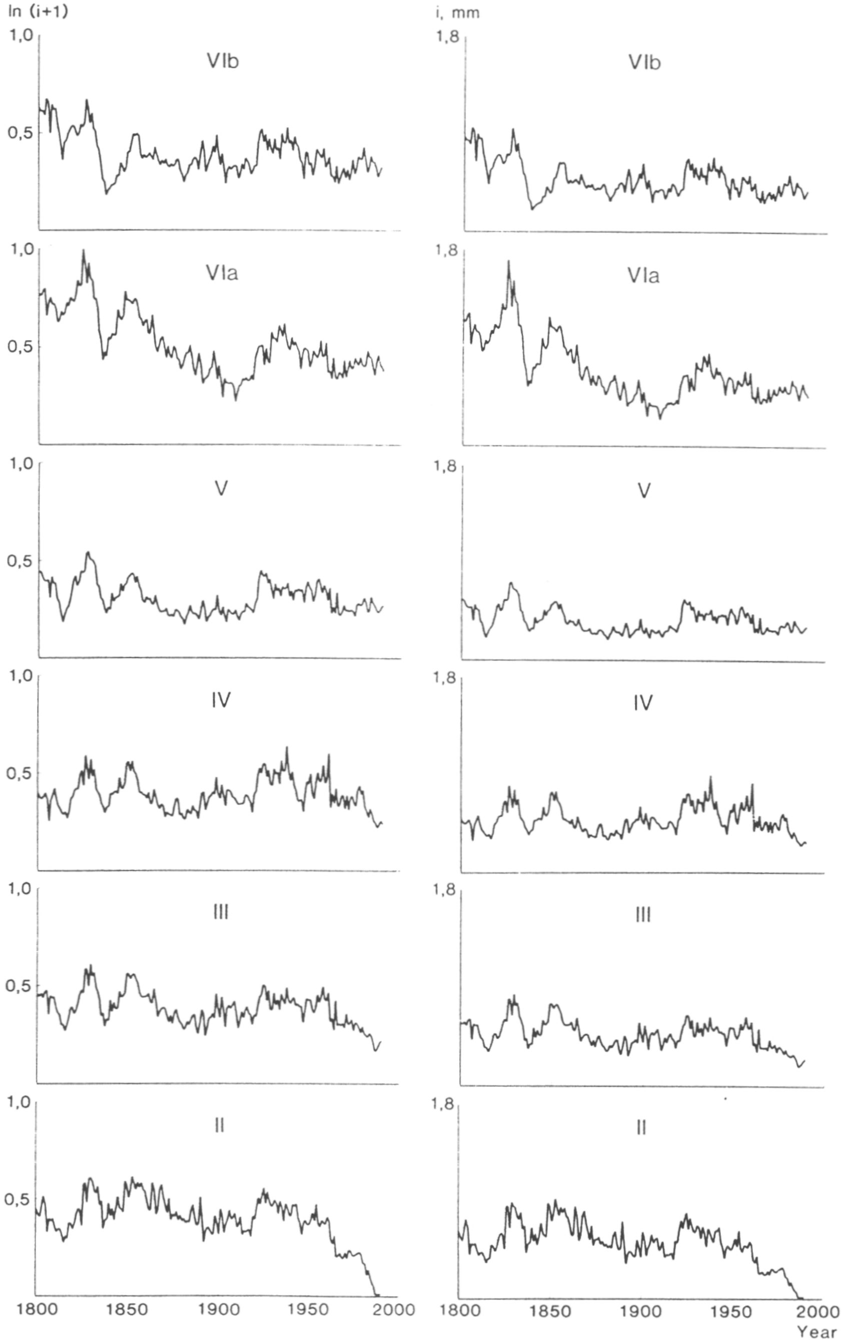

Figure 5. Mean ring widths for geographic zones representing varying exposure to pollution (presented in detail in article III) (right) and respective means of transformed the ring widths using the formula ln (i+1) (left).

Certain reservations, typical for studies of this type, should be noticed. A source of uncertainty connected to growth studies near point sources of pollution has been termed survivor bias. As individual trees gradually lose their vigor and eventually die, the remaining, more resistant trees will receive additional growing space. As a result their growth may temporarily enhance. A sample based on the survivor trees may represent the original tree population poorly. However, since severe growth reductions were observed soon after the onset of smelting, this particular source of error has probably not a affected a significant bias on the observed growth trends.

It is obvious that the results do not offer adequate grounds for generalizing the findings in order to produce estimates of growth reductions on areal bases. First, only Scots pines of certain age-classes growing on infertile mineral soils are described. Secondly, only one transect starting from the pollution source was sampled. In the region of Monchegorsk the local topography strongly affects the transport of pollutants; the sampled areas south of the smelter receive higher loads of pollutants than equidistant areas on average (Baklanov et al. 1994).

A forest inventory with adequate resources and a sampling design that covers all sites regardless of tree species and soil types would be needed for producing estimates on areal bases. It is also possible to conduct a forest inventory based on stratified sampling for producing information on a specified stratum, e.g. pine forests on mineral soils. Stratified sampling requires considerable amount of prior information about the population which is to be sampled, however.

# The effect of climate on the variation of Scots pine growth

## *The pattern of variation for the period 1800–1990*

As is evident from Fig. 3 (p. 38), the ring-width chronologies include strong variation. The pattern of low-frequency variation is markedly similar for all study sites prior to the establishment of the smelter in 1939. Very few climate measurements describing the area of eastern Lapland exist prior to the present century. Nevertheless the pattern of variation has most likely been induced mainly by climate. It seems unlikely that any other factor could have effected such a uniform pattern in such a large area, from Monchegorsk to eastern Lapland. Moreover, quite similar patterns of Scots pine growth have been observed in other parts of northernmost Fennoscandia as well (e.g. Mikola 1952, Sirén 1961, Briffa et al. 1986).

Prior to the onset of smelting the most obvious feature in Fig. 3 (p. 38) is the sudden decrease of growth beginning during the early 1830s and culminating in the year 1837. The temporary, but severe decline has been reported in other parts of northern Fennoscandia as well (Erlandsson 1936, Mikola 1952, Sirén 1961, Briffa et al. 1986). In great likelihood it is of climatic origin, either a result of a series of consecutive cold summers or, perhaps more likely, a climatic disturbance that has caused acute damage to trees. A better documented example of a climatic disturbance is the low growth in the beginning of the present century. Mikola (1952) suggests that it was most likely connected to the sudden hard frost in late September 1902, occurring at a time point when pines were not fully dormant. Many of the following summers were colder than average, which probably has had an effect on the below average growth as well.

Disturbances like the ones mentioned above are common for the whole study area; comparison of ring-width chronologies from different locations is unlikely to be biased by them.

During the latter half of the 20th century — crucial for this research — the growth of Scots pine has not been affected of climatic fluctuations of equal scale to those of 1830s and the beginning of the present century. However, two minor scale disturbances of climatic origin have been reported: relatively cold summers of the early 1960s caused pine growth to fall to a relatively low level (Pohtila 1980). The frost damage initiated during the winter 1986–1987, as reported by Tikkanen and Raitio (1990), caused only slight growth reduction.

## *Climate-growth models for Scots pine in northern Fennoscandia*

The considerable growth variation caused by climate can be described with the aid of climate-growth models. Such models can also be used for removing the climate-induced component of variation from ring-width chronologies. The effect of climate on Scots pine growth was studied in article IV. Three models representing different approaches were applied.

Two of the models, a dynamic model presented by Hari and Sirén (1972) as well as a traditional regression model describe mainly the effect of midsummer temperatures on growth. Especially the model of Hari and Sirén (1972) produced a reasonable fit with data from the northern forest limit. The origin of the test data limits the applicability of the models for conditions of southern Lapland.

It seems natural to assume that climatic variables connected to the length of the growing season — spring and autumn temperatures are the obvious examples — would be useful in predicting annual growth. Previous attempts of quantifying the relationship between spring and autumn temperatures and Scots pine growth in northern Scandinavia have been unsuccessful. An attempt of filling the gap was made by constructing a dynamic growth model, based on results by Pelkonen (1981), which describe the seasonal variation of $CO_2$ uptake capacity of Scots pine (IV). The model, applied in a most straight-forward manner, did not provide a solution to the dilemma, however (IV). It produced results that were very weakly correlated with annual growth.

The usefulness of the growth models in eliminating the effect of climate from ring-widths is limited. A growth model is valid only for the conditions for which it has been calibrated. In northern Fennoscandia climatic differences can be quite large between two locations representing different latitudes. Also altitude affects mean temperatures considerably. As shown by Fig. 1, considerable differences in longitude do not necessarily have a similar effect.

It is well-known that growth models describing the detrended high-frequency variation of growth can explain a high proportion of the total variation of growth. If the focus, like in the present study, is on the low-frequency variation of growth, a rather more limited share of growth variation can be explained with climate-growth models.

## *Changes in the response of tree growth to climate*

Analyzing time dependent changes in the climate-growth relationship is a fairly recent innovation, which has been used for detecting pollution effects on tree growth (Innes and Cook 1989). The approach was tested using the tree-ring data from the transect starting from Monchegorsk (III). A simple regression model describing the relationship of climate and the high-frequency growth variation was constructed using the years (1906–1970) as a calibration period. The model predicted the high-frequency growth variation for the subsequent period 1971–1990 rather well in areas not exposed to high pollution loads. Somewhat surprisingly a similar result was obtained in the heavily polluted areas near Monchegorsk. A clear climate signal was observed decades after the growth trends had clearly started to decline. The high-frequency growth variation of trees sampled at 15.5 km south of Monchegorsk depended clearly on July temperatures as late as the early 1980s; a few years before the growth of those trees totally ceased. The result thus contradicts previous results. In a number of studies (Conkey 1979, Johnson et al. 1986, Cook et al. 1987, McLaughlin et al. 1987) changes in the climate-growth relationship, more or less coinciding with an anomalous decline in growth trends, were detected. A possible interpretation for the differing results is offered by the fact that the tree-ring data for this research was collected near the polar timber line, where the climatic signal in tree-rings is exceptionally strong. In more temperate regions pollution may interfere more easily with the climatic signal in tree rings. Also, in northern Fennoscandia the effect of climate on Scots pine growth is dominated by the effect of July temperatures. In the above mentioned studies the climatic signal in tree rings was far more complex: several climatic variables that have an influence on growth were identified. In any case, the applicability of the approach seems doubtful in the conditions of northern Fennoscandia.

## Removing disturbing variation from the regional ring-width chronologies

The decreasing growth trends, observed near the smelter soon after the smelting began, are very strong. Because of that, one can identify the pollution-induced signal even by studying the original ring-width data, from which no components of variance have been removed. The task would become easier, however, if one were able to reliably remove other components, such as climate-induced or site-specific variation. Numerous techniques, often involving refined statistical analyses, have been developed for the purpose. In this chapter four simple methods are used to illustrate the possibilities for removing components of ring-width variance, which may hide the pollution-induced signal in the data. To compare the methods with each other, the coefficient of variation (the standard deviation divided by the mean) is calculated across the seven regional chronologies. The period 1906–1939 was chosen for the comparison since climate data is available since 1906 and the smelter in Monchegorsk started operation in 1939. The coefficient of variation for the original values was 0.262.

### *Method 1*

The mean growth for each regional chronology from article II is calculated for the years 1850–1939, before the smelter started operation. Each chronology is then corrected to a comparable level with the westernmost one, sampled from eastern Lapland:

$$Y_t = \frac{\sum_{i=1850}^{1939} Iw_t}{\sum_{i=1850}^{1939} I_t} I_t \qquad [1]$$

where

$Y_t$ = corrected ring-width for year t in a given zone

$Iw_t$ = mean ring-width for year t of the westernmost chronology

$I_t$ = mean ring-width for year t of the chronology to be transformed.

The transformation removes differences in mean level of growth between chronologies. The most likely causes for such differences are site quality and stand structure. Fig. 6a shows the original regional chronologies (solid line) as well as each chronology adjusted so that its mean for 1850–1939 equals the mean of the westernmost chronology for the same period (dotted line). The procedure affects especially the chronology sampled at 70 km southwest of Monchegorsk. The coefficient of variation across the seven regional chronologies and for the period 1906–1939 is 0.235.

### *Method 2*

An equally simple method is to divide each regional chronology by the westernmost one (Fig. 6b). The procedure effectively removes disturbing climatic variance, if one assumes that:

1. the component of growth variation that is unconnected to pollution is mainly induced by climate and
2. the regional chronologies represent climatically identical locations.

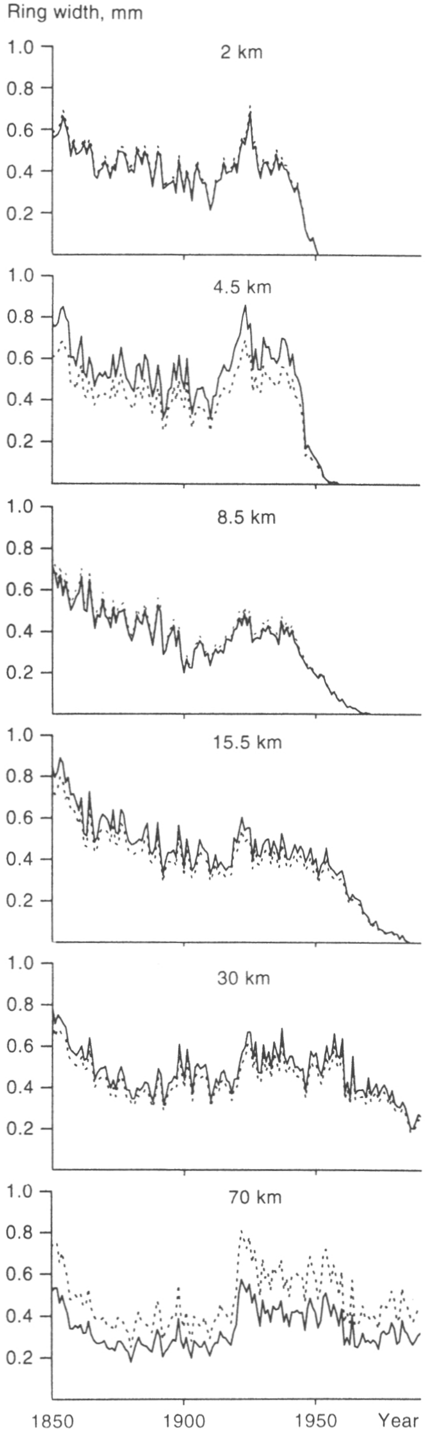

Fig. 6a.

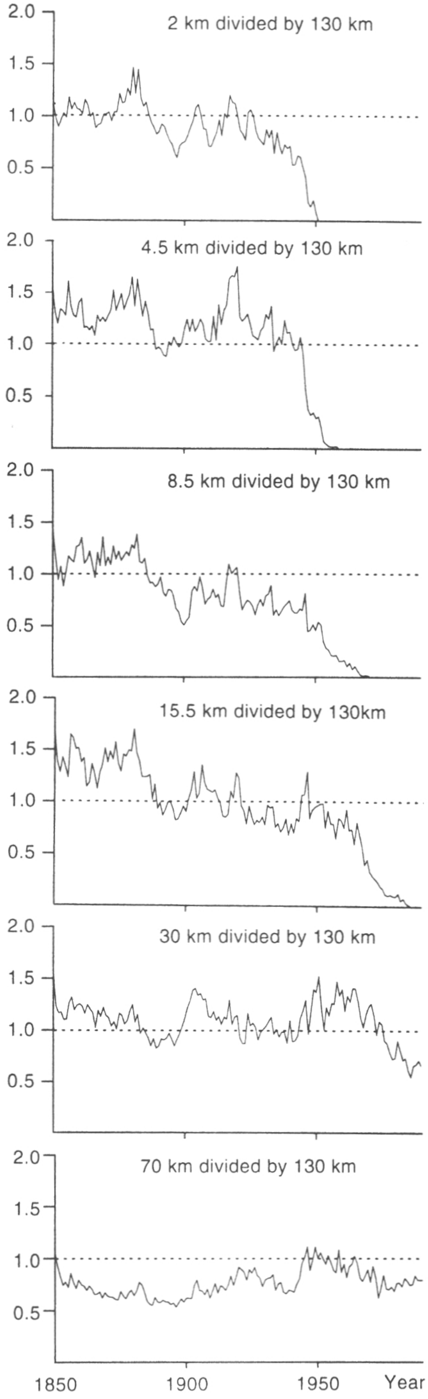

Fig. 6b.

*(Cont. on p. 35 and 37)*

The remaining variation would be due to differences in site quality and stand structure as well as local disturbances encountered by individual stands. The procedure makes it easier to judge the time, when each chronology diverges from the westernmost one, representing the least polluted region.

It is evident, that considerable variation is present during the period 1850–1938, when the stands were not affected by pollution from Monchegorsk (Fig. 6b). Differences at the beginning of the interval were most probably affected partially by tree age. At young age many conifers form wide annual rings; with increasing age radial growth gradually decreases (Fritts 1976). Coefficient of variation over the six easternmost chronologies for 1906–1939, before the industries in Monchegorsk were started, is 0.234.

The chronologies from sites close to Monchegorsk diverge from the westernmost one soon after the production started in 1939. This type of comparison makes it easier to judge that growth at 30 km from the smelter clearly diverges from the least polluted region in around the year 1970. The negative trend is preceded by a growth increase during the 1940s and 1950s. Since a similar effect was not detected at other locations, it is evidently due to a local, site-specific disturbance.

The chronologies near Monchegorsk differ from the westernmost one more clearly than those sampled near the Finnish-Russian border prior to the onset of smelting. There may be several reasons for the differences. Data sets near the smelter consist of a small number of trees. In such cases disturbances encountered by individual trees leave a stronger mark on the average chronology. Deductions about stand history are also less reliable in the area where severe forest damage presently exists; previous disturbances like forest fires are more difficult to detect retrospectively. The greater distance between the sites near Monchegorsk and the Finnish Lapland most likely increases climatic differences, which may also partly explain the differences in growth pattern.

### *Method 3*

In Figs. 6c and 6d a common approach, modeling the climate-growth relationship, is applied for removing the

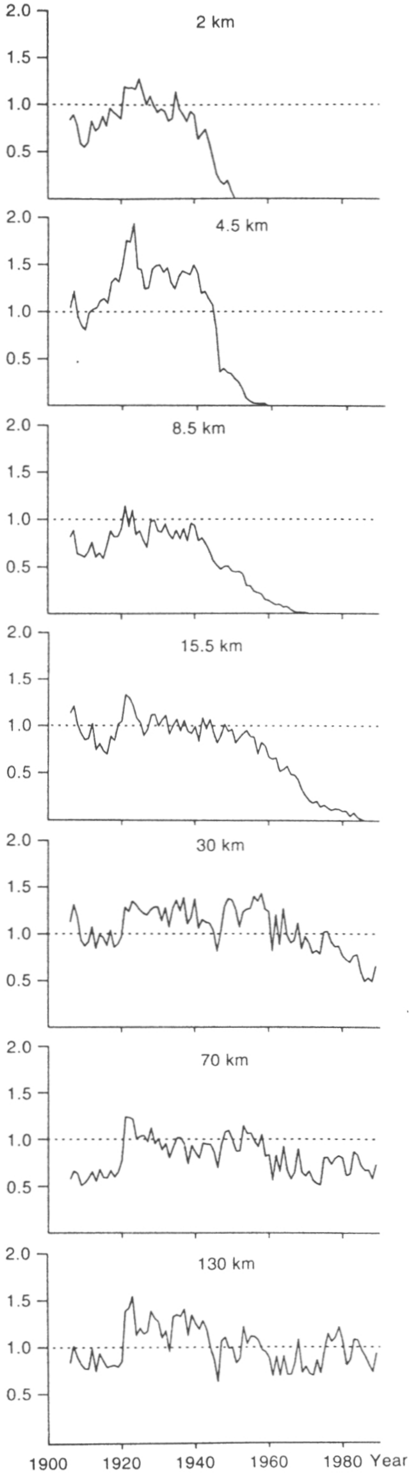

Fig. 6c.

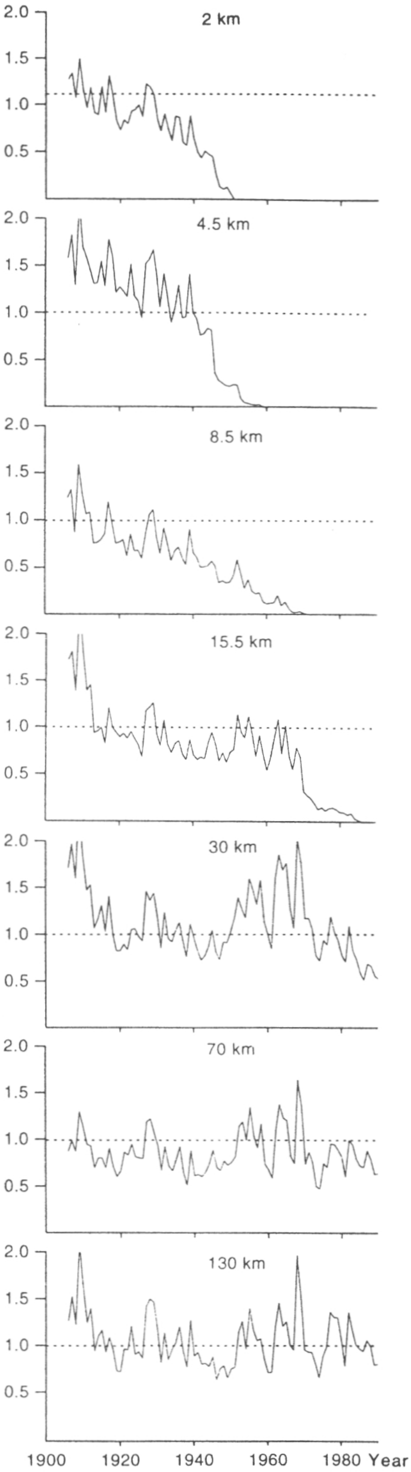

Fig. 6d.

*(Cont. on p. 37)*

climatic signal from each regional chronology. A simple linear model based on ordinary least squares was constructed for the purpose. Monthly mean temperatures and precipitation for the period (1906–1989) of the meteorological station in Sodankylä (67°22'N, 26°39'E, 178 a. s. l.) were related to the westernmost chronology from article II. Only the temperature for July proved to be significantly correlated with ring-width variation.

$$Y_t = b_0 + b_1 (T_{july,t}) + e \qquad [2]$$

where
$Y_t$ = standardized tree-ring index for year t
$T_{july,t}$ = monthly mean air temperature of July for year t
$b_0$, $b_1$ = regression coefficients
e = random element.

The coefficients and p-values of the model are given in Tab. 2. The highly simple structure of the model is made possible by the fact that, evidently due to the extremely short growing season, the climatic signal in tree rings is dominated by the effect of July temperature.

In Fig. 6c the seven chronologies from different locations have been divided by the climate-growth model, presented above. The procedure illustrates the difficulties connected to modeling rings widths from climate. The model is unable to adequately describe the strong low-frequency growth variation, which is typical for Scots pine at the high latitudes, such as the period of fast growth during the 1920s and 30s (see Fig. 3, p. 38). The recent ring-widths observed for Finnish Lapland do not deviate strongly from the predicted ones. In areas close to Monchegorsk the differences are evident, of course. The coefficient of variation is 0.251, somewhat higher than by using method 2.

Table 2. Regression equation describing the relationship of climate and and the westernmost regional chronology. The p-values for each coefficient are given in parenthesis.

| Model | $r^2$-value |
|---|---|
| Yt = 13.41 + 2.213 ($July_t$) | 0.163 |
| (0.080) (0.000) | |

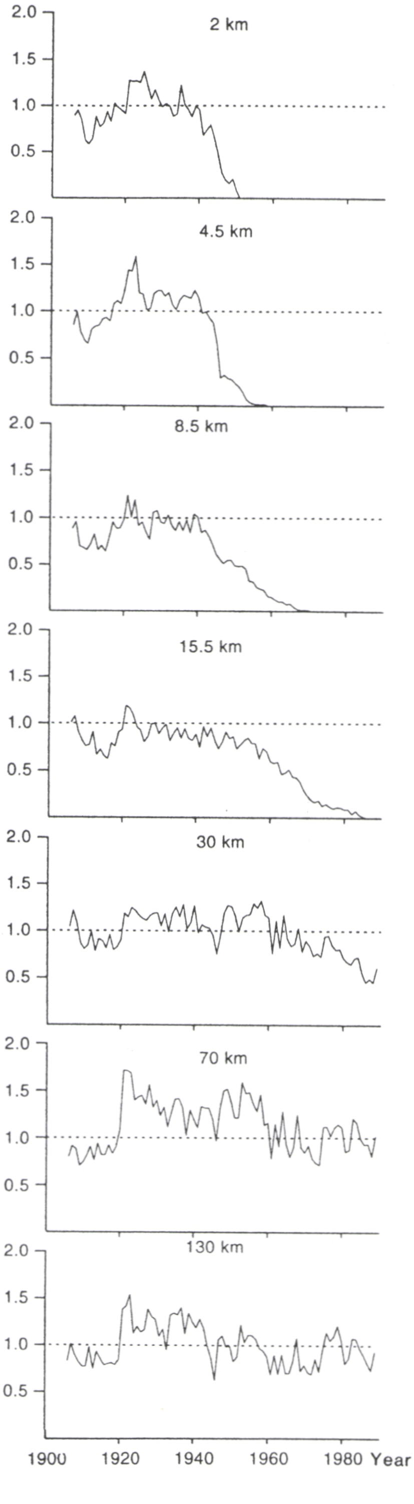

Figure 6. The regional ring-width chronologies, presented in article II, transformed with methods which remove climate-induced or stand specific growth variation: Unstandardized ring widths (solid line) and transformed by method 1 (6a); each chronology divided with the westernmost one (6b); each chronology divided by the growth-climate model, based on linear regression (6c); each chronology divided by the dynamic growth model of Hari and Sirén (1972) (6d) and the combination of methods 1 and 3 (6e).

Fig. 6e.

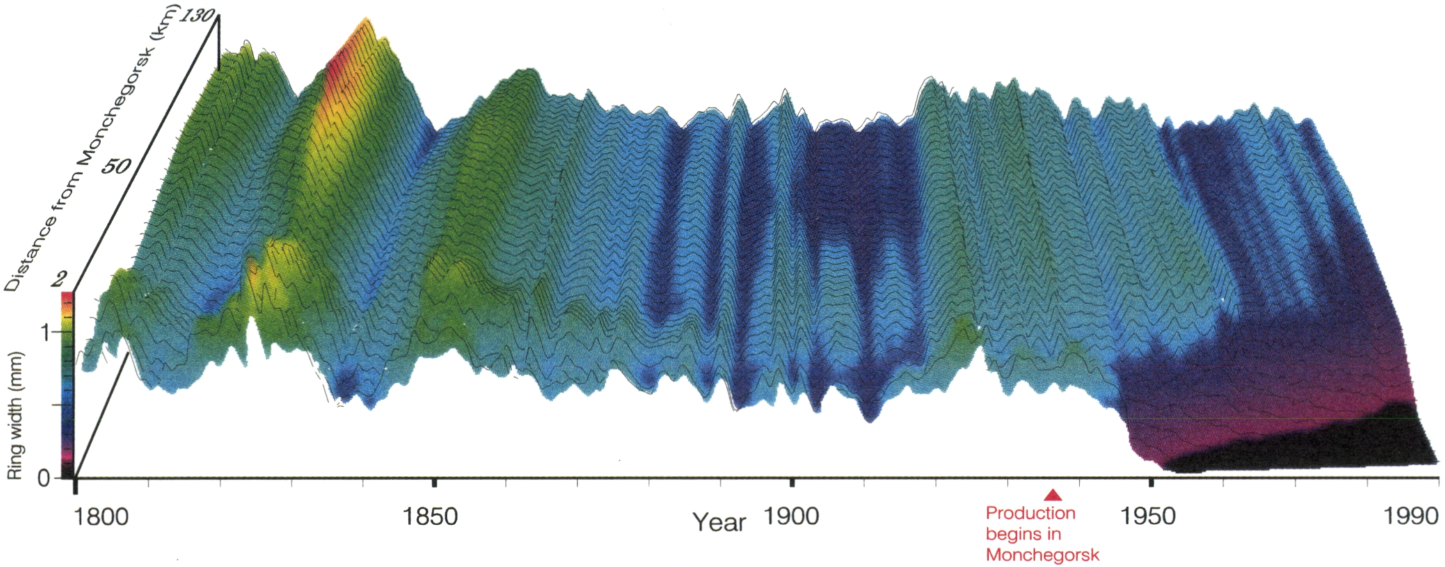

Figure 3. A three-dimensional surface describing radial growth of Scots pine as a function of time and distance south-southwest of the smelter (II).

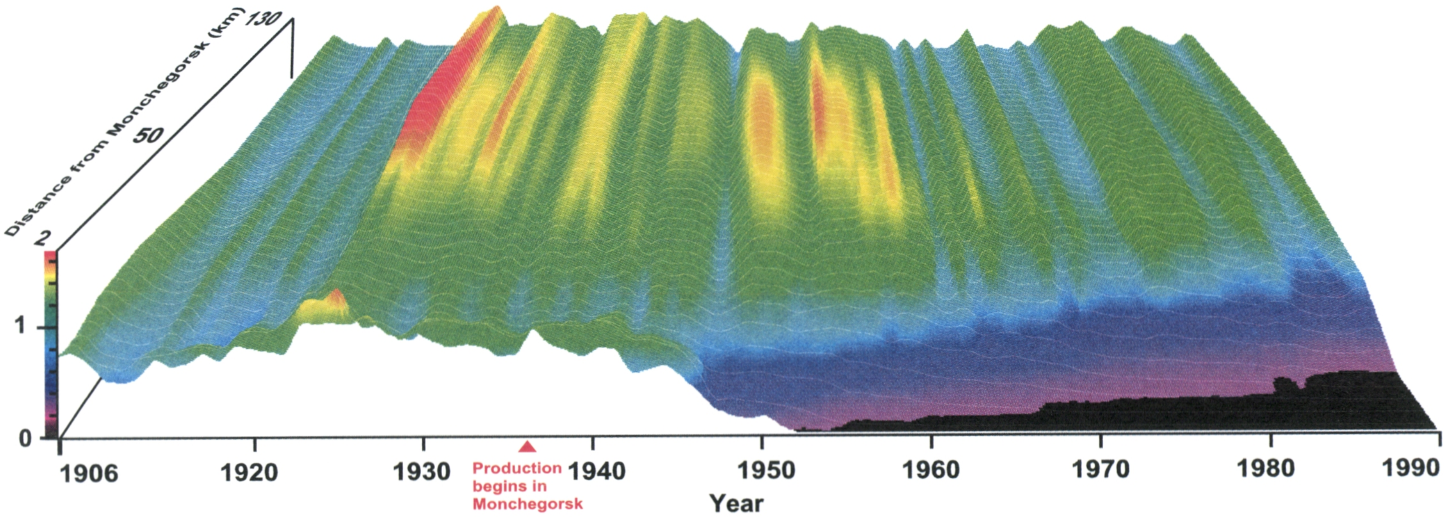

Figure 7. A three-dimensional surface describing the remaining ring-width variation, after climatic and site-specific variation have been removed by using formulas (1) and (2), as a function of time and distance south-southwest of the smelter.

Similarly, in Fig. 6d the dynamic growth model of Hari and Sirén (1972), presented in article IV, has been used for removing the climatic signal from the data. The result is clearly not satisfactory. The reason is quite obvious: the model is calibrated for describing growth variation at the northern forest limit. As shown by Mikola (1952), a 200 km shift towards south means a considerable change in growth variation. The coefficient of variation of growth is much greater at the northern forest limit than at the conditions of the sampling gradient for studies II and III. Because of the difference of locations, the model of Hari and Sirén (1972) overestimates growth during favorable periods and underestimates the growth of unfavorable periods.

The coefficient of variation for 1906–1939 is 0.280; considerably larger than respective figure for the other methods.

### *Method 4*

The fourth method in a combination of methods 1 and 3. Each chronology is adjusted so that its mean for 1850–1939 equals the mean of the westernmost chronology. Thereafter each chronology is divided by the regression model presented above. The results are shown in Fig. 6e. The coefficient of variation of the data is 0.219.

The three-dimensional graph in Fig. 7 is based on the chronologies produced by applying formulas 1 and 2. The graph was produced in a similar fashion as Fig. 3 (p. 38). Comparison of the two graphs illustrates what has been achieved by removing components of the variance.

It is evident from Figs. 6 and 7 that despite every effort in selecting undisturbed Scots pine stands representing comparable sites and climatically similar locations, considerable variation between sites is present. The methods described for removing climatic or site-specific variation proved fairly inefficient: the coefficient of variation for 1906–1939 was reduced from 0.262 (original ring widths) to 0.219. However, the pollution-induced signal in data is so strong, that it can't be masked by the uncontrolled variation. The presence of the fairly large noise component discourages one from drawing conclusions on the basis of subtle differences between regional chronologies, however.

# The results in the framework of other studies describing the pollution gradient

During the 1990s the ecological problems in the region of Monchegorsk have been subject to intensive research. In addition to the Lapland Forest Damage Project, financed by the Finnish Ministry of Agriculture and Forestry, research teams from other Scandinavian countries and Russia have been involved in the studies. While many study results are yet to be published in scientific journals, it is already possible to compare the findings of this thesis with other results describing environmental quality in the region of Monchegorsk. Fig. 8 summarizes the results of studies describing air quality (Tuovinen et al. 1993), deposition (Jevtjugina 1991), the accumulation of pollutants in foliage (Raitio 1992, Kozlov et al. 1995), needle retention (Jalkanen 1996), frost hardiness (Sutinen et al. 1996) and recent growth trends across the pollution gradient south and southwest of Monchegorsk.

The network of air quality measurements stations in the region of Monchegorsk is inadequate for describing the dispersion of pollutants satisfactorily. Tuovinen et al. (1993) filled the gap by constructing a semi-empirical dispersion model describing the mean annual $SO_2$ concentrations of the air in the region surrounding Monchegorsk. Monthly statistics about emissions and climate were used in constructing the model. In Fig. 8a the gradual change of the mean annual $SO_2$ concentration is described across the gradient from which the tree-ring data was collected. Near the smelter the gradient is very sharp, but at greater distances the concentrations gradually begin to stabilize, a typical pattern near large point sources of pollution. While very high mean annual concentrations (300 $\mu g/m^3$) have been reported at the immediate vicinity of the smelter (Kryuchkov 1993), the modeled mean annual $SO_2$ concentrations are fairly low (approximately 10 $\mu g/m^3$) 30 km south of Monchegorsk, a region where clear growth reductions were observed (II, III).

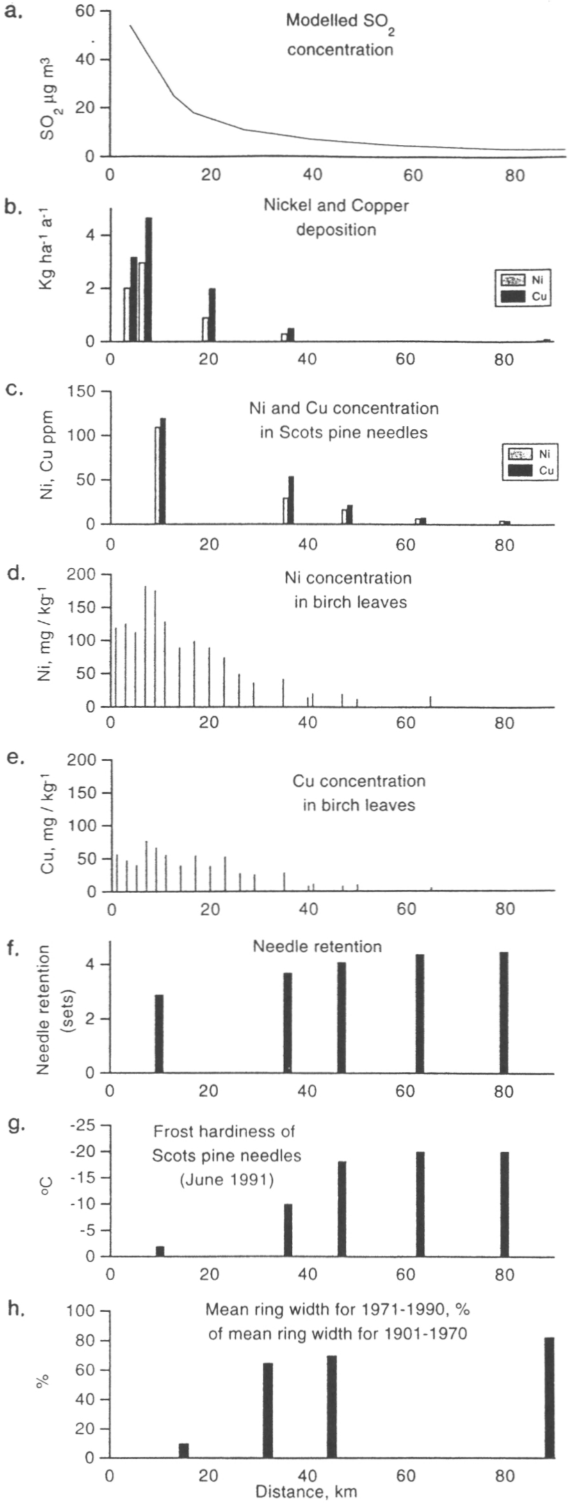

Figure 8. Indicators of pollution from other studies describing environmental quality in the region of Monchegorsk (Tuovinen et al. 1993 (a), Jevtjugina 1991 (b), Raitio 1992 (c), Kozlov et al. 1995 (d, e), Jalkanen 1996 (f), Sutinen et al. 1996 (g) and the ratio of mean ring-width for 1971–1990 and 1901–1970 (h)).

Annual depositions of sulphur Ni and Cu, reported by Jevtjugina (1991) follow a somewhat similar pattern. Very high concentrations are measured within 7 km of smelter (Fig. 8b). At a sampling site 36 km south of Monchegorsk, both nickel and copper depositions are still clearly elevated.

Raitio (1992) studied the element concentrations of Scots pine needles on the same sample plots from which the tree-ring data was collected. The analysis showed that Ni and Cu concentrations were slightly elevated at the distance of 63 km southwest of the smelter (Fig. 8c). At distances greater than that the concentrations stabilize. Cu concentrations of 50–60 ppm were measured at 36 km south of Monchegorsk; considerably more than the values of less than 5 ppm measured from needles collected at the distance of 80 km. The respective concentrations for nickel are approximately 30–40 ppm at 36 km and 2–3 ppm at 80 km. The concentrations for sulphur in pine needles at 36 km were approximately 1 200 ppm, compared to background values of 900–1000 ppm.

A dense sampling gradient was used by Kozlov et al. (1995), who measured nickel and copper concentrations in birch leaves at 18 sites, all within 65 km south of Monchegorsk. Both concentrations appear to stabilize at distances greater than 40 km (Figs. 8d, e).

Jalkanen (1996) used a novel quantitative approach, the needle trace method (NTM) (Jalkanen and Kurkela 1990), for reconstructing a time series about the variation of needle retention. A young Scots pine stand located 10 km south of Monchegorsk had on average 2.9 needle sets in 1991 (Fig. 8f). The sampled stand died subsequently during the winter 1991/1992. At the distance of 80 km, where the sampling was performed in 1992, the average needle retention was 4.5.

Sutinen et al. (1996) analyzed the frost hardiness of Scots pine needles on the sample plots of the Lapland Forest Damage Project. Clearly lowered frost hardiness was observed at plots located 10 and 36 km south of Monchegorsk. The differences between study sites were greatest in June 1991 (Fig. 8g). Low temperature is the most critical natural abiotic stress factor for plants in the subarctic environment, and sulphur dioxide has been shown to lower the frost hardiness of forest trees (Keller 1981). Therefore the findings of Sutinen et al. (1996) represent one of the few direct causal links between pollution and forest damage in the region of Monchegorsk.

It is rather difficult to summarize information on regional growth trends into a stack column diagram. In Fig. 8 growth trends are described, somewhat arbitrarily, by the ratio of mean growth during 1971–1990 and the mean for 1900–1970, i.e. recent growth is compared to long term average.

One can conclude from Fig. 8, that the observed growth trends follow a logical pattern, when compared to results describing the exposure of forest ecosystems to pollution at varying distances from Monchegorsk. Clear growth reductions of old Scots pines were observed 30 km south of the smelter (II, III), and some hints of a recent anomalous downward trend at the distance of 40–45 km (III). The results summarized in Fig. 8 show convincingly, that forest ecosystems within 30–40 km have been affected by the cumulative deposition of pollutants. The values of the various indicators in Fig. 8, measured at distances between 30 and 40 km, clearly differ from background values. At distances greater than 40 km the values seem to gradually stabilize.

The fact that the various indicators in Fig. 8 produce a rather uniform result can partly be explained by local topography. Areas within 30 km south of Monchegorsk are located between two mountain ranges which direct the movement of air and dispersion of pollutants. After reaching the end of the valley between the mountain ranges the air will disperse to a wider sector, and concentrations of pollutants will quickly reduce.

The sampled old Scots pines seem to have reacted to quite moderate concentrations of pollutants. Roberts (1984) reviewed experimental data and suggests 100–150 $\mu g\ m^{-3}$ as a threshold value for long-term mean $SO_2$ concentration, which is likely to cause growth effects for forest trees. At 30 km south of Monchegorsk, where growth effects were observed, the modeled mean annual concentrations of $SO_2$ are much lower, approximately 10 $\mu g\ m^{-3}$. Such $SO_2$ concentrations are common in Central Europe in areas without extensive forest damage. On the other hand considerably elevated nickel and copper depositions were observed in the same area. Also the nickel and copper concentrations in pine needles exceed background values by a factor of 10. While it has proved to be hard to draw definite conclusions about the relative importance of sulphur and heavy metals, these observations tend to emphasize the role of heavy metals as causal factors for the forest decline.

Using the most sensitive detectors it is possible to demonstrate effects of pollution from Monchegorsk at distances exceeding 100 km. Measurements of individual meteorological stations in Finland show that traces of the pollutants from Monchegorsk can be measured in the form of infrequent episodes of high $SO_2$ concentrations. At the western end of the study gradient at Värriö concentrations exceeding 100 $\mu g\ m^{-3}$ have been measured (e.g. Hari et al. 1994). The episodes of high concentrations are rare, though. The phenomenon is exemplified by results from a measurement station at Jäniskoski, near the Finnish–Russian border (68°58'N 29°37'E, 425 m a.s.l.). While 0.5 % of observations exceed 100 $\mu g\ m^{-3}$, the median $SO_2$ concentration has been very low, approximately 1 $\mu g\ m^{-3}$ (Tuovinen et al. 1993).

The fact that the forests in eastern Lapland are not totally unaffected by pollution is also shown by measurements of the chemical composition of certain moss species as well as pine bark. Elevated heavy metal concentrations were discovered in two moss species (*Pleurozium schreberi, Hylocomium splendens*) (Ruhling et al. 1987). Similarly, elevated concentrations of Ni and Cu in pine bark were observed more than 100 km southwest of the smelter in Monchegorsk (Poikolainen 1992).

The distribution of recent growth reductions along the studied gradient also corresponds well with a recently published classification based on existence of certain plant species, which are useful indicators of environmental quality (Kryuchkov 1993) (III).

# 5 Conclusions

Wide-spread growth reductions were discovered in the region surrounding Monchegorsk. The initiation of the downward trend could be dated back to mid-1940s at the immediate vicinity of the smelter. Near the smelter the growth of the sampled Scots pine ceased by the year 1952. Thereafter the damage has gradually expanded. The sampled mature Scots pines no longer form annual rings within 15 km south of Monchegorsk. Clear growth reductions were observed at the distance of approximately 30 km. Young Scots pines (30–80 rings at breast height) proved to be more resistant against the effects of pollution than old ones (170+ rings at breast height). The area south of Monchegorsk, within which the sampled old Scots pines no longer form annual rings, has expanded at a rate of approximately 0.5 km per year.

The climatic signal in tree-rings, commonly analyzed with the intention of detecting effects of pollution, proved less sensitive to changes than the actual growth trends.

The observed growth trends match well with various indicators of environmental quality. A number of studies have shown that forest ecosystems within 30 km south of Monchegorsk — where obvious growth reductions were observed — have accumulated quantities of sulphur and heavy metals which clearly exceed background levels. In addition, shortened needle retention and lowered frost hardiness of Scots pine has been observed in the area, which provides further evidence of the fact that the physiological functioning of the trees has been altered.

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# I

# Detecting Forest Growth Responses to Environmental Changes – a Review of Finnish Studies

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## Summary

The growth of the Finnish forest has increased considerably during the last few decades. Several attempts have been made to analyse whether the increase can be attributed to improved silviculture and changes in forest structure. Alternatively, changes in the $CO_2$ concentration of the air and the fertilising effect of acidic deposition could partly explain the phenomenon. According to most of the studies reviewed, the increase in growth seems to be too large to be caused solely by silvicultural measures. Methodological problems connected with studies of this type are also discussed.

## Introduction

New types of forest damage have recently been reported in different parts of Europe. "Novel forest damage" has received considerable publicity in the mass media. During the past decade, research connected with this phenomenon has increased greatly. A vast number of relevant details about changing environmental factors and their effects on forest ecosystems have been generated, ranging from atmospheric reactions to soil processes and tree physiology.

Although quite a lot is known about the details, it has proved difficult to combine the available information into a convincing theory concerning the reactions of entire forest ecosystems to environmental changes. Without such a strong theoretical understanding it is difficult to make predictions about the future development of forest impacts. This is especially true in the case of predicting forest growth, which is a typical complex process, involving several tree-specific processes, interactions between trees, soil processes and the different effects of the environment.

Forest growth can be studied by simulating the functioning of forest ecosystems. Models for this purpose have developed tremendously in recent years. In Finland the methodology of system analysis was used by Hari et al. (1987) for predicting changes of forest growth due to environmental changes. In the first versions of their model only a very few basic factors (toxic compounds in the air, $CO_2$ content and some others) were applied.

Kauppi et al. (Eds).
Acidification in Finland

The obvious alternative is to study empirical data in order to obtain basic knowledge about the effects of environmental changes on tree growth.

Experimental studies are the most straightforward example of this approach. However, forest trees are not ideal subjects for studies under laboratory conditions. Experiments with small plants can produce valuable results about biological processes, but it is not easy to generalize the results to cover varying natural ecosystems. Another drawback is that the time scale of the reactions of plants to different toxic substances varies greatly. Acute damage, caused by high doses of pollutants, can be studied relatively easily. The more gradual sort of damage, caused by subtle changes in soil processes, that may develop during several decades, are rather more difficult to reproduce.

Studying increment data from field measurements permits analysis of the actual development of forests.

It is relatively simple to measure the increment of a stand with reasonable accuracy. Assessing the causal factors behind the measured growth development is a rather more demanding task. There are a number of natural factors including climatic changes, competition and the ageing of the tree, which cause fluctuation as well as trend-like changes in the growth pattern. Human influence, especially silvicultural measures, also have an effect.

The effects of a changing environment may also take several forms. Changes in the composition of the atmosphere do not exclusively cause decline in the increment pattern. The constant increase in the $CO_2$ content of the atmosphere stimulates tree growth (LaMarche et al. 1984). Increased nitrogen deposition will have a similar effect under Finnish conditions, where forest soils are generally nitrogen-deficient (Viro 1967). Acidic deposition is known to cause a release of base cations in the soil (see e.g. Ulrich 1983). In theory this would, in the first phase, improve the nutrient status of trees, and bring about a growth increase. In the long run the effect of this process would be negative, increased leaching of cations would cause nutrient deficiencies and a subsequent decline in growth. Still another factor, which could have a positive effect on forest growth in most climatic zones, is the possible increase in average temperatures, caused mainly by the use of fossil fuel. It is not easy to assess the effects of temperature changes, since they might be associated with severe changes in annual rainfall, and the structure of ecosystems could be completely altered.

On the other hand, most hypotheses emphasize the role of different air pollutants as growth-reducing factors. Many of these hypotheses have strong experimental support. Most attention has been focussed on studying the effects of sulphur, nitrogen, ozone and heavy metals deposition. The levels of pollutants prevailing in many industrial regions have produced reductions in the growth of small plants under laboratory conditions. The combined effect of two or more pollutants have proved especially harmful. Increment studies near pollution sources have also clearly shown the possibility of severe growth reductions (see e.g. Wilhelmsson 1983).

The task of the forest growth researcher is to separate the possible effects of environmental changes – positive or negative – from the total variation in growth, which is the combined effect of a multitude of factors. This is not made any easier by the fact that the exact causal factors behind "the novel forest damage" are not understood very well. It is therefore hardly surprising that it has proved difficult to demonstrate direct relations between pollutant deposition levels of and growth changes over large forest areas. The analytical techniques available for this purpose have improved considerably during recent years.

This chapter is a review of recent Finnish studies concerned with analysing the growth development of Finnish forests. Special attention is focussed on the component of growth variation, which is unaffected by changes in forest structure.

## Growth Results from National Forest Inventories

An exceptionally long time series exists concerning Finnish forest resource development. The first national forest inventory (NFI) was started as early as 1922 and completed in 1924. The inventory was repeated during 1936–1938. As the land area of Finland diminished after the Second World War it is difficult to compare the results of these first two inventories with later ones. In the main they have been omitted from the following figures. The result of the third inventory (1951–1953) is more comparable with subsequent ones. Line plot sampling was used in the first three as well as in the fourth inventory (1960–1963). Visual estimations were made along the lines between plots. In the fifth and subsequent inventories systematic cluster sampling was used. The field work rotated from Southern Finland towards the north, between one and four districts being inventoried each summer. It has taken 7–8 years to cover the whole country. The latest inventory to be completed was the 7th NFI (1977–1984).

In the present inventory (the 8th NFI), the sampling unit is a tract which consists of 21 sample plots. In Southern Finland the distance between tracts is 7 × 8 km. In the northern part of the country, where the conditions are not so favourable for forestry, a less intensive sampling design utilizing aerial photographs is used.

The total area of forestry land is 26.4 million hectares, representing 86.6% of the total land area of Finland. (Kuusela et al. 1986).

As can be seen from Figs. 1 and 2, there has been a considerable increase in the growing stock as well in the annual growth of Finnish forests during the last few decades (Yearbook 1987).

The most recent results are from southern Finland. The 8th NFI was started in 1986. The results for the area, which was covered by 1988 are presented in Fig. 3, together with respective results from earlier inventories. The differences in growth between mid the 1960's and early 1970's were fairly small. Since then there has been a considerable increase, the most rapid increase being in spruce growth

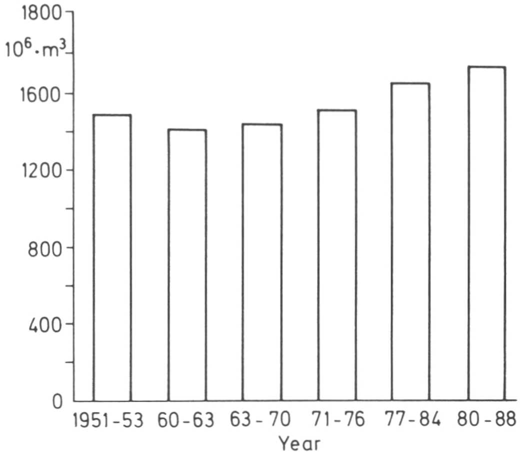

**Fig. 1.** Total volume of growing stock in Finland in 1951–1984. (Yearbook 1987)

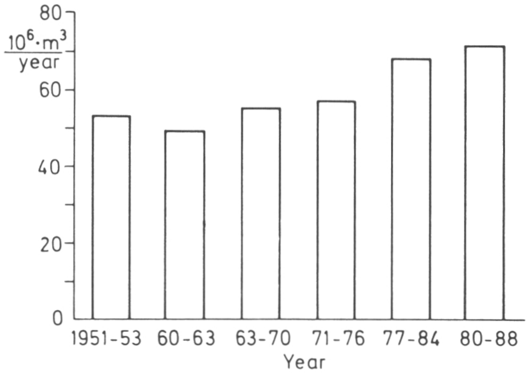

**Fig. 2.** Total annual growth in Finland in 1951–1984. (Yearbook 1987)

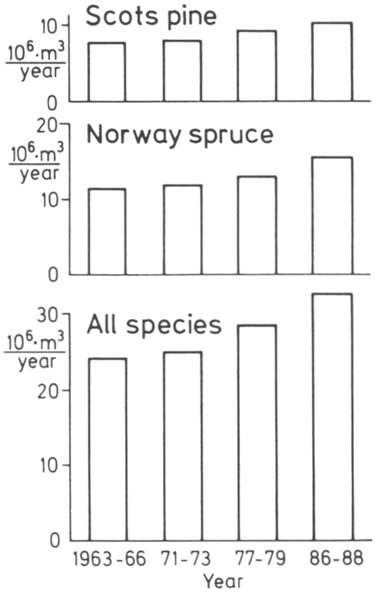

**Fig. 3.** Total annual growth in the nine southernmost forestry districts of Finland in 1963–1988

between 1977 and 1979 and 1986 and 1988 (Kuusela and Salminen 1980; Kuusela et al. 1983; Kuusela and Salminen 1986).

Many obvious factors have contributed to this development. During this century 4.5 million hectares of peatland (17% of the forestry area of Finland) have been drained. This has, according to Paavilainen and Tiihonen (1988), increased the annual growth by as much as 6–7 million $m^3 a^{-1}$. In the early 1970's 1–1.5% of the forest land was fertilized annually (Yearbook). Silvicultural methods have also developed greatly, changes in cutting methods being the most obvious improvement.

The age structures from four different inventories (Fig. 4) show a clear increase in the proportions of newly regenerated stands and stands older than 80 years (Yli-Kojola 1985). As the growth of over-aged stands is relatively low, the present age structure is hardly ideal for maximum growth. At first glance it seems that the age structure would have been favourable for growth at the beginning of the century. These age figures can be rather misleading, however. During the first half of the century selective cuttings were very common, which resulted in uneven age structures. Thus a stand in age class 40–60 years may actually include a mixture of trees from all age classes.

## Studies Based on Extensive, Representative Data

The question arises whether the considerable increase in the growth of Finnish forests can be totally attributed to improved silviculture. The alternative hypo-

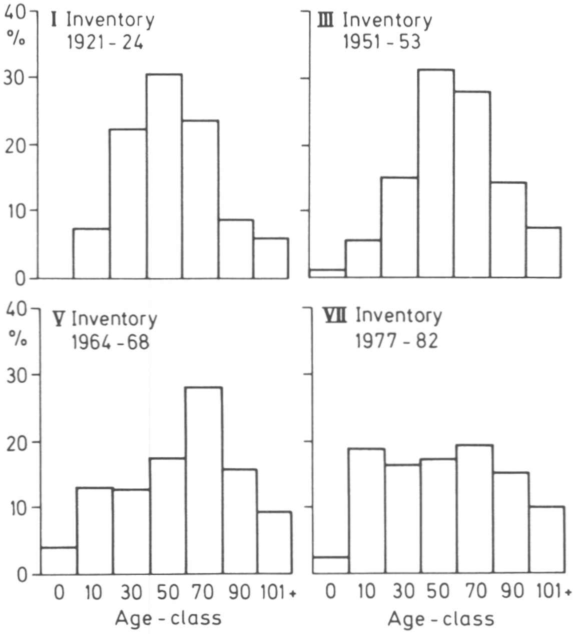

**Fig. 4.** Age structure in four different national forest inventories. (Yli-Kojola 1985)

thesis is that changes in atmospheric composition have significantly affected the growth.

As pointed out previously, there are many difficulties involved in studying such questions. However, some interesting research with the aim of enlightening this question has been carried out in Finland in recent years.

One basic problem associated with many growth and yield studies is that the data lack representativeness. If the study material is selected subjectively, the results describe the chosen trees or stands, but cannot be generalised to cover large areas. On the other hand, it is usually very laborious to collect an objectively selected sample of increment data.

The sample tree data from Finnish national forest inventories is an example of such study material. Three out of the 21 plots on each inventory tract are selected as sample tree plots. The trees are selected using a relascope. The basic dimensions, age and yearly increments for the preceding 5-year period are measured on each tree. The total number of sample trees in the 7th NFI was 66.113 (Kuusela and Salminen 1983; Kuusela et al. 1986). Also basic stand characteristics like site class and basal area are measured on each plot.

Arovaara et al. (1984) used sample tree data from three national forest inventories for analyzing the growth development of pine on subdry mineral soil sites. Their aim was to determine whether the growth of these subsamples differs significantly from one to another. If such differences were to be found, it would support the theory that increased atmospheric $CO_2$ levels would have affected forest productivity. Sample tree data from the third (1951–1953), sixth (1971–1976) and seventh (1977–1984) NFI's were used. In order to achieve maximum comparability, the most important stand characteristics causing variation in increment, including site quality, age class and stand quality, were selected. Stands belonging to certain characteristic classes were selected for the analyses. Following this procedure, the subsamples from these three inventories proved to be rather similar with respect to different stand characteristics.

The increment figures compared were under-bark volume increment percentage and under-bark volume increment, both for a 5-year period. The average 5-year increments for the third and sixth inventories were on a similar level (19.0–19.5 $m^3\ ha^{-1} \times 5$ yr), whereas the results of the seventh inventory indicated a considerably higher increment level (22.0 $m^3\ ha^{-1} \times 5$ yr).

These studies were supplemented by determining a function (Fig.5), based on the material from the 7th NFI, which predicts 5-year increment percentage without bark:

$I_v - \% = 5.287 - 0.048 \ln(A) - 0.027 \ln(V)$, where $I_v - \%$ = 5-year volume increment percentage, A = stand age, V = stand volume without bark.

The function was used for predicting the growth level for the material from the third and fifth inventories. The results of this comparison (Fig. 5) also showed that the growth results from the 7th NFI were on a significantly higher level than those in the previous ones.

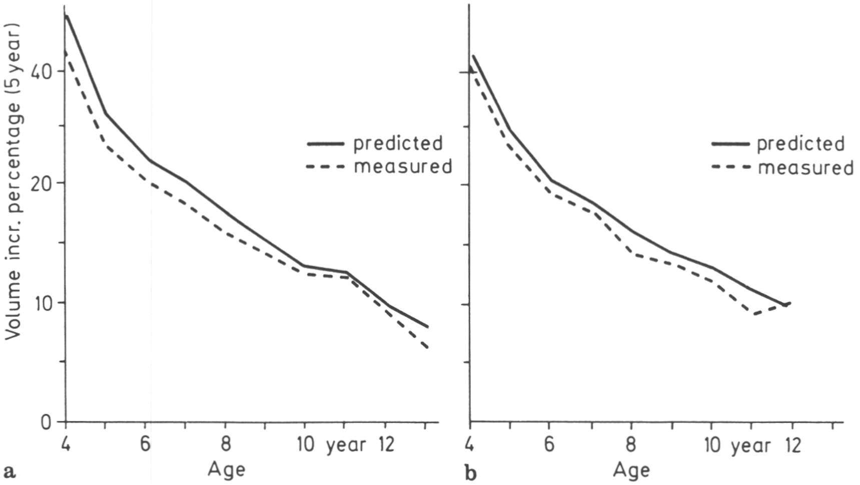

**Fig. 5a,b.** Mean of the volume weighted increment percentage in different age-classes, (e.g. 6 = 60–69 yr). *Solid lines* according to the function which was created using data from the 7th NFI. *Dashed lines* estimated from the material sampled from the third (**a**) and sixth (**b**) inventory data. (Arovaara et al. 1984)

The sensitivity analyses carried out showed that the result was fairly sensitive to possible systematic errors in determining stand age. Climatic conditions were also studied by calculating temperature sums for the increment calculation periods using a method presented by Ojansuu and Henttonen (1983). No significant differences between time periods of the inventories were found. A study carried out on two series of growth indices (Thammincha 1981; Tiihonen 1983) suggested that the period of the 7th NFI had perhaps been slightly more favourable for tree growth. However, the authors concluded that the observed difference in growth was too large to be attributed solely to climatic variation.

The sample tree material from the national forest inventories has also been used for analysing diameter growth variation of Scots pine and Norway spruce for the period 1960–1988 (Ilman epäpuhtauksien 1990; Henttonen Helena interview with author). Data from the area in southern Finland, which was covered by 1988 in the 8th NFI, were used. In the preliminary phase of the study the growth variation was analysed using a mixed linear model that predicts the annual increment of the average diameter of a stand:

$$y_{ik} = x_{ik} + v_k,$$

where $y_{ik}$ = the mean diameter increment of sample plot i in year k; $x_{ik}$ = a vector of the fixed explanatory variables on sample plot i in the year k; $v_k$ = the random residual term.

The fixed explanatory variables include the average diameter, the basal area and the age of a stand. In addition, 29 dummy variables are used to specify at which year the tree ring has developed. The coefficients of the dummy variables are then estimates of the annual ring indices.

Some sources of growth variation were partly eliminated by selection of the study material. For example stands growing on peatlands, two-storied stands and stands with intermediate cuttings during the last 10 years were omitted from the material.

The results of the study illustrate the yearly fluctuations in diameter growth, but also provide interesting information about possible trend-like changes. As the explanatory variables included some basic stand characteristics, changes in forest structure (age distribution, average density) should not affect the results.

As can be seen from Fig. 6, the growth indices for Norway spruce (*Picea abies* K.) have been increasing throughout the study period. The indices for Scots pine (*Pinus silvestris*) follow a similar pattern up until the mid-1970's, since when there has been a rather clear decline (Fig. 7).

As the time period of 28 years is rather short, it is obviously quite impossible to deduct whether the decline marks the start of a falling trend or merely temporary

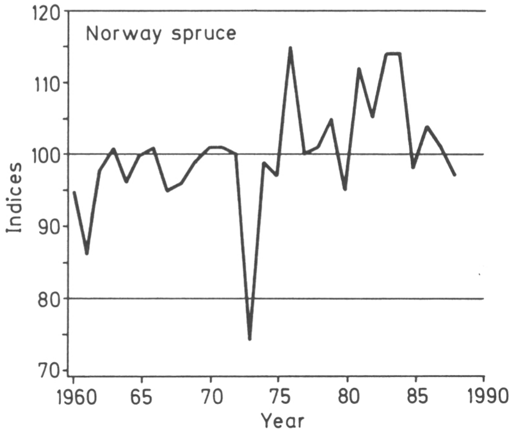

**Fig. 6.** Growth indices Norway spruce (*Picea abies K.*) for south Finland, calculated from the sample tree material from national forest inventories. (Ilman epäpuhtauksien 1990)

**Fig. 7.** Growth indices Scots pine (Pinus silvestris) for South Finland, calculated from the sample tree material from national forest inventories. (Ilman epäpuhtauksien 1990)

variation. A longer time series would be essential for making such conclusions. Sample tree data from earlier national forest inventories are unfortunately not very useful for studies of this type. The measurement techniques as well as data storage and processing capacity were very primitive compared with the situation today.

Climatic variables are not included in the model used in the preliminary phase of the study. Temperature sums for the period which is roughly equal to the average growing season and rainfall in June-July during the course of the study period are presented in Figs. 8 and 9. Both seem to have been at a low level at the beginning of the 1960's, which was also a period of low growth for both Norway spruce and Scots pine. At first glance it could appear that neither variable can explain the fairly rapid decline in the increment of Scots pine that started in the

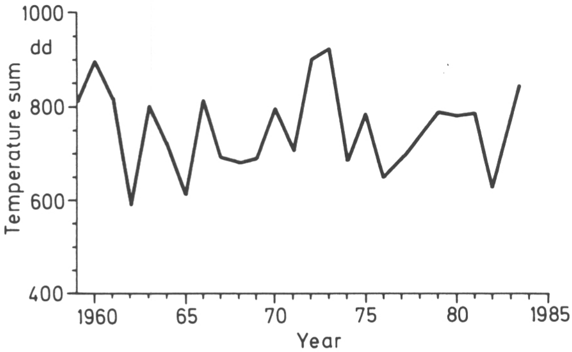

**Fig. 8.** Average temperature sums for south Finland for the period from January to August in 1959–1984. (Ilman epäpuhtauksien 1990)

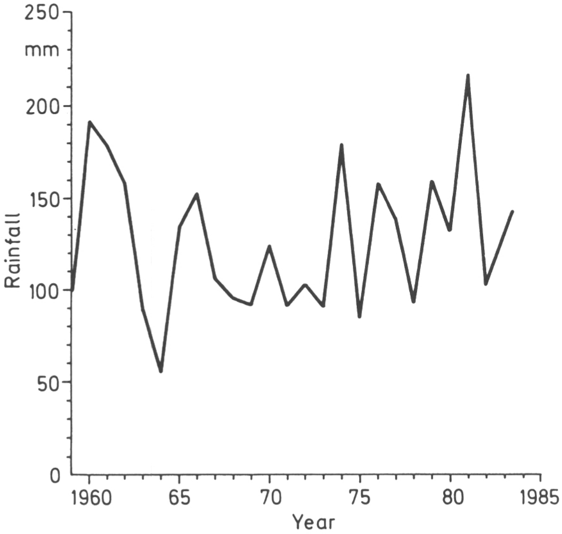

**Fig. 9.** Average rainfall in June–July for south Finland in 1959–1984. (Ilman epäpuhtauksien 1990)

mid-1970's. Compared with the mid-1970's, temperature sums have been somewhat lower in the 1980's, but rainfall in June-July has generally been at a higher level. It should also be pointed out that according to Henttonen (1984), the proportion of the variance of the growth indices that is explained by climatic factors using the existing models has been fairly low under the conditions prevailing in southern Finland. In the northern part of the country the situation is different, temperature being a major growth-regulating factor.

One likely reason behind the decline in pine growth is an extensive epidemic of *Ascocalyx abietina*. This fungal pathogen has increased rapidly during the 1980's. According to preliminary results from the 8th NFI, it has affected some 10% of the pine stands in southern Finland. The effects of the pathogen on pine growth have not been studied adequately. It strongly reduces the amount of needle biomass, also damaging the young shoots, which have very effective net photosynthesis. It is therefore likely to cause a considerable decline in growth in a severely affected stand.

It is interesting to note, however, that pine growth reached a peak around the mid-1970's, the period for the increment results of the 7th NFI. It therefore seems likely that if a study were to be repeated using the methods of Arovaara et al. (1984), then the growth results for the 1980's would be significantly lower than those for the 1970's.

A seemingly plausible means of studying the effects of environmental changes on tree growth is to relate the growth development of the tree to some measure of its state of health. During the 1980's most European countries joined the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests, coordinated by the United Nations Economic Commission for Europe. The main method recommended for studying tree vigour is ocular estimation of needle loss on individual trees. Considerable effort has been made in studying the possibilities of utilizing these results for growth trend studies (see e.g. Athari and Kramer 1983; Kramer 1986). The correlation between the estimated needle loss and the radial growth of a single tree has been studied by Nöjd (1989). The material consisted of sample tree data from the 8th National Forest Inventory, collected from southern Finland in 1986–1987. The aim was to eliminate – as well as possible – the variation in increment caused by other factors using a mixed linear model. The diameter and the age of the tree were used as fixed explanatory variables. The random variation in increment was partitioned into variation between stands and variation within stands. The needle loss classes were represented by dummy variables. The results (Fig. 10) showed a clear correlation. It is interesting to note that trees with needle loss of 41–50% (very easily visible damage) had lost, on the average, only about 20% of their diameter increment.

It may, however, be rather difficult to utilise this information in estimating possible growth reductions at the stand level. If the increment of a single tree declines due to a reduction in its needle mass, the neighbouring trees will have more growing space and nutrients available, and their growth will be increased. Such interactions are not easy to evaluate. The fact that environmental changes

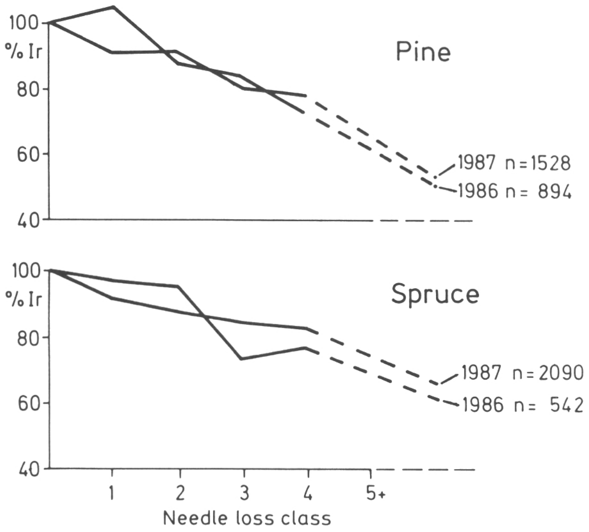

**Fig. 10.** The growth of trees in different needle loss classes (e.g. class 2=11–20%) compared to the growth of trees with needle loss of 0–10%. (Nöjd 1989)

may also have a positive effect on forest growth also has to be taken into consideration. It would thus appear that there is no simple way of utilising the results of forest damage surveys for growth trend analyses. Of course, if the vitality of most of the trees in a stand, measured by the needle loss method, declines really drastically, the stand growth is also likely to decline. However, such conclusions are not very accurate. Results about the dependence between the amount of needle mass and the diameter growth will be of interest to ecosystem modellers, but they are of dubious value for the forest inventory expert.

## Studies Based on Subjectively Selected Material

Studies carried out using subjectively selected data also have certain advantages. It is possible to concentrate on those study objects which are most likely to produce informative results for the study in question. In growth studies it is possible to eliminate to a certain extent some sources of increment variation, like site and competition between trees. It is often possible to reduce the size of the study material. Against this, the results are of dubious general value. However, a lot of basic knowledge can be generated with the help of studies of this kind.

Hari et al. (1984) studied the growth development of dominant Scots pines (*Pinus silvestris*) in conservation areas in southern Finland. Regression analysis was used to estimate the dependence between the increment and the age of the tree. The parameters for the equation were calculated using increment ring data from old pines; only trees older than 200 years were used. A group of younger dominant trees from the same sites was then studied. Deviations from the established dependence between tree age and growth were assumed to be due to either climatic or trend-like changes in tree growth. The results (Fig. 11a) indicated that the

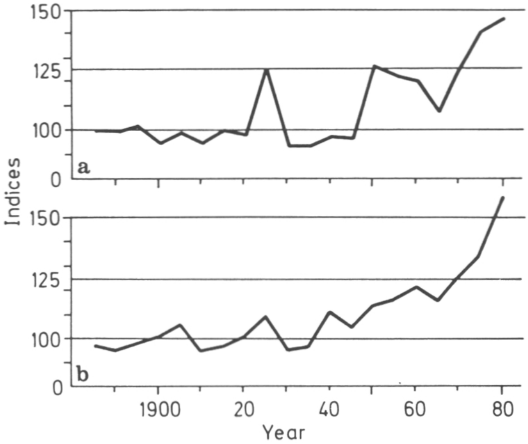

**Fig. 11a,b.** Mean joint effect of weather and trend on the pine growth. Uncorrected data (**a**) and data corrected with growth indices (**b**) (5-year averages). (Hari et al. 1984)

growth of the younger group had followed the pattern generated by the equation at the beginning of the century. A suprisingly large increase in ring width seems to have subsequently taken place over the last decades. The possible effect of climate on the result was studied by correcting the annual figures with growth indices (Thammincha 1981). The final, weather-corrected curve is presented in Fig. 11b.

Obviously, the results describe trend-like changes in tree growth only if the two groups of trees have been growing in fairly similar conditions. The effects of silviculture have been minimized by selecting the material from unmanaged stands on conservation areas. Nevertheless, it is impossible to totally eliminate the uncertainty concerning the growing conditions of the two groups, as the length of the study period is almost 300 years.

Ilvesniemi (1985) studied growth development of Scots pine on infertile sites. The starting hypothesis was that sites with a low nutrient status would be most sensitive to acidic deposition. Increases in aluminium concentrations, as well as the leaching of nutrients, would cause changes in growth development. The basic idea was to use the earlier development of the sample trees in order to predict their growth during the period 1962–1981. The measured annual ring widths were then compared with the predicted values. The results, however, did not show very clear changes in growth level. In 12 stands out of 17 the growth was somewhat lower than predicted. The study also included soil samples from each forest stand. Correlations between growth development and some basic soil characteristics like pH, the exchangeable aluminium concentration and the Ca/Al ratio were studied. Only the aluminium concentration appeared to be correlated with growth, albeit weakly.

Forests close to the arctic tree line are interesting subjects for growth trend studies. It is relatively easy to find very old trees, which have long ago passed the culmination point of radial growth. Their radial growth therefore shows very little decrease in ring width due to ageing. On the other hand, trees growing in such harsh climatic conditions react strongly to external changes, which is shown by the great short-term fluctuations in increment (Mikola 1952).

Hari and Arovaara (1988) studied 300- to 400-year-old pines growing at high elevations (300–350 above sea level) in northern Finland. In these conditions the natural density of the stands is very low, and competition between trees has probably had little effect on the growth of individual trees. As no silvicultural measures are allowed at such high elevations, only climatic and possibly environmental changes are likely to have major effects on tree growth.

Using the methods developed in an earlier study an equation describing the dependence between daily maximum temperature and daily radial increment was constructed (Hari and Siren 1972). The parameters for the equation were estimated using data from the period 1906–1940. (Daily meteorological data from northern Finland are not available prior to 1906). Estimates of daily radial increments were then calculated for the period 1906–1983 using the model and daily weather data. Annual increments were calculated using the model:

$$I_j = (R_j + a(I_{j-1} - 100))D_j,$$

where $I_j$ = the radial growth index of year j; $R_j$ = the radial growth in mm in year j calculated as a sum of daily increments; $D_j$ = cone correction (no correction $D_j = 1$); $a(I_{j-1} - 100)$ = an autoregressive term.

As can be seen from Fig. 12, the measured increments for the period 1941–1983 are on the average much higher than the predicted values. This appears to support the theory of growth enhancement due to an increase in the $CO_2$ level of the atmosphere.

Interpretation of this result is somewhat problematic. The weather conditions in northern Finland were unusually cold at the beginning of the century. Also forest productivity was at a low level. If there is a direct causal link between these two phenomena, the model of Hari and Arovaara is likely to predict the increment for the period 1941–1983 reasonably well. If, however, the most important reason for the low growth at the beginning of the century was some other factor, then the model will overemphasise the effect of daily maximum temperatures on growth. Mikola (1952) suggests that sudden frosts early in the autumn of 1902 may have

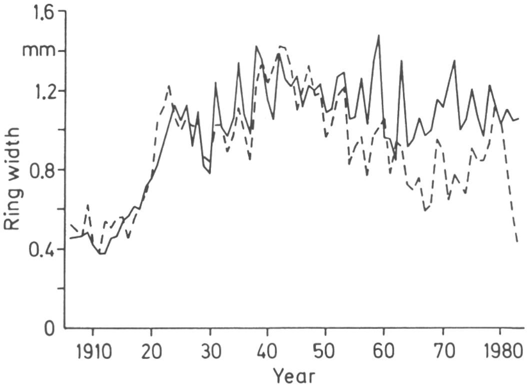

**Fig. 12.** Measured (*solid line*) and calculated (*dashed line*) ring widths from 1906 to 1983. (Hari and Arovaara 1988)

damaged forest trees severely, which could partly explain the unusually low forest growth in northern Finland during the first years of the century.

If daily meteorological data prior to 1906 had been available, it would have been interesting to use calibration periods of different lengths to study the sensitivity of the model.

## Discussion

The studies reviewed here do not give a completely unambiguous view of the effects of environmental changes on forest growth in Finland.

The results of the national forest inventories show a quite rapid and continuing increase in increment, starting from the 1960's. The standard error for these figures is very low.

The sample tree material from National Forest Inventories was used for analysing the growth development in two studies (Arovaara et al. 1984; Ilman epäpuhtauksien 1990). The results from both studies suggest that, despite many obvious causes for the growth increase, changes in the structure of forests cannot exclusively explain the phenomenon. The study period of both studies is rather short, which makes it difficult to draw definite conclusions, but environmental changes can hardly be excluded as a possible contributing factor.

The studies by Arovaara and Hari for South Finland (1984) and the northern part of the country (1988) gave similar results, namely a significant growth increase for Scots pine. These studies describe a longer period, suggesting that the increase in the growth indices during the period 1960–1975 (Ilman epäpuhtauksien 1990), may indeed be part of a long-term trend. According to both studies by Arovaara and Hari, the rising trend started already in the 1940's. In the latter study (Arovaara and Hari 1988) the calibration period selected (1906–1940) for the model perhaps decreases the significance of this finding.

The possible effect of climatic variation on these results is not easy to analyse. The use of growth indices for "correcting" the results is especially problematic, since they may (depending on the calculation method) actually be affected by the same trend-like change that is being analysed. The approach used for analysing the growth data from national forest inventories (Ilman epäpuhtauksien 1990) offers possibilities for using climatic factors as explanatory variables for the model.

The results of Ilvesniemi (1985) suggest that the growth of Scots pine stands on infertile mineral soils did not exhibit any growth increase during the 1960's and 1970's. In most cases it had actually slightly diminished. The result clearly differs from that of other studies, which demonstrate a significant increase in pine growth during the 1960's and 1970's. As the data for the other studies were generally collected on better site types or from different geographical locations, these results are not necessarily contradictory. According to Tamminen and Mälkönen (1986), coarse, infertile soils are the most susceptible to the effects of acidification. This could be one possible explanation for the differences.

It is interesting that the most recent results (Ilman epäpuhtauksien 1990) suggest that the increase in the growth of Scots pine did not continue during the 1980's. On the contrary, there has been a considerable decline.

Only one of the studies (Ilman epäpuhtauksien 1990) includes also results about Norway spruce. The difference between the growth results for Scots pine and Norway spruce after the mid-1970's is quite suprising (Figs. 6 and 7). Although the two species obviously do not have a similar reaction to climatic variations, one would not expect such a different development.

As results about the years prior to 1959 are completely lacking, it is impossible to draw conclusions about the length of period of enhancement in spruce growth. It would be rather problematic to study the growth development of Norway spruce using the methods of Arovaara and Hari (1984). As a shade-tolerant species, it may grow very slowly under other species. The growth may later increase rapidly due to an increase in growing space. Because of the differences in early development, it may be quite misleading to make conclusions about the growth of Norway spruce, based on the dependence between age and increment.

The uncertainty connected with the interpretation of these study results reflects the general problems with analysing time series. The conclusions should be based on sufficiently long study periods. Frequently, however, such data do not exist. When the time unit of the series is 1 year, additional data, although of great interest, will also not provide a "final" answer within reasonable time.

It would be interesting to study the sample tree material from the Finnish national forest inventories by stratifying the material according to site class and tree species. The results should be of great help in evaluating the hypotheses concerning the different suspectibility of different site types to the effects of acidic deposition.

A highly interesting subject for further studies is the eastern part of northern Finland. Northern Fennoscandia is not densely populated, and the local pollutant sources in North Finland are rather insignificant. The only large industrial centres are situated on the Kola peninsula close to the border of the U.S.S.R. and Finland. According to the latest model calculations, an unusually steep gradient in sulphur deposition can be found in the region (Tuovinen et al. this Vol.). The forests of the area should therefore provide excellent possibilities for studying the spatial relationships between tree growth and pollutant deposition.

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# II

# History of forest damage in Monchegorsk, Kola; a retrospective analysis based on tree rings

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**Nöjd, P., Mikkola, K. & Saranpää, P. 1996.** History of forest damage in Monchegorsk, Kola; a retrospective analysis based on tree rings. Canadian Journal of Forest Research 26.

Emissions from a nonferrous smelter have damaged forest ecosystems in the vicinity of the city of Monchegorsk located in northwestern Russia. We analyzed the timing and rate of growth reductions of Scots pine (*Pinus sylvestris* L.) as well as the timing of the eventual cessation of radial growth using the methods of tree-ring analysis. The study material consisted of 304 dead and living Scots pines, sampled between 2 and 130 km south and southwest of the smelter. Near the smelter, growth declined abruptly and ceased within 12 years after the smelter started operation in 1939. The area where the studied mature Scots pines no longer form annual rings has expanded at a rate of approximately 0.5 km per year since 1951.

**Keywords:** Scots pine, forest damage, air pollution, tree-ring analysis

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# Introduction

Disaster-scale examples of the effects of air pollution on forest ecosystems can be found at the Kola peninsula, northwestern Russia (Fig. 1). Intensive exploitation of minerals has caused severe ecological problems near the town of Monchegorsk, where a large smelter (the Severonickel Combine) was put into operation in 1939 (Luzin et al. 1994). The industries produce nonferrous metals, primarily nickel. Together with another smelter of

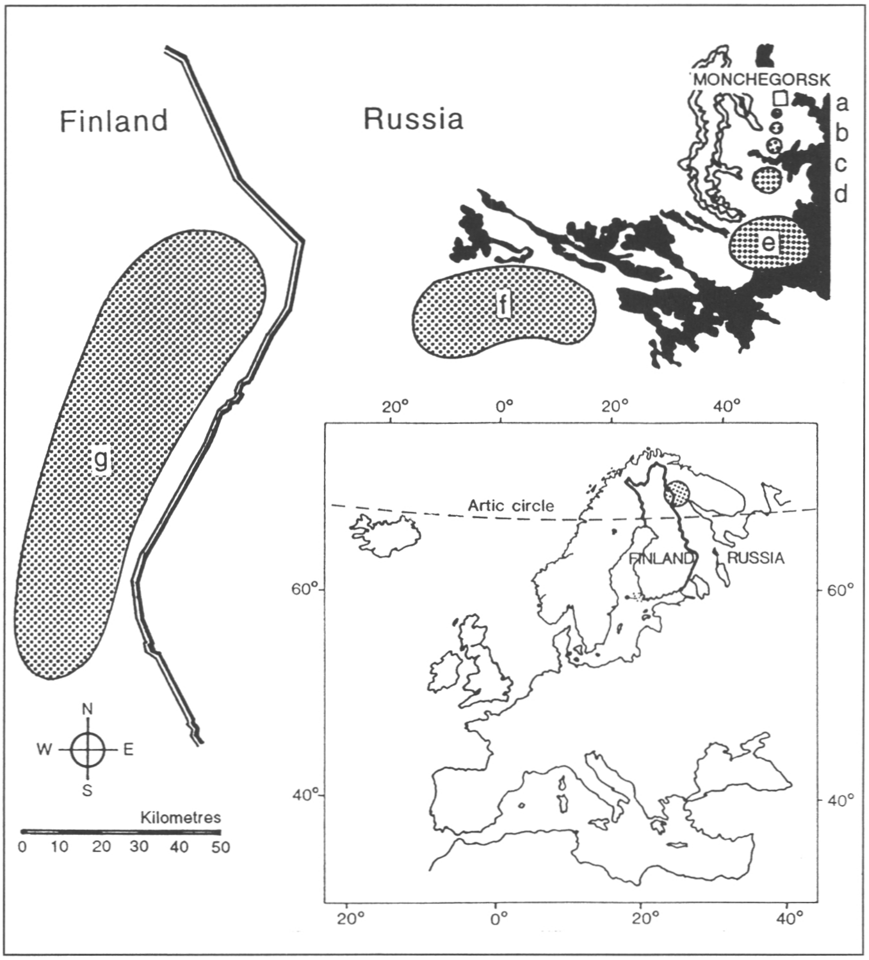

Figure 1. The sampling locations at the Kola peninsula and northern Finland.

similar size at Nikel, 200 km northwest of Monchegorsk, the industries in Monchegorsk produce more than 80 % of the total $SO_2$ emissions of the Kola peninsula (Tuovinen et al. 1993). According to recent statistics Monchegorsk ranks as the fourth and Nikel as the fifth largest emitter of sulfur in Europe (Barrett and Protheroe 1994). Modeling results of Tuovinen et al. (1993) suggest that the Kola sources have a dominant effect (>50 %) on the annual average concentrations of $SO_2$ over distances of up to 200 km from the sources. Sulfur dioxide emissions from Monchegorsk increased gradually until the mid-1980s, reaching the level of 280 $Gg \cdot a^{-1}$ (280 000 $t \cdot a^{-1}$) (Tuovinen et al. 1993). Part of the increase is due to the highly sulfurous ore has been shipped to the Kola area from Norilsk, Siberia since 1964. The heavy metal emissions from Monchegorsk are also substantial: 3 000 t of nickel and 2 000 t of copper annually (Laurila and Tuovinen 1991).

As a result of the long-lasting exposure to pollutants, the forest ecosystems near Monchegorsk have been totally destroyed; the descriptive term technogenic wasteland has been used by Russian scientists (Kryuchkov 1990). Virtually no living conifers can be found within 5 km from the smelter. Initial degradation of forest ecosystems has been reported to extend up to 80–90 km from the smelter. A detailed overview about the present state of nature in the region has been given by Kryuchkov (1993).

At present the Kola Peninsula is extremely militarized, including the worlds largest military base complex (Doiban et al. 1992). Because of the strategic importance of the region, data on the Kola peninsula has not been readily available (Luzin et al. 1994). Prior to the late 1980s the ecological problems were known mainly locally in Russia. Since then the ecosystems of the area have been studied intensively, with researchers from the neighboring Scandinavian countries cooperating actively with the local scientists (e.g. Kozlov et al. 1993, Tikkanen 1994).

While data on the current state of forest ecosystems in the region of Monchegorsk are accumulating rapidly, information about the history of the degradation of the environment is virtually lacking. Methodological options for filling this gap retrospectively are very limited. The methods of tree-ring analysis are among the very few approaches that can be used for producing a retrospective time series closely related to environmental quality. The first studies on analyzing the effects of air pollution on tree growth were made in Germany in the late 19th century; a review of the early research is given by Scurfield (1960a, 1960b). Possibly the most widespread growth reductions clearly connected to pollution from a point source have been reported in the region of Sudbury, Canada. Linzon (1958) discovered anomalous growth trends of *Pinus strobus* L. at a distance of 40 km from the source of pollution on sample plots that were located in line with the prevailing wind. Recent advances in dendrochemistry and new methods for analyzing the climatic signal in tree rings have proved to be useful in detecting effects of pollution. Reviews of the modern methodology have been given by Innes and Cook (1989) and Innes (1990).

While tree growth is generally not considered one of the most sensitive indicators of the effects of pollution, it correlates with crown defoliation (e.g., Franz 1983, Kramer 1986, Nöjd 1990). An abrupt and continuous reduction of growth is likely to reflect a deterioration of the health status of a tree.

The aim of this article is to document the history of forest damages in the region of Monchegorsk by studying long-term trends of Scots pine (*Pinus sylvestris* L.) growth. We analyzed the timing of initial growth reductions and the eventual cessation of radial growth at varying distances from the smelter.

# Materials and methods

In the region of Monchegorsk the most common wind direction is north (41 % of observations in winter, 32 % in summer) (Jevtjugina 1991). Mountain ranges both east and west of the town direct the winds, which partly explains the phenomenon. The spatial distribution of the mean annual $SO_2$ concentration of the air, presented by Baklanov et al.

(1994), also suggests that areas south of Monchegorsk are more exposed to pollution than equidistant areas in other directions. Our sampling gradient started 2 km south of the smelter of Monchegorsk and extended to Finnish Lapland (Fig. 1), covering the complete spectrum from totally dead to healthy stands. At the western end of the gradient, sensitive detectors are needed to trace emissions from Monchegorsk (Hari et al. 1994).

Old Scots pine stands on dry, infertile mineral soils were chosen. In an attempt to minimize the effect of stand dynamics, we selected only unmanaged stands, where signs of strong natural disturbances could not be detected. A sharp climatic north–south gradient exists in northern Fennoscandia (e.g., Atlas of Finand 1987). Thereagainst differences between two locations on the same longitude are relatively small, which suggests that climatic conditions are relatively similar across the sampling gradient.

The sampling locations (Fig. 1) can be divided into four categories: only dead trees (trees without green foliage) available for sampling (locations a–c; 2–8.5 km south of the smelter), dead and living sample trees (d; 15.5 km south of the smelter), living sample trees, all of which have visible crown symptoms (e; 30 km south of the smelter), and living sample trees without obvious foliar damages (f, g; 65–130 km southwest of the smelter).

Dominant and codominant Scots pines were sampled. Within 8.5 km from Monchegorsk, where virtually all old Scots pines are dead, less decomposed standing trees were selected. Generally the sample trees had between 180 and 300 annual rings at breast height. A total of 55 dead and 249 living Scots pines were sampled. The material was collected mainly in September 1990.

Two cores were taken at breast height from the dead trees. As the dead trees had been softened by decomposition, it proved necessary to take cores from the least decomposed directions. One core was taken from each living tree.

Ring widths were measured to within 0.01 mm. The ring width series were cross-dated using the Dynaclim software (Van Deusen 1993). The cross-dating of the series was checked using the program COFECHA (Holmes 1994). Of the 55 dead trees sampled 4 had died prior to the onset of the industrial production in Monchegorsk. As many as 12 proved impossible to cross-date. Those trees were invariably more strongly decomposed than the rest of the sampled trees and consequently more difficult to core and to measure.

The atypical structure of the last annual rings of the dead trees near the smelter is demonstrated with photographs (Fig. 2). Small blocks of wood were kept in boiling water for 3–4 h and wet samples were frozen in a deep freezer. Cross-sections of 16 µm in thickness were cut at –16ºC with a cryomicrotome.

Tree-ring analysis commonly begins with an attempt to remove less informative components of growth variation. This is achieved by methods of standardization or detrending; the methodological options are discussed in Cook (1987) and Cook and Kairiukstis (1990). It is obviously vital not to remove a significant part of the signal that is being studied. Standardization methods aiming to retain only high-frequency variation, commonly used for studying climate–growth relations, are obviously unsuitable for analyzing regional growth trends. We chose not to standardize the tree-ring data. With the data consisting of trees older than 180 years, tree age does not influence the growth trends for the present century strongly (e.g., Figs. 3f–3g).

The ring-width series of individual trees from several sites were averaged over regions to describe the growth of each sampling area. A Reinch spline, as defined by Van Deusen and Reams (1993), was fitted to each average series to describe the low-frequency growth variation. The spline is defined as

$$h(u) = \frac{1}{1 + \frac{Q(u)}{Q(c)}}$$

where

$$Q(u) = 6 + 2\{\cos[(T-2)\lambda_u] + \cos[(T-1)\lambda_u]\} - 4\cos(\lambda_u).$$

$c$ = a cut-off frequency, specified as 8,
$T$ = number of observations in each ring-width series,
$\lambda_u$ = $u$th Fourier frequency,
$h(u)$ = the frequency response function.

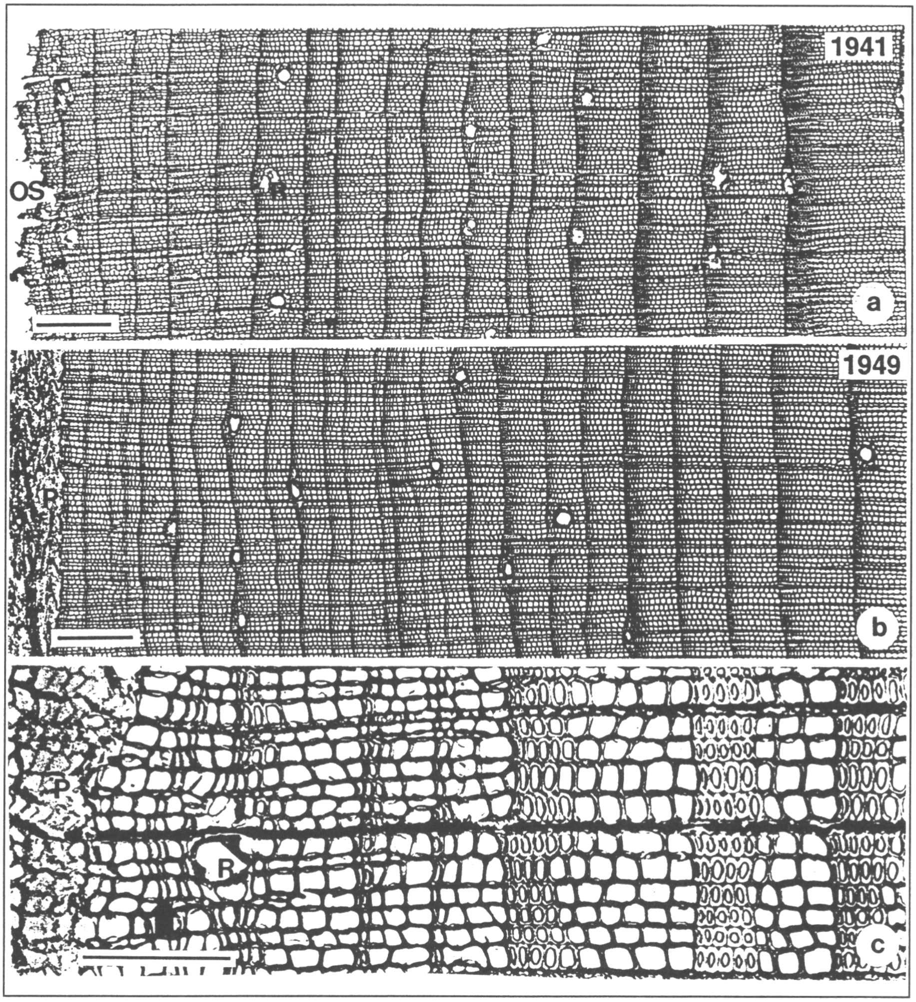

Figure 2. a.) A cross-section of the last 19 annual rings of a dead standing tree 8.5 km south of the smelter. The latest ring observed was formed in 1959. The ring width was 0.08 mm compared with 0.51 mm in 1941. OS, outer surface; R, resin canal. Note the rather abrupt change in the growth ring width. Scale bar = 0.5 mm. b.) A cross-section of the 25 last annual rings of a living tree 15 km south of the smelter. The ring formation ceased after 1973 at breast height. Ring widths show a gradual decrease toward the cambium. P, phloem. Scale bar = 0.5 mm. c.) A greater magnification of the last annual rings of the increment core shown in Fig. 2b. The annual rings consist of only a few earlywood tracheids and one or two layers of laterwood tracheids (arrow). Note the irregular shape of the last-formed tracheids close to the cambium. However, cell walls are very thin and may have collapsed during sample preparation. Scale bar = 0.2 mm.

The calculations were performed in frequency domain and the results were transformed back into time domain. Subroutines of the Dynaclim sotfware were used for the calculations (Van Deusen 1993).

In addition to two-dimensional calendar year–ring width diagrams, the growth trends are described by creating a three-dimensional surface (Fig. 4), based on the seven regional chronologies. The axes defining the surface are calendar year (*X*), distance from Monchegorsk (*Y*), and average ring width (*Z*). The surface was created by the ARC/INFO geographic information analysis package (ESRI 1992). The surface was created by using an algorithm called TIN (Peucker et al. 1978). For each grid point the subroutine interpolates a *Z*-value from the nearest three observations.

# Results

Regardless of location, several growth patterns are common for the sample trees during 1800–1938, before the smelter was put into operation. Especially favorable periods for Scots pine growth occurred in the 1820s, 1850s, and 1920s (Fig. 3). The most obvious unfavorable periods culminate in the years 1813 and 1837. Growth was also at a relatively low level in the beginning of this century. All these features have been observed in previous tree growth studies in northern Fennoscandia, e.g., Hustich (1945), Mikola (1952), Sirén (1961), Briffa et al. (1986).

After the industries came into operation in 1939, the growth trends from the different locations differ markedly. Near the smelter the radial growth of the presently dead Scots pines generally decreased strongly for a varying number of years and eventually totally ceased. The latest annual rings were extremely narrow, often consisting of only a few cells. Examples of the structure of the latest annual rings of two trees are shown in Fig. 2. The dead tree (Fig. 2a) is situated at 8.5 km south and the living tree (Figs. 2b, 2c) 15.5 km south of the smelter.

Cross-dating of the ring-width series of presently dead sample trees revealed considerable differences in the timing and rate of growth reductions after the smelter began operation in 1939. Near the smelter cessation of radial growth took place abruptly, usually in less than 10 years. None of the sample trees at the nearest sampling location A (2 km south of the smelter) have developed annual rings at breast height after 1951 (Fig. 3a). Currently only a few plant species exist on those sites, small birches (*Betula pubescens* Ehrh.) among them. The top soil is largely

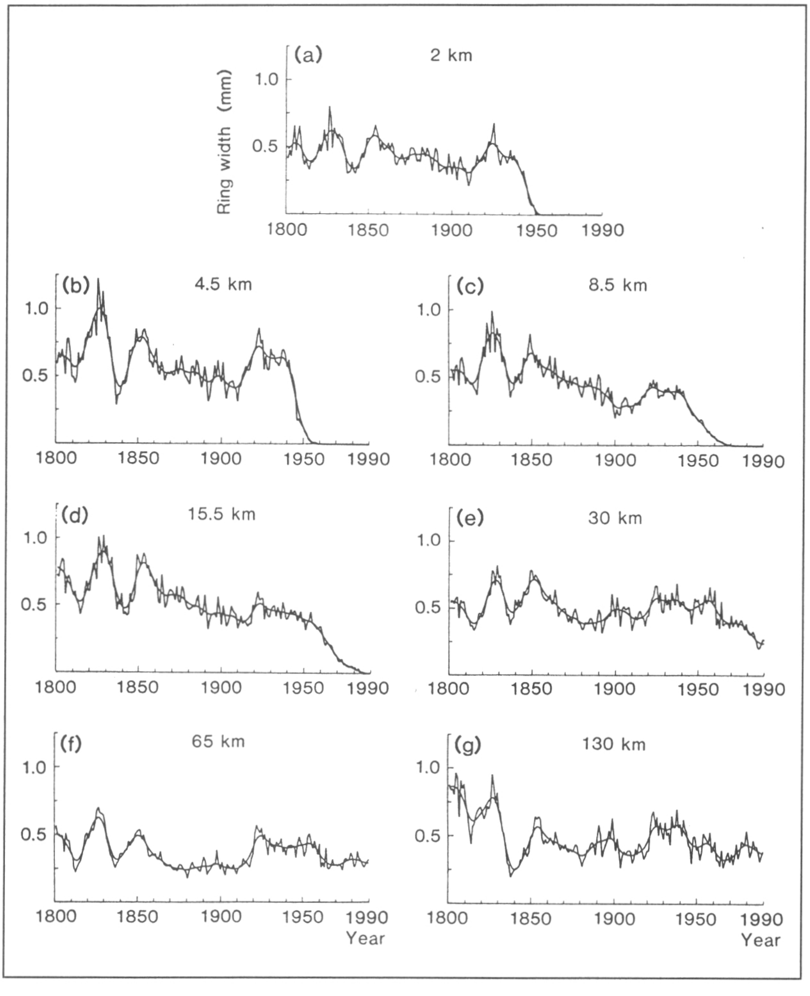

Figure 3. Average ring-widths for the sampling locations for 1800–1990 with an Reinsch spline (cut-off frequency 8 years) fitted to each series.

uncovered by vegetation and exposed; severe erosion is present.

At location B, 4.5 km south of the smelter, forest ecosystems are similar to location A, although some additional living plant species can be found. A few young conifers have survived in low, moist sites. The growth trends are markedly similar in both locations (Fig. 3b).

A number of living small Scots pines can be found at the next sampling location (8.5 km), although the crowns are strongly defoliated. No living old trees were available for sampling. The growth of the sampled trees had generally decreased since the 1940s (Fig. 3d). The rate of growth reductions has been less rapid than in locations closer to the smelter. Six of 11 sample trees have continued developing rings in the 1960s, albeit the ring widths in the 1960s were almost invariably very narrow.

At location D, 15.5 km south of the smelter, some sample trees still had green foliage. Those trees were all severely defoliated. None of the sampled trees had developed annual rings after 1987. In an extreme case a pine with green foliage had no annual rings after 1971. Similar observations on Norway spruce (*Picea abies* (L.) Karst.) in Central Europe have been reported by Athari (1981) and Athari and Cramer (1983). While the radial growth of a few sample trees ceased in the 1950s, in most cases a downward trend in growth did not become evident until the 1960s. Most sample trees at location D continued to form annual rings in the 1970s.

The trees sampled at location E, 30 km south of the smelter, consist entirely of living trees. Ten percent of the sample trees had not developed annual rings in recent years. A downward growth trend started in the 1960s (Fig. 3e) and thereafter the average ring widths continued to decrease.

No obvious decline can be seen in the average growth trends of sample trees at 65 and 130 km southwest of Monchegorsk (Figs. 3f, 3g). In fact growth has recovered slightly after the 1960s, a climatically unfavorable period for Scots pine growth in northern Fennoscandia. A strong dependence between growth and summer temperatures was revealed by the first dendrochronological studies in

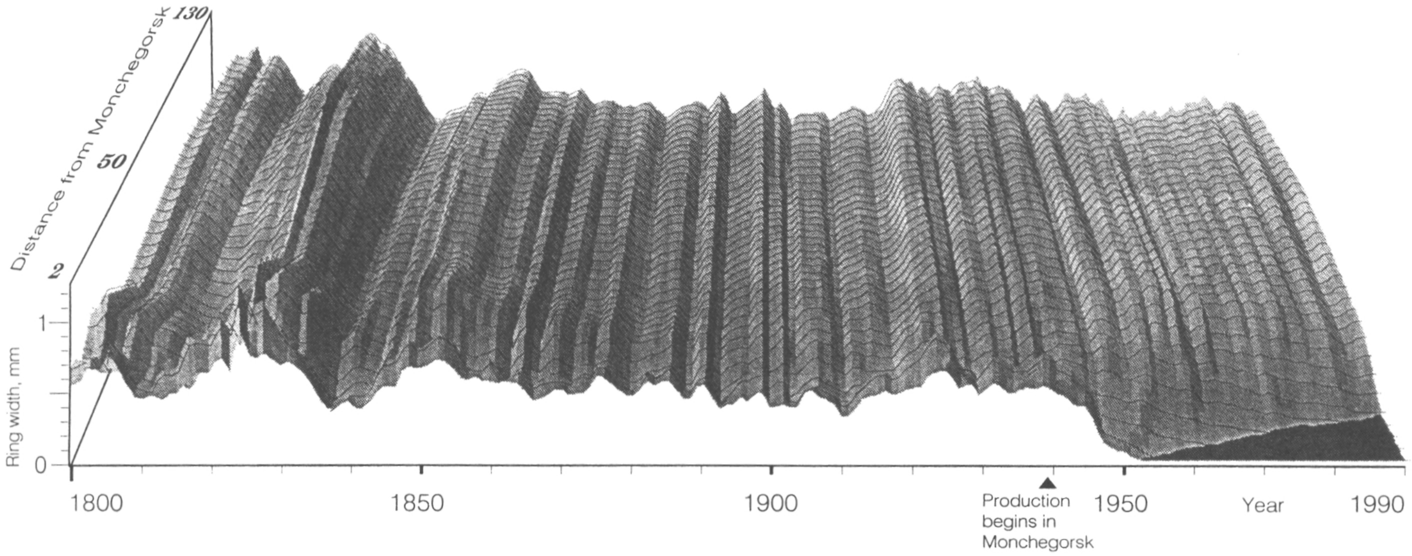

Figure 4. The surface describing ring width as a function of time and distance from the source of emissions.

northern Fennoscandia (e.g., Erlandsson 1936, Hustich 1945, 1948). During the 1960s summer temperatures were below long-term average (Briffa et al. 1990). Subsequent attempts of modeling the climate–growth relationship strongly suggest that the slow growth during the 1960s is of climatic origin (Briffa et al. 1986, Hari and Arovaara 1988).

The three-dimensional surface in Fig. 4 combines the information of the Figs. 3a–g. It summarizes the main findings and also enables one to compare the medium and high-frequency growth variation at the different locations. The favorable and unfavorable periods for growth coincide for the whole study area between 1800 and 1940. Thereafter the growth decline near the smelter becomes evident, while the rest of the data still show regularity of both low- and high-frequency growth variation. The dark flat surface in the lower right corner illustrates when the radial growth of pines ceased at varying distances. The surrounding section of the surface represents a low level of growth, unprecedented during 1800–1940, and therefore most likely connected to pollution exposure.

The damage has not reached a steady state: the area where reductions of radial growth can be observed has continuously increased (Fig. 4). The triangular shape of the dark, flat area suggests that the rate of damage expansion has been fairly steady for the years 1950–1990. After the abrupt beginning, the growth reductions also seem to have expanded at a fairly steady rate.

# Discussion

Tree-ring analysis proved a useful approach for detecting the timing of the initial growth decline in the region of Monchegorsk and also for describing the rate of the damage expansion. The task of reconstructing growth trends of old Scots pines was in many ways simplified by the prevailing conditions. In northern Fennoscandia old-growth virgin forests are easy to find for sampling of study material. The history of individual stands is rarely known, but signs of silvicultural treatments remain recognizable for about a century, because of slow decomposition of wood. Near the Polar timber line stand densities are usually low. As a result, stand dynamics affect the growth of individual trees much more gradually than in climatically more favorable areas. Scots pine may reach the age of 800 years (Sirén 1961) and near the northern timber line 300- to 400-year-old trees are fairly common. Long ring-width series are easy to reconstruct.

Some limitations concerning our data should nevertheless be considered. The data close to the smelter are based on the least decomposed remaining trees. Those trees may have been more resistant to pollution. If that is the case, the described growth trends may underestimate the rate of the actual declines. In any case a rapid reduction of growth was observed in the 1940s, soon after the industries started operation (Fig. 4).

Erosion of wood causes some uncertainty to the interpretation of the results. The sample trees nearest to the smelter had no protective bark layer remaining. Since some of the trees stopped forming annual rings nearly half a century ago, it is possible that a few annual rings had eroded. Because of this, it may be impossible to determine the exact year, when the growth of each individual tree completely ceased. The task is further complicated by the fact, that the last annual rings were often deformed (Fig. 2a). However, the last remaining tree rings of the dead trees were usually very narrow. The fact, that some narrow rings may have eroded does not mean that the presented growth trends are severely biased. Erosion definitely cannot be the main factor explaining the missing annual rings after the most recent one: in a number of cases cross-dating revealed, that some living trees with intact bark had not produced rings for decades (Figs. 2b, 2c).

The cessation of tree-ring development at breast height is not necessarily a simultaneous event with the death of the tree. Annual ring development usually does not cease the same year at different heights. The results of Leikola (1968) suggest that ring formation of old Scots pines is likely to cease first at the lower section of the stem. Higher up the stem growth may continue even decades longer.

The phenomenon could be explained by the fact that cambial activity is related to auxins, which move in a basipetal direction starting at the developing buds in the crown (Roberts et al. 1988). Also, while the death of a tree is not easy to define, the definition should probably be based on the metabolic functioning of a tree, not stem increment.

Therefore, the total death of the pine stands may have taken place years, even decades after xylem growth of the trees had stopped at breast height. On the other hand, like many other species the growth of Scots pine correlates with crown defoliation (Nöjd 1990). It is highly probable that the observed rapid growth decline in the region of Monchegorsk coincided with the appearance of severe crown symptoms of trees.

One-dimensionally, in the direction of our sampling transect, the distance within which Scots pine growth has ceased expanded to 15.5 km between 1951 and 1987. Given the observed steady rate of damage expansion, this equals to slightly less than 0.5 km per year. Normally deposition caused by a point-source of pollution sharply decreases in a nonlinear fashion with increasing distance from the emission source. Therefore one would not expect the damages to expand at a constant rate like we observed. The emissions from Monchegorsk have increased markedly until the mid-1980s, however, which may explain the phenomenon (Tuovinen et al. 1993).

It is difficult to generalize our one-dimensional observations into estimates of damaged forest area. In the region of Monchegorsk local topography strongly affects the transport of pollutants. Mountain ranges both east and west of the town direct winds. Forest ecosystems, equidistant from Monchegorsk, may have received quite different cumulative loads of pollutants. The effect of this can be seen in the irregular shape of zones representing varying degrees of vegetation damages, described by Kryuchkov (1993). A similar result was produced by classifying forest ecosystems into damage classes using satellite images (Mikkola and Ritari 1992).

# Conclusions

The results clearly indicate that forest deterioration started soon after the industries in Monchegorsk began operation in 1939. Near the smelter obvious growth reductions started in the 1940s. Within 4.5 km south of the smelter the growth of old (over 180 years) Scots pines ceased in most cases within 10 years after the smelter began operation. Farther south of the source of pollution, growth reductions started later and the rate of decline has been slower. All Scots pines sampled within 15.5 km of the smelter (both living and dead) had ceased forming annual rings at breast height. The distance south of the smelter, within which sampled old pines no longer form annual rings, has expanded at a rate of approximately 0.5 km per year.

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# III

# Growth variation of Scots pine across a pollution gradient on the Kola Peninsula, Russia

Pekka Nöjd
Gregory A. Reams

**Nöjd, P. & Reams, G. A. 1996.** Growth variation of Scots pine across a pollution gradient on the Kola Peninsula, Russia. Environmental Pollution.

Decadal exposure to emissions from a non-ferrous smelter has damaged the forest ecosystems surrounding the city of Monchegorsk located on the Kola Peninsula in Northwestern Russia. We use the methods of tree-ring analysis to study the areal extent and timing of recent growth reductions of Scots pine (*Pinus sylvestris* L.) in the region surrounding the smelter in Monchegorsk. Reduced growth of Scots pine was observed up to 30 kilometers southwest of the smelter. This directional gradient of forest damage is related to the dispersal of pollutants which is influenced by the prevailing northern winds and local topographic features. Old Scots pines (age 200+) appeared to be more sensitive than younger ones: growth reductions of old trees had started earlier and reductions were observed farther from the smelter than for younger trees

The findings are compared to a classification which describes the state of forest ecosystems based on the occurrence of certain plant species; the classification matched well with the observed growth trends.

Pollution-induced changes in the climatic signal in tree rings are also studied. The strong dependence of growth on mid-summer temperatures, typical for Scots pine on high latitudes, proved to be insensitive to effects of pollution. Changes in the climate-growth relationship took place decades after growth trends had started to decline.

**Keywords:** Scots pine, forest growth, air pollution, time series analysis, climate-growth models

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# Introduction

Extreme examples of the effects of industrial pollution on forest ecosystems can be found on the Kola Peninsula in Northwestern Russia (Kryuchkov 1993). While long-range transport of pollutants into the area is fairly low (Tuovinen et al. 1993), two local industrial centers, Monchegorsk and Nikel, rank among the largest emitters of sulphur in Europe (4th and 5th, respectively) (Barrett and Protheroe, 1994). The pollution is caused by non-ferrous smelters producing primarily nickel. In addition to sulphur, high levels of heavy metals are emitted, especially from the smelter of Monchegorsk, where the reported annual emissions of nickel and copper are 3 and 2 million kilograms, respectively (Tuovinen et al. 1991).

Both in Monchegorsk and Nikel smelting of nickel deposits started in the late 1930s (Luzin et al. 1994), and the volume of production has increased gradually (Tuovinen et al. 1993). $SO_2$ emissions prior to 1970 are not documented, however, during the 1970s a large increase of emissions occurred (Fig. 1) (Baklanov et al. 1994). Between 1970 and 1975 the emission increased from 100 to 280 Gg $a^{-1}$ (1000 tons $a^{-1}$). Part of the large increase was caused by

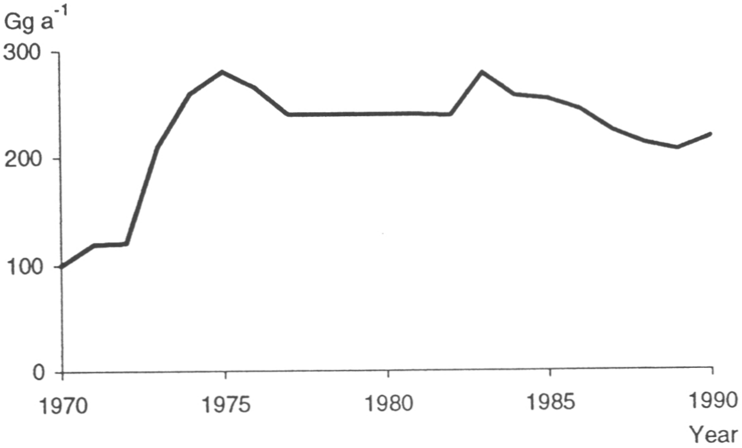

Figure 1. The annual $SO_2$ emissions from the smelter in Monchegorsk for the period 1970–1990 (Baklanov et al. 1994).

a change in the source of ore. With the local supply of ore nearly exhausted, increasing amounts of raw material have been transported from the Norilsk region in the Ural. The ore from Norilsk has an especially high sulphur content (up to 25%) (Tuovinen et al. 1993).

As a result of high-volume and multi-decade exposure to pollutants the forest ecosystems around both cities have been severely damaged. Birch (*Betula Pubescens* Erhr.) appears to be one of the most resistant plant species. Few coniferous trees have survived within 4 kilometers of the smelter, although small areas of forest can be found in wet hollows. Because of local topographic features and the prevailing winds from the north (Jevtjugina 1991), the extent of damage is directional with the greatest damage occurring south of the smelter. The destruction of plant species in the vicinity of the smelter is not always the direct result of plant response to pollution. Factors like forest fires or soil erosion have undoubtedly in many cases interacted with pollutants in causing the destruction of plant communities.

In a detailed description of forest ecosystems on the Kola Peninsula, Kryuchkov (1993) classified zones describing the degree of ecosystem degradation. The classification is based mainly on the occurrence of plant species that have proved useful as bioindicators of air pollution. Six different zones are identified, ranging from ecosystems with severely eroded soils and very few plant species remaining (zone I), to areas where the most sensitive plant species still exist (zone VI). An initial stage of degradation (zone V) was reported up to 80–90 kilometers from the emission source.

Tree growth has been used as an indicator of air pollution effects since the early industrial revolution; a review of the early studies has been given by Scurfield (1960a, 1960b). Subsequently the techniques of tree-ring analysis have been used to describe growth depressions connected to point sources of pollution (Linzon 1958, Nash et al. 1975, Wilhelmsson 1983). While more sensitive indicators of air pollutants do exist, tree growth has obvious advantages as a bioindicator. These include objectiveness of measurement techniques and the possibility of producing a retrospective time series. Being closely related to both biological and economic parameters, data on tree growth can provide useful background information for planning measures for pollution control.

The focus of our study is to produce and compare quantitative data on tree growth across the degradation zones identified by Kryuchkov (1993). By using dendrochronological data and techniques to produce retrospective time series of Scots pine growth in each zone we: 1) compare growth trends prior to and after the smelter in Monchegorsk was put into operation in 1939, 2) compare growth trends of the zones representing varying degrees of degradation (II–V) to trends of the unaffected (least polluted) zone (VI), 3) compare the climate-growth relationship over time and across zones to test for pollution effects.

# Materials and methods

## The forest damage zones

The classification of Kryuchkov (1993) is based mainly on occurrence and health status of certain plant species, especially conifers, shrubs, lichens and mosses. Major changes in soil structure are also described. The essential characteristics of each zone are as follows: Zone I (industrial wasteland): Top soil is severely eroded. Ground vegetation and trees exist mainly in depressions. Zone II (the severely degraded area): Characterized with largely exposed top soil. The majority of conifers are dead. No epiphytic lichens exist. Zone III (the fundamentally altered forest): Soil is mainly covered with ground vegetation. Most conifers are alive, although the percentage of dead trees is high. Severe crown symptoms are common. A few species of mosses and lichens can be found. Zone IV (the outer industrially altered zone): Top soil is completely covered with vegetation, but visible signs of plant damage still exist. Various crown symptoms of conifers can be observed. Needle retention of Norway spruce is about half

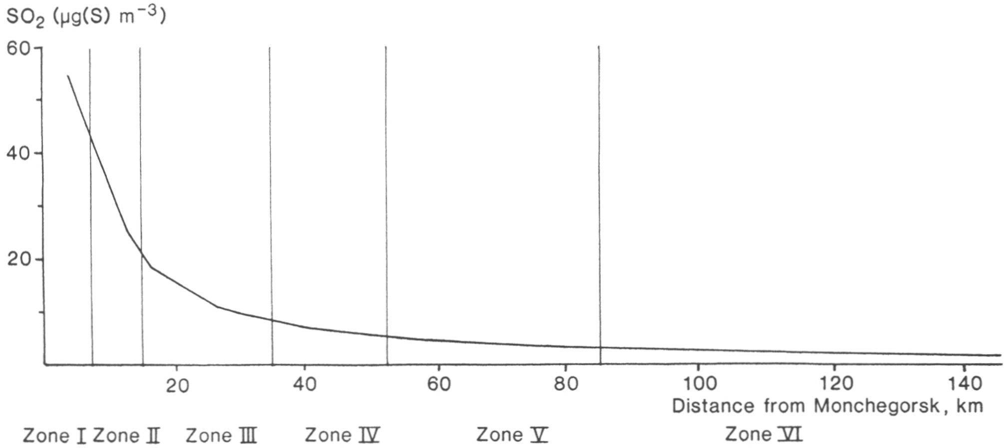

Figure 2. The annual mean $SO_2$ concentration of the air as a function of distance from Monchegorsk according to the model of Tuovinen et al. (1993) and the zones representing varying degrees of ecosystem degradation as defined by Kryuchkov (1993).

of normal. Epiphytic lichens are mainly absent. Zone V (the zone of initial degradation): Visible signs of damage are less obvious. Needle retention of Norway spruce is below normal. Epiphytic lichens begin to appear. Zone VI : The plant species most sensitive to pollution exist.

The spatial distribution of the annual mean concentration of $SO_2$ in the region of Monchegorsk has been modeled by Tuovinen et al. (1993). Their semi-empirical dispersion model is based on monthly statistics of emissions and climate. The damage zones defined by Kryuchkov (1993) correspond to a steep gradient of mean annual $SO_2$ concentration within 50 kilometers from the smelter, after which the concentrations stabilize (Fig. 2).

# Methods of data collection

The tree-ring data were collected from a transect oriented southwest of Monchegorsk. The sample locations as well as the distribution of the degradation zones as defined by Kryuchkov (1993) are shown in Fig. 3. Both subsamples cover the zones II–VI, while zone I is defined as a region where virtually no living conifers exist at present. Data

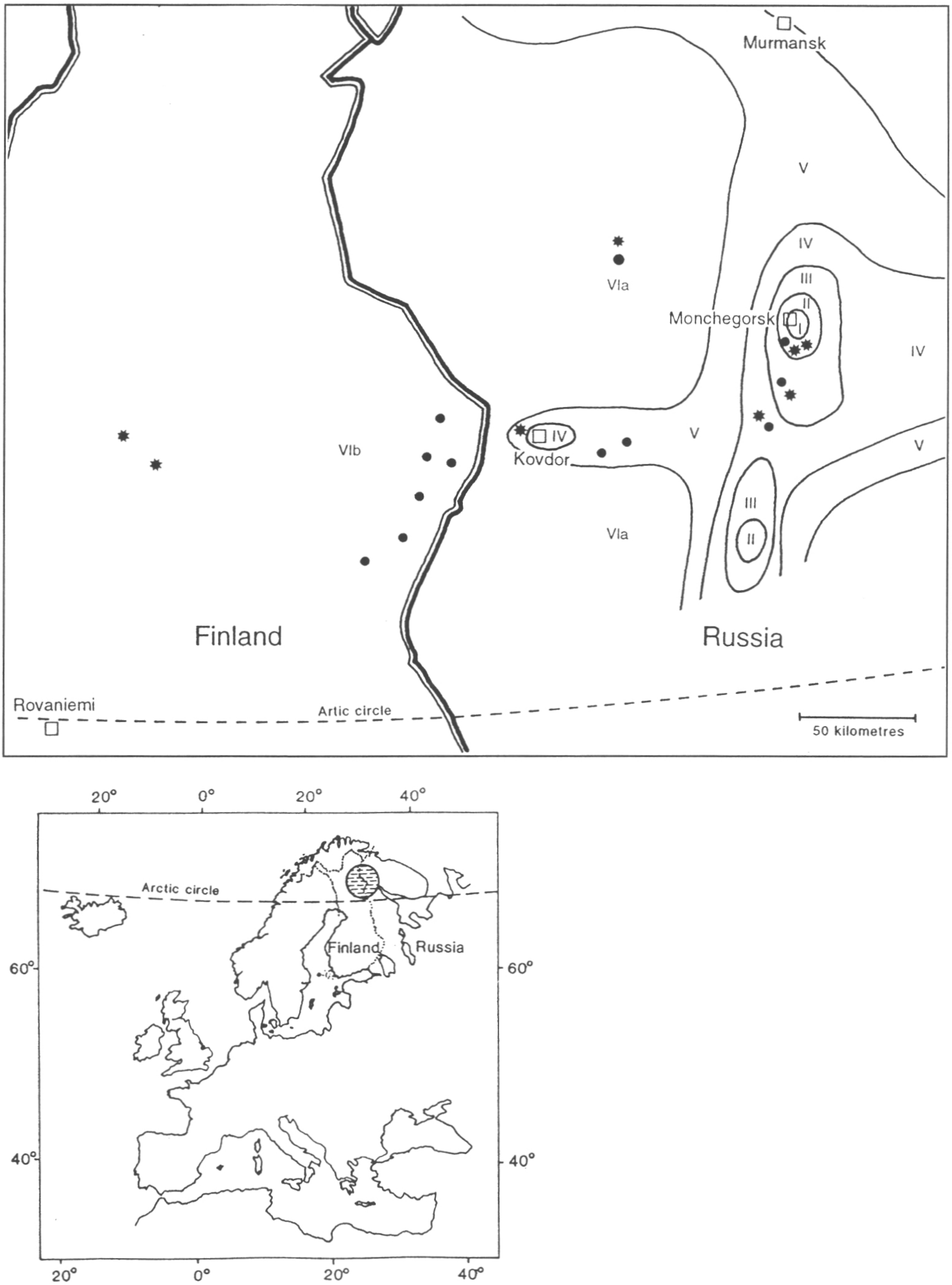

Figure 3. The sampling locations on the Kola Peninsula and Northern Finland and six zones representing varying degrees of ecosystem degradation as defined by Kryuchkov (1993). (● sampling sites for old trees, ✱ sampling site for young trees.)

from zone VI (no effects on plant species composition) were divided into two geographically separate data sets: one from Russia (VIa) and the other from Finland (VIb).

Scots pine stands of two different age categories were sampled in each zone. The older subsample consists of trees with more than 170 annual rings at breast height (1.3 m). Owing to the very slow early development of Scots pine in the conditions near the northern tree line, this roughly corresponds to a tree age of 200 years, as it takes approximately 30 years for trees to attain a height of 1.3 m. While Scots pine has been reported to reach an age of over 800 years (Sirén 1961), 200 year old trees are already close to their maximum height, which in the region rarely exceeds 25 meters. The age distribution of the younger subsample for each zone is presented in Fig. 4. Presently the dominant heights of these stands are 5–7 m.

The sampled Scots pine stands occur on infertile sites that have been undisturbed by harvesting. The region of Monchegorsk is situated approximately 100 kilometers south of the polar timber line. Intensive forest management was not practiced in the region until the second half of the present century. Due to the cold climate, natural decomposition processes are extremely slow in the area; after a cutting, stumps remain easily recognizable for at least fifty, often one hundred years. Because of this, the exclusion of stands with silvicultural treatments was accomplished reliably.

Field measurements were carried out during the summers of 1990–1992. Increment cores were extracted at breast height (1.3 m), one core from each tree. Ring widths were measured to within 0.01 mm. After measurement each ring-width series was cross dated using the Dynaclim software (Van Deusen 1993). Cross dating is the process by which each annual ring-width is matched to the exact calendar year of formation (Fritts 1976). Trees that would not cross date reliably were not used for further analysis.

Some unusual difficulties were encountered in cross dating trees close to the emission source. Trees clearly living, but suffering from severe crown defoliation had in some cases not produced annual rings for more than a decade. In such cases the most current ring widths were extremely small (often less than 0.1 mm).

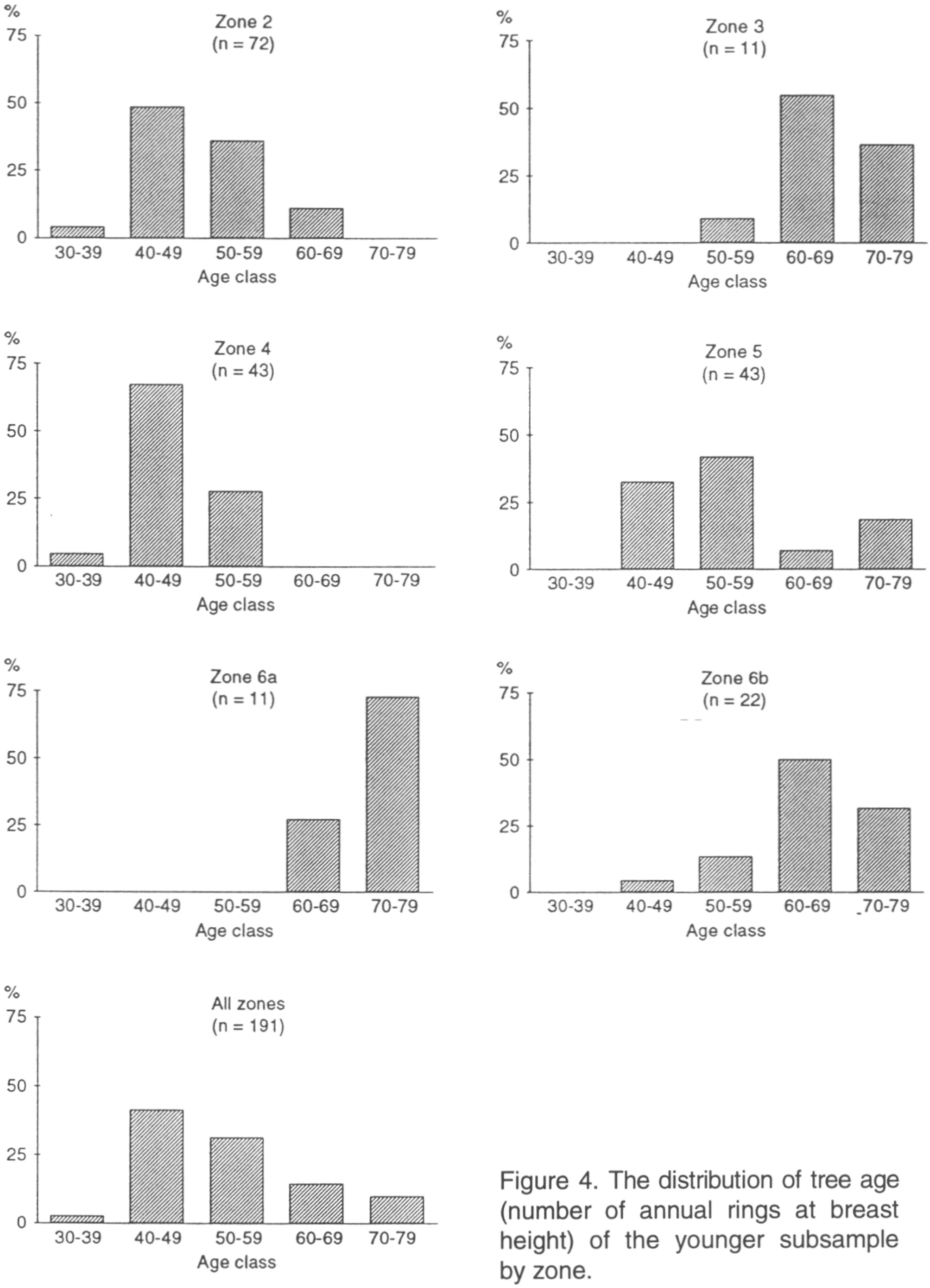

Figure 4. The distribution of tree age (number of annual rings at breast height) of the younger subsample by zone.

# Dendrochronological methods

## *Trend removal and trend estimation*

Many studies investigating the effects of air pollutants on forests are based on dendrochronological (i.e. dated tree-ring) data. One of two possible analysis philosophies are followed, trend removal or trend estimation (Warren 1989). Most often studies have opted for trend removal whereby the data are mathematically transformed to a set of tree-ring indices by various standardization techniques (Reams et al. 1994).

Standardization, i.e. the removal of the low-frequency growth trend is a traditional data conversion technique for dendroclimatological research. Methods of standardization can either be classified as model based or data based. When the growth of a tree is dominated by the geometrical constraint of adding a volume of wood to a stem of increasing radius, also known as the age and size constraint, the trend will exhibit an exponential-like decay as a function of time (Warren 1989). Accordingly, a long-standing model based method of standardization has been to fit a negative exponential function to the sequence of raw ring widths (Fritts 1976).

If the low-frequency growth trend is dominated by an age effect then a simple monotonic function such as the negative exponential will provide an adequate fit to the raw ring widths. However forest trees, especially those growing in a competitive environment of a forest stand will display non-monotonic trends, due to changes in among tree competition and other causes (Reams and Van Deusen 1993). For such trees removal of the low-frequency growth trend from the raw ring widths has been done by a variety of more flexible mathematical models such as low-pass digital filtering (Briffa et al. 1983), cubic smoothing splines (Cook and Peters 1981), weighted exponential smoothing (Barefoot et al. 1974), and differencing (Van Deusen 1987a).

Examples of data dependent standardization techniques include the "corridor" method (Shiyatov and Mazepa 1987), and the cambial age method of Becker (1989). The method proposed by Becker (1989) for standardization of silver fir (*Abies alba* Miller) in the Vosges mountains of France can lead to results that are quite similar to fitting a negative exponential function to the data. However, this is only true if the age effect is the primary factor influencing ring-width variations. The concept of adjusting for only the cambial age effect fails to adjust for additional perturbations that occur in natural forest stands. Such perturbations that can significantly influence radial increment include insect infestations, disease, windstorms, and reductions in among tree competition through self-thinning and other causes. Many of the ring-width series of the old-growth Scots pines in our study have been influenced by factors other than age.

The very concept of standardization is most applicable for dendroclimatology. If the isolation of the high-frequency climate signal from tree-ring data is the goal then removal of the low-frequency growth trend is a necessary step (Van Deusen and Reams 1993). While there is certainly a place for growth trend removal in dendrochronology it is not a fail-safe technique for exploring the effect of atmospheric pollution on tree growth. During the standardization process the probability of removing the pollution disturbances from the data is unknown yet high (Warren 1989). Since the pollution signal should be embodied in the growth trend, another strategy is to track the actual growth trend of individual trees to determine whether there are segments of the population that behave in different ways, i.e. trend estimation (Warren 1989).

## Cluster analysis

Cluster analysis is a statistical procedure ideally suited for finding groups of trees with growth trends that behave similarly within a group and differently than those within other groups. To search for segments of the population that have different growth patterns we used cluster analysis. A third-degree orthogonal polynomial of the form $y = b_0f_0(x_0) + b_1f_1(x_1) + b_2f_2(x_2) + b_3f_3(x_3)$, where the $f_i(x_i)$ are the orthogonal polynomial in x of the i:th degree, was fit to the last 30 years (1961–1990) of radial growth for each ring-width series. The coefficients for each tree were then used as input to a clustering algorithm in a search for common growth patterns in each of the pollution zones.

The cluster analysis provides a unique data reduction technique for characterizing the variability of individual growth patterns of each tree by placing each tree within a group of trees with similar growth characteristics. The procedure was used for identifying common growth patterns in each zone; the patterns were then compared across zones to infer pollution effects. Details of the analysis follow the guidelines presented in Reams and Van Deusen (1993). The basic theory as well as the algorithm applied (PAM for partitioning around medoids) are presented in Kaufmann and Rousseeuw (1990). Clustering was performed using the Dynaclim software (Van Deusen 1993). Only data from the older subsample was used for cluster analysis; for the younger data set, in which normal growth trends are invariably descending from the effects of individual tree and forest stand development, the procedure would be less informative.

## *Climatic signal in tree rings*

Modeling the climate-growth relationship is a common approach for evaluating the response of tree growth to pollution (Innes and Cook 1989). We analyzed recent changes in the response of growth to climate by using linear model based on ordinary least squares. Before establishing the relationship, the growth data was transformed by standardization to growth indices, which were calculated using a method suggested by Van Deusen (1987b):

$$Y_t = \ln (I_t) - \ln (I_{t-1}), \qquad [1]$$

where

$Y_t$ is the standardized ring-width in year t
ln is the natural logarithm
$I_t$ is the ring-width in year t.

As the calculation of the growth index for year t is based only on the ring widths of the current and previous year, the standardization method obviously retains only the high-frequency (year to year) growth variation. All trend-like components of variation will be lost.

The standardized ring widths were related to a set of climatic variables that included the current and previous year mean temperature and cumulative precipitation for each month. Data from the meteorological station at Sodankylä (67°22'N, 26°39'E) covering the years 1906–1990 were obtained from the yearbooks of the Finnish Meteorological Institute. All possible combinations of three regressors were tested and the best combinations identified using a model:

$$Y_t = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + e, \qquad [2]$$

where

$Y_t$ is the standardized tree-ring index for year t
$x_1, x_2, x_3$ are potential regressors
$b_0, b_1, b_2$ are regression coefficients
e is a random element.

The mean temperature of July of the current and previous year are the only variables significantly correlated with the growth indices. The model describing the relationship of growth and climate is:

$$Y_t = b_0 + b_1(T_{July,t}) + b_2(T_{July,t-1}) + e, \qquad [3]$$

where

$Y_t$ is the standardized tree-ring index for year t
$T_{July,t}$ is the monthly mean air temperature of July for year t
$b_0, b_1, b_2$ are regression coefficients
e is a random element.

The parameters of the models were estimated for zones II, III and the combined zones IV–VI using the years 1906–1970 as a calibration period (Table 1). The fit between the model and the data for the calibration period and the subsequent verification period 1971–1990 is described with the coefficient of correlation (Fig. 7).

Table 1. Regression equations describing the relationship of climate and growth during 1906–1970 for zones II, III and the combined zones IV–VI. The p-values for each coefficient are given in parenthesis.

| Zone | Model | $r^2$-value |
|---|---|---|
| IV–VI | $0.0138 + 0.0286\,(\mathrm{July}_{t}) - 0.0295\,(\mathrm{July}_{t-1})$<br>(0.936) (0.003) (0.002) | 0.206 |
| III | $0.0389 + 0.0272\,(\mathrm{July}_{t}) - 0.0308\,(\mathrm{July}_{t-1})$<br>(0.815) (0.004) (0.004) | 0.180 |
| II | $-0.4874 + 0.0529\,(\mathrm{July}_{t}) - 0.0212\,(\mathrm{July}_{t-1})$<br>(0.012) (0.000) (0.051) | 0.254 |

# Results

## Historical growth trends of old trees

The pattern of mean ring widths of old trees has been fairly similar for all zones over the period 1800–1950 (Fig. 5). A period of fast growth in the 1820s, followed by a rapid decrease culminating in the year 1837 is the most obvious common feature. The 1850s and 1920s were also periods of above average growth. These observations match the findings of prior tree-ring studies in Northern Fennoscandia (e.g. Mikola 1952, Sirén 1961, Briffa et al. 1986). Since the 1960s the radial growth trends have diverged by zone. The zones closest to the smelter were first to diverge. In zones II and III a downward growth trend became evident in the 1960s. In zone IV signs of a declining growth trend appeared in the 1980s. Growth variation has been minimal over the last 50 years for zones V and VI.

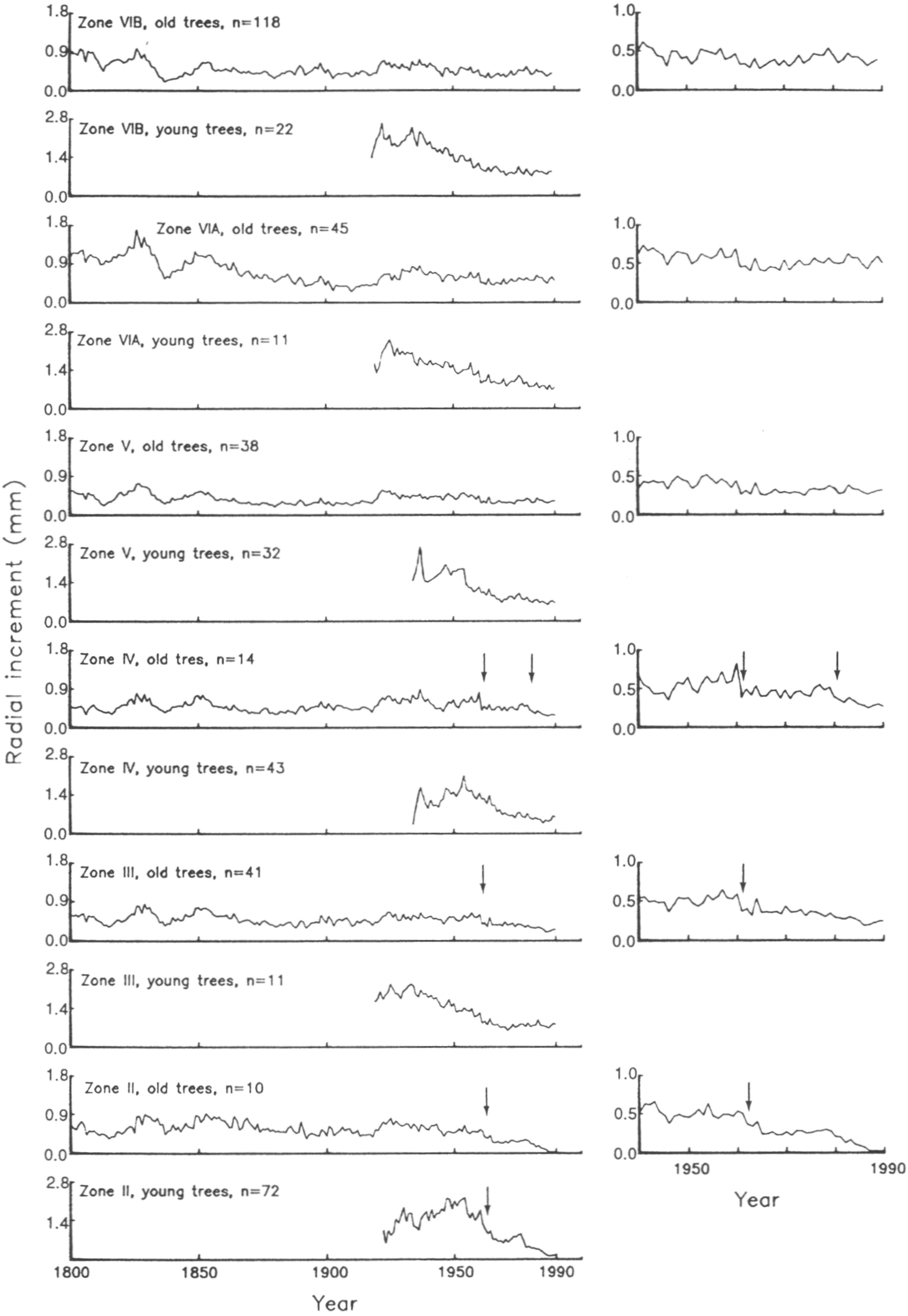

Figure 5. Average ring-widths for the old and young trees by zone. The graphs in the right-most column are enlargements of the last 50 years ring widths to highlight recent trends.

## Zone VIb (Unaffected zone, Finland)

The average growth for zone VIb (Northern Finland) has been fairly steady since the 1850s (Fig. 5). Fast growth during the 1920s and 1930s is the most marked deviation from the long-term average. The growth has remained close to the long-time average since 1939, when the industries in Monchegorsk were started. A slight reduction can be observed for the 1960s, followed by a recovery in the 1970s. The results from cluster analysis for zone VIb reveal two growth patterns for 1961–1990. The first cluster shows a clear enhancement of growth after the 1960s, while stable growth has been typical for the second one (Fig. 6).

The average growth for young Scots pines shows a stable downward trend (Fig. 5). The average growth pattern is typical for a number of tree species undergoing the differentiation phase of stand development in an undisturbed environment (Fritts 1976, Oliver and Larson 1990). In recent years the average growth has varied between 0.75–0.90 mm.

## Zone VIa (Unaffected zone, Russia)

In comparison with zone VIb the old sample trees from zone VIa have grown faster on average, but the pattern of variation is the same: above average for the period 1920–1940, below during 1900–1915 (Fig. 5). The cluster analysis also produced two clusters fairly similar to those for VIb (Fig. 6). The mean growth of the young trees follows a pattern very similar to the young trees in zone VIb.

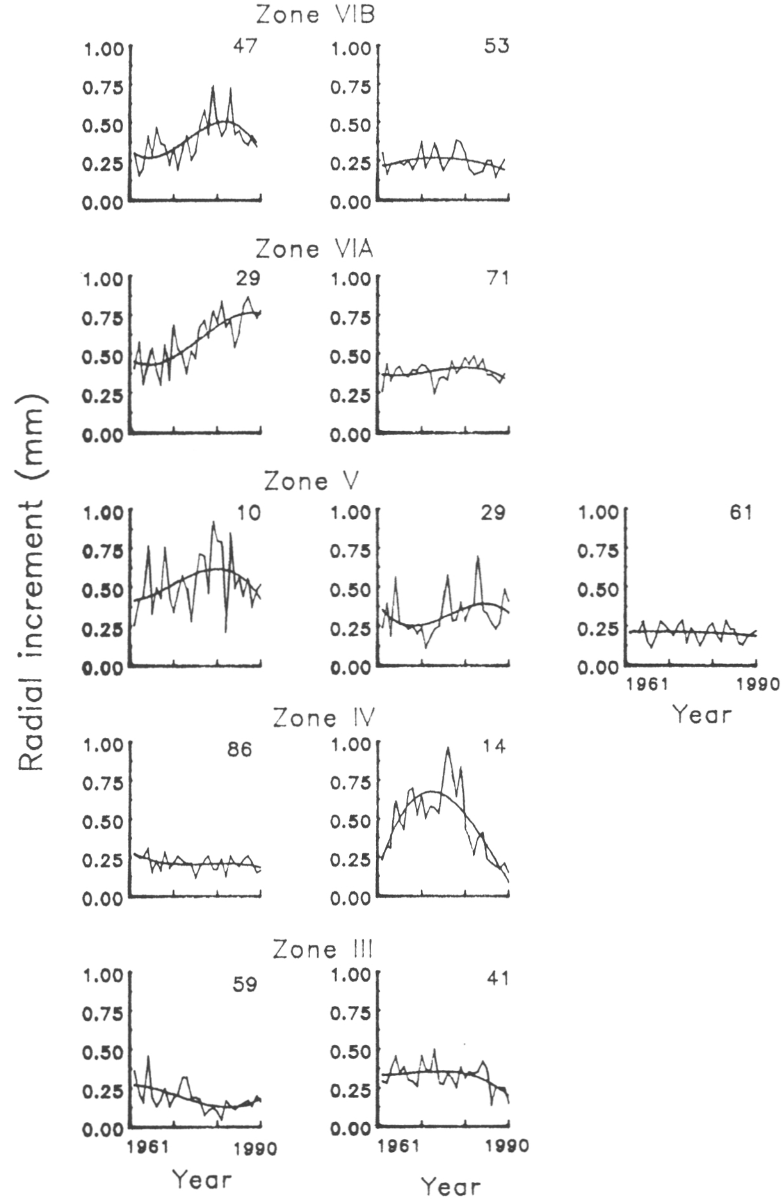

Figure 6. Medoids of clusters based on radial growth patterns (1961–1990) for zones III–VI. The number in the upper right corner is the percentage of sampled trees assigned to that cluster.

## Zone V
## ("The zone of initial degradation")

For zone V (70 kilometers from Monchegorsk), the long-term average growth is less than any other zone (Fig. 5), indicative of a lower site quality. The growth since 1939 has generally been above the average when compared to the previous century. As in zone VI, a reduction has occurred in the beginning of the 1960s, most likely caused by colder than average summer temperatures during the 1960s (Pohtila 1980). Only a slight recovery can be observed thereafter. The medoids (representative trees) of the three clusters either show signs of growth increase (clusters I, II) or stable development (cluster III) (Fig. 6). Differences in radial growth trends between young trees from zones V and VI are slight (Fig. 5).

## Zone IV
## ("The outer industrially altered zone")

Slow growth for 1860–1920 followed by an increase in 1920–1960 is also typical for zone IV (roughly 40 kilometers from Monchegorsk) (Fig. 5). The reduction of growth from 1960 to 1961 was unusually sharp. Thereafter growth was stable from 1961 to 1980. A clear downward trend began in the 1980s. Unlike zones V and VI, neither cluster medoid shows a continuous growth increase during 1961–1990 (Fig. 6).

Compared to other zones, the young trees in zone IV have grown slowly on average (Fig. 5). No rapid reduction can be observed, however. Between 1970–1990 average ring widths have varied between 0.50 and 0.75 mm.

## Zone III ("The fundamentally altered forest")

For zone III (the material sampled at 29–32 kilometers from Monchegorsk) growth trends before 1939 do not differ strongly from the other zones, however a downward trend begins in the 1960s (Fig. 5). Growth has continuously decreased throughout the 1970s and 1980s. Both cluster medoids show a reduction of growth over the last 30 years, indicating that the decrease is typical for the majority of trees (Fig. 6). Ten percent of the sample trees from zone III had not formed rings at breast height during recent years.

In contrast to the old trees, the young Scots pines from zone III have developed steadily for the past three decades (Fig. 5). In recent years the average growth has generally varied between 0.7–0.85 mm, rates similar to trees in zone VI. None of the young trees had missing rings during the 1980s.

## Zone II ("The severely degraded area")

Since zone I is defined as a region with virtually no living conifers present, our nearest sample trees to the smelter are from zone II. While most old Scots pines are dead in zone II as well, a few living ones were found 16 kilometers south from Monchegorsk. None of those had formed rings at breast height since 1987. In the most extreme case, 19 rings were missing. Growth decreased strongly during the early 1960s (Fig. 5) and there has been no subsequent recovery. During the 1980s the growth of the old sample trees has totally ceased at breast height.

While only slight differences can be observed for the young trees in zones III and IV, a clear decline is evident in zone II during recent decades. Average ring widths of over 2 mm were observed in the 1950s (Fig. 5). Thereafter an unusually large reduction takes place. By the late 1960s the mean ring widths were roughly 0.5 mm. These trees are slightly younger than the subsample of young trees in most other zones (Fig.4). Therefore the decline in growth is not attributable to the geometric size constraint, that occurs during later stages of stand development. Moreover, during the 1980s, 48 out of the 72 trees ceased developing annual rings at breast height.

## Changes in the climate-growth relationship in the different zones

A degradation of the climate-growth signal is a more subtle form of the effects of pollution on tree growth. We analyzed the possible changes in the climate-growth signal for zones II, III and the combined zones IV–VI. The parameters of the model were calibrated for 1906–1970; the model values for the verification period 1971–1990 are therefore extrapolations.

For zones IV–VI the model performs well in predicting the high-frequency variation of growth for the verification period (1971–1990): the correlation between the model and actual growth differs very slightly between the calibration and verification periods (0.41–0.45) (Fig. 7). For both zones II and III the correlation of the verification period is lower than for the calibration (0.55–0.42 and 0.45–0.29, respectively) (Fig. 7). However, a clear climatic signal still exists in the data, despite of the fact that the low-frequency growth trends for both zones have declined strongly. Only in zone II, where recent growth indices markedly deviate from the model, is there any suggestion of a distortion of the climate-growth relationship.

# Discussion

Trees from regions close to the polar timber line have traditionally been used for tree-ring studies, mainly because

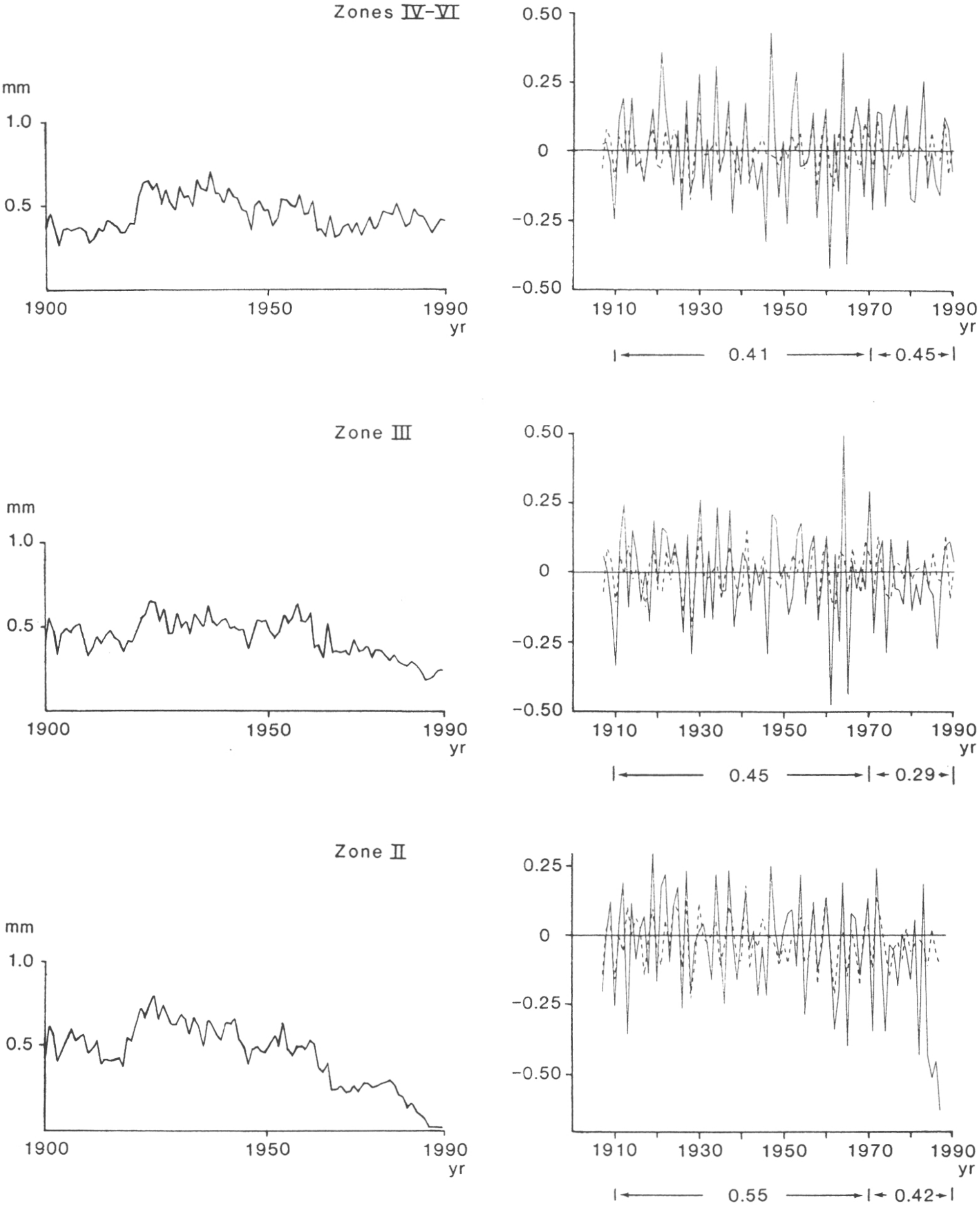

Figure 7. Growth trends for the current century for zones IV–VI, III, II (left). Growth indices (solid line), the growth model (dashed line) and correlations for 1906–1970 and 1971–1990 for the respective zones.

tree growth is strongly correlated with summer temperatures. Also, due to low stand densities, competition usually affects tree growth less than in more temperate regions. Another advantage is that it is relatively easy to find old specimens and thus construct long time series.

While stand dynamics have a lesser effect on growth than for trees in more temperate regions, the effect of climate is evidently very strong. The growth of old trees in all zones follows a similar pattern prior to 1939, when the industries in Monchegorsk were put into operation: below average growth from 1870 to 1915, followed by a rapid increase culminating in the early 1920s. High correlation between July temperatures and radial growth suggests that the pattern of variation is mostly induced by climate (Hustich 1945, Sirén 1961, Briffa et al. 1986).

Recent studies on the tree growth-climate relationship are informative for assessing the role of climate as a causal factor behind the growth trends. Briffa et al. (1986) analyzed ring-width variation of Scots pine in Northern Sweden and Finland. Their model suggests that low growth during the early 1960s is connected to lower than average late summer temperatures. While the data used by Briffa et al. (1986) only extends to 1964, similar results were produced by Hari and Arovaara (1988), whose data cover the years 1906–1982. Hari and Arovaara's (1988) dynamic growth model also suggests that the climate in Northern Fennoscandia has subsequently become more favorable for Scots pine growth during the 1970s and 1980s.

Our data from the unaffected zones V and VI follow the pattern suggested by the model of Hari and Arovaara (1988): low growth in the 1960s, followed by a recovery (Fig. 5). The data for other zones, however, do not. In zone II a continuously decreasing growth trend started in the 1960s. In zone III a similar downward trend was observed, although the rate of decrease has been slower. In zone IV growth has been stable after the year 1961, until a slight reduction took place in the 1980s.

In addition to climate, the abrupt growth reduction from 1960 to 1961 is probably connected to the fact that 1961 was an exceptional year for Scots pine regeneration in Northern Scandinavia (Pohtila 1980). Seed production consumes the energy reserves of trees and as a result narrow annual rings are formed (Hustich 1945).

The vegetation-based classification by Kryuchkov (1993) seems to correlate well with the observed growth trends. The remaining living old trees in the severely damaged zone II no longer formed annual rings in the late 1980s. In the strongly affected zone III a reduction of growth in recent decades is evident. Old trees in zone IV also show slight signs of reduced growth in the 1980s, whereas those in zones V and VI show recent growth increases.

The results of the older and younger subsamples clearly differ, suggesting that the rate of growth response to atmospheric pollution is related to the physiological development of the tree. In the severely affected zone II, the growth of both old and young trees has clearly been affected. For zones III and IV, however, the older sample trees clearly show signs of reduced growth, while the young trees do not. The same type of difference can also be noted in the rate of mortality. As pointed out by Kryuchkov (1993) old conifers have mostly died in zone II, while a number of living younger ones can still be found.

Cluster analysis has proved to be a valuable statistical tool for the detection of synchronous changes in radial growth among individual trees (Reams and Van Deusen 1993). We used the procedure for analyzing the variability of recent growth trends of individual old-growth trees. The results of cluster analysis suggest that the recent growth of individual trees follows a fairly consistent pattern. In zones classified as clearly damaged (III and IV) by Kryuchkov (1993) the growth of cluster groupings are descending, while for zones with only initially degraded (V) or unaffected vegetation (VI) the recent growth trends of all groups are either stable or ascending. According to the growth model of Hari and Arovaara (1988), a growth increase of climatic origin is to be expected for the period 1961–1984. However, in zones III and IV growth decreased, evidently because of pollution exposure.

Since 1990 intensive ecological research has been conducted at Kola peninsula (see e.g. Kozlov et al. 1993, Tikkanen 1994). While many study results are yet to be published in scientific journals, it is already possible to compare our analysis of growth trends with other studies performed in the Monchegorsk region.

Annual depositions of $SO_4^{2-}$, nickel and copper, reported by Jevtjugina (1991), were all at maximum level 7 km from the smelter. Respective measurements at a location 36 km south of the smelter produced values clearly above background levels. Barcan (1992) reported 50–80 times higher nickel and copper contents of the organic layer of podsolic soils within a radius of 10–12 kilometers of the smelter. Kozlov et al. (1995) analyzed concentrations of metals in mountain birch leavesusing a network of 36 sample plots within 65 km of Monchegorsk. Nickel and copper concentrations between 200–400 mg/kg$^{-1}$ were commonly observed near the smelter, while the background values generally varied between 10–20 mg/kg$^{-1}$. At the distance of 29 km the concentrations of Ni and Cu were still 2–5 times higher than those observed at the most distant location (65 km). Lindroos et al. (1995) observed effects of sulphur emissions on snowpack composition for a distance of 30 km from the emission source. The copper and nickel emissions were also reflected in the snowpack composition, although not as far as 30 km. Elemental analysis of pine needles showed that concentrations of sulphur, nickel and copper are unusually high within approximately 50 kilometers south of the smelter (Raitio 1992). Jalkanen (1996) produced retrospective data on the needle retention of Scots pine using the needle trace method (NTM) (Kurkela and Jalkanen 1990). The studied gradient started 10 kilometers south of Monchegorsk continuing to southwest. In 1990–1993 when the sample trees were felled, young Scots pines 10 km south of the smelter had on average 2.9 needle sets, compared to 4.7–4.8 needle sets for the trees at the most distant sites (Jalkanen 1996). Sutinen et al. (1996) discovered consistently lower frost hardiness of Scots pine needles at sites 10 and 36 km south of Monchegorsk compared to more distant sites. As low temperature is the most critical natural abiotic stress factor that limits distribution of plants in the subarctic environment, and sulphur dioxide has been shown to decrease the frost hardiness of forest trees (Keller 1981), the finding of Sutinen et al. (1996) represents a potential causal link between pollution and forest damage in the region of Monchegorsk.

In Monchegorsk, the mean annual $SO_2$ concentrations, presented by Baklanov et al. (1994) are approximately 300 $\mu g/m^3$, while the highest reported values exceed 1000 $\mu g/m^3$ (Kryuchkov 1993). In Northern Finland occasional high (over 200 $\mu g/m^3$) $SO_2$ concentrations have been measured (Hari et al. 1994). Such episodes, clearly connected to easterly winds, are very rare. At a measurement station situated at the Finnish–Russian border, the median $SO_2$ concentration of the air is very low (< 1$\mu g/m^3$); only 0.5 % of observations exceed 100 $\mu g/m^3$ (Tuovinen et al. 1993). Despite the occasional high $SO_2$ concentrations in the air, the cumulative wet sulphur deposition in Northern Finland is well below the values observed in most parts of Europe (Tuovinen et al. 1993).

The results cited above suggest that emissions from Monchegorsk have influenced the forest ecosystems at the most eastern end of our study gradient. As in any epidemiological study, the exact cause-effect mechanism that reduces tree growth and eventually results in death of trees is not known. However, the main harmful components that are being emitted in large quantities are $SO_2$ and heavy metals, mainly nickel and copper. The fact that high contents of $SO_2$ inhibit photosynthesis is well established in experimental studies. Roberts (1984) reviewed experimental data and suggests a long-term concentration threshold of 100–150 $\mu g/m^3$ for growth effects of $SO_2$ on forest trees. The annual average of 300 $\mu g/m^3$ (Baklanov et al. 1994) near Monchegorsk clearly exceeds the threshold. However, our data shows decreasing growth trends also in areas where the annual $SO_2$ concentrations, according to the model of Tuovinen et al. (1993), are considerably below the threshold suggested by Roberts (1984).

The impact of heavy metals on tree growth has also been studied experimentally; the subject has been reviewed by Balsberg-Pålsson (1989). Great differences in response to heavy metals between and within species have made it difficult to determine critical concentrations at which a certain metal would be toxic to forest trees (Balsberg-

Pålsson 1989). Most experimental studies describe the impact of unrealistically high doses of heavy metals. However, it is significant that a large proportion of well-documented cases of local forest decline occur in the vicinity of mining and smelting complexes (e. g. Linzon 1958, Nash et al. 1975, Wilhelmsson 1983). The reported high emissions (Laurila and Tuovinen 1991) and depositions of heavy metals (Jevtjugina 1991) as well as the abnormally high nickel and copper contents in organic soil (Barcan 1992) suggest that heavy metals have played a part in the development of forest damage in the region of Monchegorsk. Still other studies have found that Scots pine needles contain significantly elevated levels of nickel and copper up to 50 kilometers from the smelter (Raitio 1992).

The climate-growth modeling provided a novel finding. The actual growth trends for zones II and III have been declining since the 1960s, however, the standardized (high-frequency) growth variation continues to be accounted for by a simple climate model. Only for the severely affected zone II the most recent growth indices clearly deviate from the predictions of the model (even though the correlation of the model and data over the last 10 years is still 0.22). On the basis of a climate model based on high-frequency variation of growth one might well conclude that growth has not been affected for zone III and that zone II has been affected during the 1980s only. The unstandardized growth trends clearly show that such conclusions would be fallacious.

Much research has been directed to analyzing pollution-induced changes in climate-tree growth relationships. An example of this approach are studies on the causes of the synchronous post-1960 decline in the growth of red spruce (*Picea rubens* Sarg.) in the northeastern United States. A regression model explaining approximately 50 % of the total variance of tree-ring indices was developed (Cook 1987). From the onset of the decline onwards, the models explain a considerably smaller share of the total variance. The results of this study suggest that the response of Scots pine growth to climatic variation is fairly insensitive to effects of pollution. A possible reason for this could be the origin of our data. In regions close to the forest limit, ring width variation generally contains a very strong climatic signal. This is exemplified by our data, which was collected roughly 100 kilometers from the polar timber line. One possible interpretation is that the impact of climate is strong enough to be identified even in conditions where growth processes have been profoundly altered by pollution.

# Conclusions

The damage zones as defined by Kryuchkov (1993), based on occurrence of plant species, match well with our results of recent growth trends. The growth trends from the different pollution zones followed a similar pattern prior to the establishment of the smelter in Monchegorsk in 1939. After that, especially during the period 1961–1990, differences between the zones began to appear. Near the smelter, recent growth has been considerably below the long-term average and the trend continues to decrease. In zones II and III a clear the downward trend began in the 1960s, and in zone IV a slight reduction was observed in the 1980s. The most distant zones V and VI have similar growth trends for 1800–1990, indicating that growth to date is unaffected by pollution. Our results indicate that the growth of young Scots pines (30–70 rings at breast height) has been less sensitive to the effects of pollutants than the growth of old ones (170+ rings at breast height).

A simple climate-growth model showed that the high-frequency growth variation contains a climatic signal which does not disappear even though the actual growth trend declines strongly. The detrended growth for zone II (severely affected by pollution) follows the pattern indicated by the growth-climate model until the 1980s although a decrease in growth was evident in the 1950s.

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# IV

# The effect of temperature on the radial growth of Scots pine in northernmost Fennoscandia

Pekka Nöjd
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**Nöjd, P. & Hari, P. 1996.** The effect of temperature on the radial growth of Scots pine in northernmost Fennoscandia. Submitted for publication.

The effect of temperature on radial growth of Scots pine was analyzed using tree-ring data from the northern forest limit, northern Finland. Three models representing different approaches were used for describing the dependence. Two of them: a dynamic model based on daily maximum temperatures and a traditional linear model emphasize the effect of midsummer temperatures. In addition, a dynamic model was constructed for describing the effects of spring and autumn temperatures, based on describing the seasonal variation of the $CO_2$ uptake capacity of Scots pine.

The results were similar to previous findings. The climatic signal in tree rings proved to be dominated by the effect of July temperatures. The dynamic model describing the effect of spring and autumn temperatures produced results that were fairly weakly correlated with the radial growth of Scots pine.

**Keywords:** Scots pine, tree-ring analysis, dynamic model, time series analysis

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# Introduction

In traditional dendroecology the effects of climate on tree growth are usually studied by response function analysis (Fritts 1976). The ring-width indices are related to a set of climatic variables and those with significant correlations identified. This is usually achieved by ordinary least squares techniques or procedures like generalized least squares and principal components analysis (Innes and Cook 1989). A comprehensive review on the methodology has been given in Cook and Kairiukstis (1990).

Most often climate is described by using monthly precipitations and mean temperatures. The most important climatic predictors vary between regions. Best results are generally achieved at regions, where a severe climatic hazard is present; typically in arid or cold locations. In areas where severe drought is a frequent event, monthly precipitations have proved highly useful in predicting growth variation (Fritts 1976). Near the high latitudinal forest limit the short growing season and low summer temperatures limit tree growth. First attempts of dendroecology in northern Fennoscandia showed that summer temperatures, especially mean temperatures for July, effectively predict growth variation (Erlandsson 1936, Hustich and Elfving 1944, Hustich 1945, Sirén 1961). Precipitation is generally considered to be of minor importance, although a dependence has been observed in some studies (e.g. Jonsson 1969). The early findings have been confirmed by subsequent studies (Briffa et al. 1986, Briffa et al. 1990, Lindholm 1995).

An alternative approach for describing the dependence of Scots pine growth on temperature was introduced by Hari and Sirén (1972). They constructed a dynamic growth model with three basic elements: temperature, day light, and the seasonal stage of development of trees. The model produces estimates of daily increments, which are integrated over the growing season. While some details of the model of Hari and Sirén (1972) were unmistakably heuristic, it predicted the high-frequency variation of growth quite well. A parameter describing autocorrelation in the ring-width chronologies proved necessary for satisfactorily describing the strong trend-like low- frequency variation of growth, typical for trees close to the northern forest limit (e.g. Fig. 2c).

It is somewhat surprising that climate variables other than mean temperature for July have proved to be of little use for predicting annual growth at the northern forest limit. Variation in the timing of phenological events of trees is known to be substantial. Häkkinen et al. (1995) analyzed time series describing the date of bud burst for birch (*Betula pendula* Roth) in central Finland for the period 1896–1955. The range of dates of bud burst, which is strongly dependent on spring temperatures, was well over one month for a given location. One would expect such differences in the timing of vital phenological events to have an effect on the annual growth of trees as well; especially in conditions where growing season is extremely short.

Advances in tree physiology have provided new tools for identifying factors affecting tree growth and quantifying the relationships. In Finland Pelkonen (1981) studied the $CO_2$ uptake of Scots pine at the beginning and at the end of growing season. It proved possible to predict the seasonal variation of the $CO_2$ uptake rate accurately, when temperature records and radiation measurements were available on hourly basis.

Since the $CO_2$ uptake rate of trees can be estimated for a given moment, it could be integrated over a growing season in order to estimate annual photosynthetic production. That, in turn, could be expected to correlate with annual growth. The procedure would quantify how effectively trees are able to make use of the available radiation during a growing season.

The aim of the study is to analyze the effect of temperature on the annual growth of Scots pine near the northern timber line. Three fundamentally different models are used, each one for describing the effect of the temperature during a specific period. The role of spring and autumn temperatures is studied using a model estimating the annual photosynthetic production, based on studies by

Pelkonen (1981). A traditional linear regression model is used for describing the effect summer temperatures. The model of Hari and Sirén (1972) makes use of daily maximum temperatures throughout the growing season; the main emphasis, however, is on midsummer temperatures.

# Materials and methods

Tree-ring data for testing the performance of the growth models was acquired from Northern Finland. Old-growth stands of Scots pine (*Pinus Silvestris* L.) near the northern timber line were selected, the latitude ranging approximately from 68°50' to 68°55'. Stands with strong disturbances, natural or man-made, were excluded in the sampling process. A set of 271 dominant trees from 13 sites all within 80 km of each other were cored. The sample trees had between 135 and 437 annual rings at the height of 1.3 metres.

One core was taken from each sample tree. Ring widths were measured to within 1/100 mm. After measurement each ring-width series were cross dated using the Dynaclim software (Van Deusen 1993).

Before data analysis ring widths are commonly standardized, the method obviously depending on the aim of the study. When a tree has been growing in competitive environment, part of the ring-width variation is due to changes in the competitive status of the tree. In such cases the low-frequency growth trend is usually non-monotonic. Standardization methods have been developed for eliminating such growth trends (Cook and Kairiukstis 1990); tight-fitting smoothing splines or high-degree polynomials are frequently used for the purpose.

If one can judge, that the trees are open grown, unaffected by strong disturbances, more simple standardization methods aiming to remove the more or less monotonically decreasing age trend are a reasonable choice (Innes and Cook 1989). An ordinary least squares model describing the dependence of radial growth percentage on tree age, introduced by Kuusela (1964), was selected for the purpose:

$$\ln(Ir\%_i) = b_0 + b_1 \ln(n) + e \qquad [1]$$

where

$Ir\%_i$ = radial growth percentage for year i

n = denoting n:th ring from the pith of a tree

$b_0$, $b_1$ = regression coefficients

e = random element.

The growth of each sample tree was compared to the model [1]. Growth indice for a given year was calculated as an average of the deviations of the observed growth percentages from the model. The procedure in fact removes only a small share of the total growth variation when the sampled trees are old. The series of mean indices is quite similar to the mean ring-width chronology.

Daily maximum temperatures covering the period 1906–1991 were obtained from stations of the Finnish Meteorological Institute situated close to the northern timber line. The location of the station was changed several times. They were situated within 68°37’–69°06’ and 27°13’–27°25’. Correction factors for adjusting for the changes of the locations were obtained from the Finnish Meteorological Institute. Monthly mean temperatures and precipitation values for 1906–1990 were obtained from the same source. from Autumn 1944 until late in the year 1946 the meteorological observations were interrupted by the war.

Temperature records on hourly basis would have been ideal for approximation of the development of the photosynthetic capacity of trees. However, only daily maximum temperatures were available for the whole period from 1906 to 1991. The hourly temperatures were estimated from the daily maximum using the statistical relationship between those two.

Growth predictions were calculated for the period of 1906–1990 using all three models. Original software was used for running the model by Hari and Sirén (1972).

In addition to graphic presentation of the results, correlation coefficients of the predicted and observed ring widths and the standard deviation of prediction error were calculated for testing the performance of the models.

A correlation coefficient of a climate-growth model and tree-ring data — standardized without removing low-frequency trends — describes mainly the fit of low-frequency variation. This is especially true in the conditions of northern tree-line, where the low-frequency variation is very strong. If one also wants to compare the fit between modelled and observed high-frequency (year to year) variation of growth, the low-frequency (trend-like) variation needs to be removed from both the model predictions and growth data. A simple transformation introduced by Van Deusen (1987) was applied for the purpose:

$$Y2_i = \ln(Y1_i) - \ln(Y1_{i-1}) \qquad [2]$$

where

$Y2_i$ = transformed value for year i

$Y1_i$ = original value (growth indice or predicted growth) for year i.

# The structure of the different models

## The model estimating on the annual photosynthetic production of Scots pine

The model is based on describing the rate of photosynthetic production at a given moment. The rate of photosynthetic production is approximated on hourly basis and integrated over the growing season. Two processes form the cornerstones of the model: the gradual onset and cessation of the photosynthetic period for each year and the availability of radiation. For each hour the model describes the $CO_2$ uptake capacity of trees and irradiance. After calculating the cumulative photosynthetic production for the growing season, the estimate is corrected by describing autocorrelation in the ring-width series.

## *Modeling the seasonal variation of the $CO_2$ uptake capacity*

The approximation of the $CO_2$ uptake capacity is based on studies by Pelkonen and Hari (1980); readers interested in details of the procedure are encouraged to consult the above reference.

The photosynthetic capacity of a tree at a given moment is described by the seasonal stage of development (Sp). The concept was originally defined by Hari (1968) by using another concept, the rate of maturation (m).

$$\mathrm{m} = \frac{dSp}{dt} \qquad [3]$$

The rate of maturation is assumed to be dependent on the temperature ($T$) as well as the stage of development ($Sp$).

Pelkonen (1981) compared several alternative formulas that describe the rate of maturation during growing season. The following formula produced the best fit with empirical data.

$$\mathrm{m}\,(\mathrm{T}, \mathrm{Sp}) = \frac{100}{1+100a^{-(T-\frac{Sp}{c})}} - \frac{100}{1+100a^{(T-\frac{Sp}{c})}} \qquad [4]$$

The values of parameters, suggested by Pelkonen (1981), are 2 for parameter *a* and 600 for parameter *c*.

The basic idea of the model 4 is that plant is acclimatized to a certain temperature range at each moment. The range varies during the season. When temperature is within this range, the rate of maturation is close to zero and the stage of development remains relatively unchanged. The difference between actual temperature (T) and the factor Sp/c determines the rate of change of the stage of development.

The stage of development, Sp, is obtained by integration of equation [4] (Pelkonen 1981):

$$\mathrm{Sp}(\,\mathrm{t}\,) = \int_{t0}^{t} m(T(t), Sp(t))dt \qquad [5]$$

Using the formulas [4] and [5] the stage of development can be calculated for any given moment throughout the year. Empirical results by Pelkonen (1981) suggest that the photosynthetic rate of Scots pine is determined by irradiance and the seasonal stage of development in spring, while the tree is recovering from dormancy. The seasonal stage of development will eventually reach a maximum — which has been observed in empirical experiments — after which the photosynthetic rate is to a great extent determined by irradiance.

After reaching the maximum the seasonal stage of development is assumed to remain at maximum level until the beginning of August.

For the purposes of this study, the seasonal stage of development was calculated for each hour between May 1st and October 31st; outside the period Scots pine is likely to show very little photosynthetic activity near the northern forest limit, because of the low temperatures and the extreme shortage of light — the tree-ring material was collected from region where the polar night takes effect in the middle of winter.

Two examples of the variation of the seasonal stage of development during a single growing season are given in Fig. 1a. Both in 1948 and 1982 the seasonal stage of

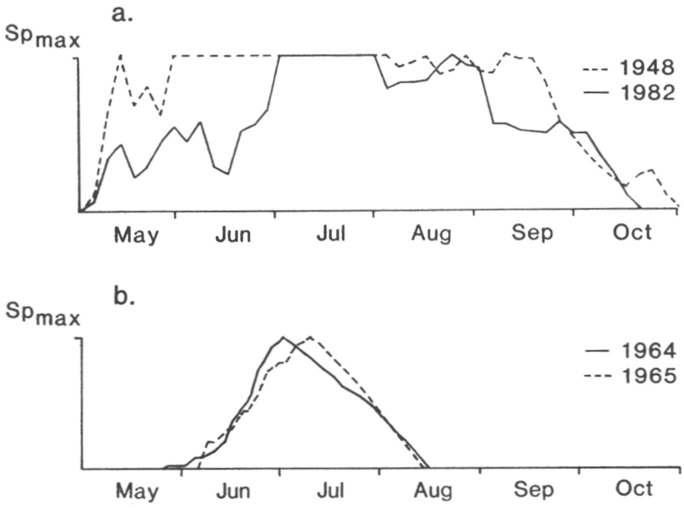

Figure 1. Examples of the development of the seasonal stage of development during growing season using a. the model estimating on the annual photosynthetic production of Scots pine and b. the model of Hari and Sirén (1972).

development started to change in early May. In 1948 it reached the maximum by the end of May. In 1982, a year with cool May and June, the maximum was reached a month later. Following the basic assumption of model, the seasonal stage of development remains at maximum level through July. In the autumn of 1982 the value of the parameter decreased faster than in 1948.

## *Description of the intensity of radiation*

In addition to the seasonal stage of development, the rate of photosynthesis at a given moment is strongly influenced by the intensity of radiation. Data based on direct radiation measurements that would meet the requirements of this study is not available; systematic monitoring in northern Finland began as late as 1956. Retrospective estimates on the variation of radiation are difficult to produce. An attempt could be made if data on daily cloudiness would be available. No such data that would cover the period since 1906 is available for northern Finland. Because of the lack of data, only the potential maximum radiation is described using a simplified approach.

The potential maximum radiation can be estimated for a given moment and location on the basis of the position of the sun. The solar elevation angle *($\beta$)* can be calculated for a given moment and location using the following formula (Gates 1980):

$$\sin(\beta) = \cos(l)\cos(h)\cos(D) + \sin(l)\sin(D) \qquad [6]$$

where

$\beta$ = the solar elevation angle

$l$ = latitude

$h$ = time of day (given in angular distance from the meridian of the observer)

$D$ = the declination angle, determined as

$D = 23.5 \cos(2\pi(i - 172)/365)$; $i$ = i:th day of the year.

The sine of the solar elevation angle gives an estimate of irradiance (*I*) for a given moment. The latter can be used for estimating the photosynthetic rate (*p*) at a given moment following the approach of Hari et al. (1985):

$$p(t) = \frac{I(t)}{I(t)+b} = \frac{\sin(\beta(t))}{\sin(\beta(t))+b} \qquad [7]$$

where
$p$ = rate of photosynthesis
$I$ = irradiance
$\beta$ = the solar elevation angle
$b$ = empirical parameter, the value 0.5.

The total potential photosynthetic production can be approximated for a given period, once hourly estimates of the seasonal stage of development (*Sp*) and rate of photosynthesis have been calculated. In order to predict the growth indice for year t, the cumulative photosynthetic production from 16th of August in year i–1 to 15th of August in year i is used; annual ring formation in Lapland being usually completed by mid-August:

$$P_i(t) = \int_{228}^{305} (Sp(t_{i-1}), p(t_{i-1}))dt_{i-1} + \int_{121}^{227} (Sp(t_i), p(t_i))dt_i \qquad [8]$$

where
$P_i$ = photosynthetic production for year i
$p$ = rate of photosynthesis
$Sp$ = stage of development
$t_i$ = time during the year i.

Numerical integration, using a time step of one hour, was used for approximation of the values of the photosynthetic production for each year (equation 8).

## *Autocorrelation in the ring-width series*

It was recognized early (Hustich and Elfving 1944, Eklund 1954, Johnsson 1969) that strong autocorrelation exists in ring-width chronologies of Scots pine from the northern forest line. To account for it, the estimate of the growth indice is corrected by using a term that describes autocorrelation in the series. The correction takes place after estimates of the annual photosynthetic production have been calculated for the years 1906–1990. In order to achieve comparability with growth indices, the estimates are also normalized, so that the mean value of annual photosynthetic production for 1906–1990 becomes equal to 100.

In order to summarize the components of the model, the estimated growth indice $y_i$ for year i is calculated as follows:

$$Y_i = \frac{P_i}{\overline{P}_i} * 100 + a\,(Y_{i-1} - 100) \qquad [9]$$

where

$Y_i$ = estimate of the growth indice of year i

$P_i$ = annual photosynthetic production, calculated from the equation [8]

$\overline{P}_i$ = mean annual photosynthetic production for the period 1906–1990

a = the parameter describing autocorrelation.

The value 0.7, suggested by Hari and Arovaara (1988), was used for the autocorrelation parameter a.

## The linear regression model

A simple traditional climate-growth model was constructed for describing the statistical dependence between mean monthly temperatures and growth; the technique of ordinary least squares was applied.

Monthly mean temperatures and precipitations were related to ring-width indices. The relationship of growth and these variables was analyzed with a one year lag as well. All possible subsets of three regressor from the set of monthly temperatures and precipitations for current and previous year were tested. The result was very similar to previous findings (e.g. Erlandsson 1936, Hustich 1945, Sirén 1961, Briffa et al. 1990): The most useful regressor combinations all include the mean temperature for July of the current year. The temperature of August is nearly significant as well. It is an unattractive choice for regressor, however, since the radial growth of Scots pine generally terminates before 31st of July at the northern forest line. Using the July temperature with a one year lag also improves the predictive power of the model slightly. As observed previously, monthly precipitation variables seem to be fairly useless for predicting Scots pine growth near the northern forest line.

The structure of the constructed regression model is:

$$Y_i = -8.0 + 6.3(Tjuly_i) + 1.6(Tjuly_{i-1}) + e \qquad [10]$$

where

$Y_i$ = growth indice of the year i
$Tjuly_i$ = mean July temperature of the year i
$e$ = the error term.

Model 10 is one of the simplest choices for describing the effect of the most influential climatic variable. While not the most effective for removing the effect of autocorrelation, the model also has the advantage of being directly comparable with the alternative models used in this study.

## The dynamic growth model based on radiation and temperature and the seasonal stage of development

The dynamic growth model of Hari and Sirén (1972) is too complicated to be presented here in detail. The annual ring-width is obtained as a sum daily radial increments. The daily increment is modelled on the basis of daily maximum temperatures, radiation and the seasonal stage of development. The main components of the model can be described shortly as:

$$Y_i = C_i + E_i + A_{i-1} \qquad [11]$$

where

$Y_i$ = growth indice for year i
$C_i$ = the sum of daily increments for year i
$E_i$ = a correction for cone production for year i
$A_{i-1}$ = autoregressive term for growth of the previous year i–1.

The term $C_i$ consists of three functions. Their sum is accumulated over the growing season.

$$C_i = \sum_{j=110}^{304} f1 * f2 * f3 \qquad [12]$$

Function *f1* contains the dependence of daily radial growth on daily maximum temperature. Higher temperatures are assumed to result in faster growth up to the value of 28° C.

Function *f2* describes the effect of the seasonal stage of development on the daily growth of the tree at a given moment during the growing season. At the time of the publication (1972) very little empirical evidence was available about changes in the seasonal stage of development of trees. In the model the seasonal stage of development increases continuously, reaches a maximum usually during the first half of July and begins to descend immediately after reaching the maximum (Fig. 1b). Thus, the conditions in the middle of the growing season strongly affect the behavior of the model.

Function *f3* describes the available radiation as a function of the solar elevation angle.

# Growth variation for the period 1906–1991; predictions of the different models

The parameters for the model of Hari and Sirén (1972) were calibrated using the period 1906–1940. The model clearly predicts both the low-frequency and the high-frequency (year to year) growth variation reasonably also for the subsequent years 1941–1990 (Fig. 2b). The amplitude of the high-frequency variation of predicted growth tends to be larger than the respective observed growth (Fig. 2b).

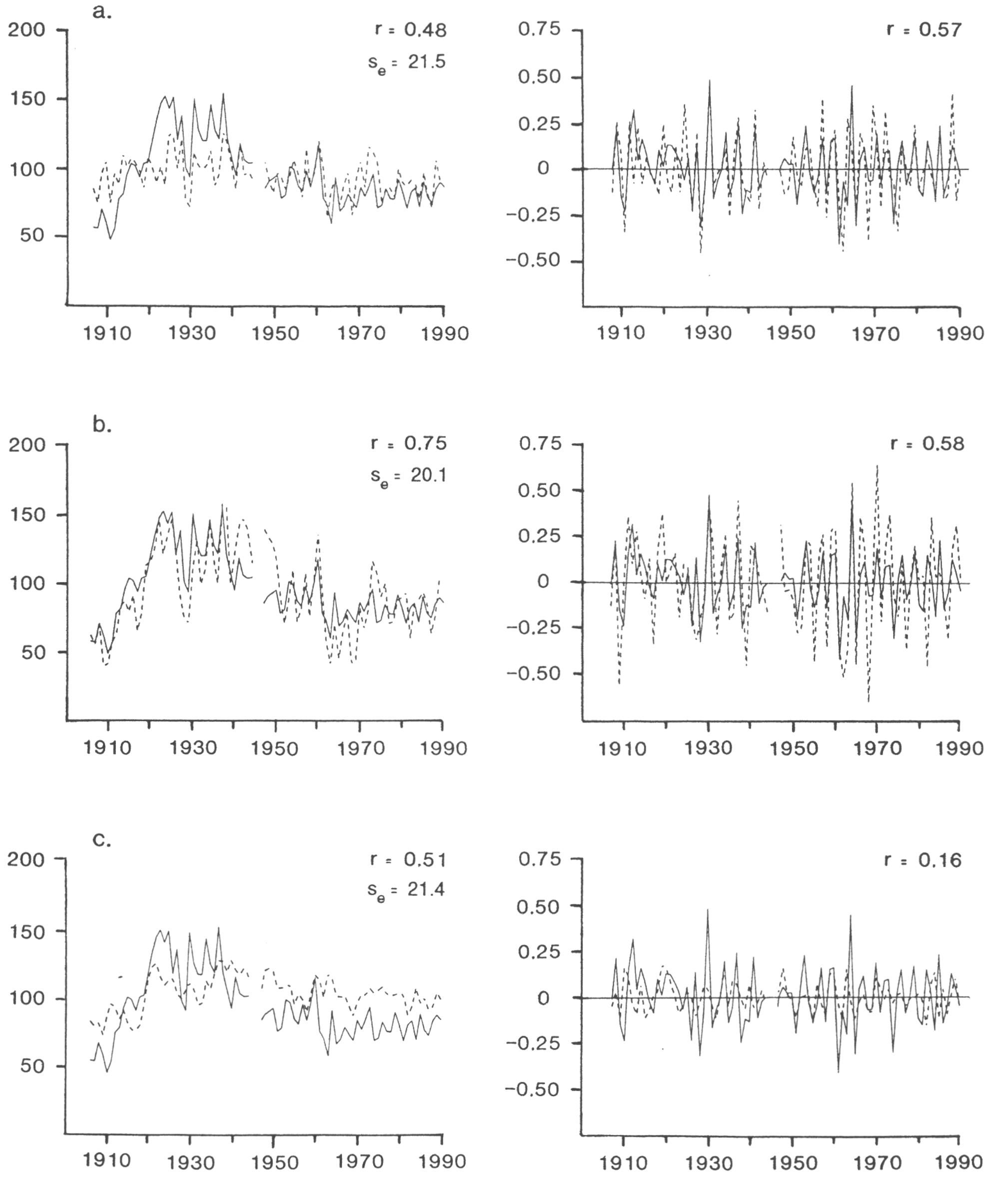

Figure 2. On the left the indices describing Scots pine growth during 1906–1990 (solid line) and the growth predictions of the three models (dashed line) a.) the linear regression model b.) the model of Hari and Sirén (1972) c.) the model based on the photosynthetic production. The fit between the data and the predictions is described with the correlation coefficient (r) and the standard deviation of the prediction error ($s_e$). On the right the respective growth indices and model predictions transformed by taking the first difference of natural logarithms [2].

The linear regression model, based on the temperature of July, is unable to describe the low-frequency variation adequately (Figs. 2a). The main weaknesses are the periods of fast growth during 1921–1925 and 1930–1937. Mean monthly temperatures and precipitation values evidently do not adequately explain the phenomenon. The model tends to underestimate periods of above-average growth and visa versa. The lack of fit is evidently caused partly by the strong autocorrelation in the ring-width series, typical for Scots pine in northern Fennoscandia. The first degree autocorrelation coefficient of the growth indices is as high as 0.75. Thereagainst the regression model performs roughly as well as the model of Hari and Sirén (1972) in predicting the high-frequency variation of growth indices (r = 0.57) (Fig. 2a).

The model based on the annual photosynthetic production of trees, while not totally without some predictive value, performs poorly (Figs. 2c). The model describes somewhat reasonably the main features of low-frequency variation, low growth in the beginning of the century followed by a favorable period during the 1920s and 1930s. Thereafter the predictions are systematic overestimates. The correlation between the predicted and observed high-frequency variation of growth is especially weak (r = 0.16).

The standard deviation of the prediction error is another frequently used criteria for describing the performance of models of different types. It also suggests that the model of Hari and Sirén (1972) produces the best fit with the observed growth indices; however, the difference between the three models are considerably smaller.

# Discussion

Trees from extreme conditions have traditionally been used for dendroecological studies, because they react strongly to climatic variation (Fritts 1976). The tree-ring data, collected for this study near the northern timber line, is an example of the approach. The tree-ring material was sampled from old-growth forests; special effort was made to eliminate the effects of natural and anthropogenic disturbances in the data collection phase. The strong response of Scots pines from northern Fennoscandia to climatic variation was observed early (Erlandsson 1936, Hustich 1945). In contrast, studies in southern part of Fennoscandia have failed to reveal equally strong dependence between climate and growth. For example models constructed by Henttonen (1986) explained approximately 20 % of the total variance of growth indices.

Three fundamentally different models were used to introduce different aspects of summer temperatures into the analysis. Two of the models, the linear regression model and the dynamic growth model of Hari and Sirén (1972), are applications of previously published techniques. The third one, based on describing the potential annual photosynthetic production, is an attempt of innovation.

Most growth models presented in literature are based on standardized data, which in many cases means that a large share of the total growth variation has been removed prior to the analysis. In some cases the high-frequency variation of growth is clearly considered to be the ”signal” and low-frequency variation the ”noise” (e.g. Johnson et al. 1995). The reported proportions of explained variance describe the fit between the model and the variation remaining after standardization, which makes it difficult to compare the performance of the various models with each other. The three models used in this study were tested against the same tree-ring data set. The data was standardized using a method that removes only a small proportion of the total variation of growth.

An extremely simple regression model was constructed; mean temperature of July was identified as the strongest regressor. The model did not produce an especially good fit with the data ($r = 0.48$). However, it shows the dependance of the strongest single regressor and growth. The model of Hari and Sirén (1972), representing a completely different approach but also emphasizing the effect of midsummer temperatures, performed considerably better. The model was calibrated for the period 1906–1940; correlation between the predicted and observed growth indeces for the subsequent period 1941–1990 was 0.72. These results confirm the previous finding, that above-average midsummer temperatures are an essential prerequisite for faster than average radial growth of Scots pine at the northern timber line.

In contrast to the two others, the model predicting the annual photosynthetic production emphasizes the temperature variation during spring and autumn. One of the two main components of the model, the seasonal stage of development, remains at maximum level virtually throughout midsummer each year (Fig. 1). The other, describing potential maximum radiation follows exactly the same annual pattern. Therefore conditions of midsummer have no effect on the behavior of the model.

Experimental studies by Pelkonen and Hari (1980) show convincingly, that seasonal changes in the photosynthetic capacity of Scots pine can be predicted accurately, if adequate temperature records are available. However, the potential annual photosynthetic production, modeled following the approach of Pelkonen (1981), proved to be rather weakly correlated with actual ring widths. While not totally without some predictive power, the results were vastly inferior to the alternative techniques, that are based on midsummer temperatures. It is of interest, that the model can connect spring and autumn temperatures with Scots pine growth — albeit loosely. The dependence is hardly strong enough, however, to encourage one to further seek for possibilities of improving climate-growth models by making use of spring and autumn temperatures.

The data available for testing the model of the annual photosynthetic production is not ideal. Only an estimate of the maximum potential radiation was available. Not having data about the actual hourly radiation is a major handicap. Cloudiness and other factors affecting the intensity of radiation obviously vary greatly within and between growing seasons. Since the rate of photosynthesis of Scots pine is mainly determined by the intensity radiation, the model obviously fails to account for an important source of variation.

The experiments, which the studies of Pelkonen (1981) are based on, were carried out in Southern Finland; their applicability to the conditions at the northern timber line has not been proved. Similar experiments were started at the ecological Research Station at Värrio, Northern Finland in 1993 (Hari et al. 1994). Preliminary, unpublished results indicate that the formulas presented by Pelkonen are reasonably applicable to the conditions of northern Fennoscandia as well.

The structure of the model includes certain heuristic assumptions. Predicting the ring-width of the year i by using the photosynthetic production from the beginning of August in year i–1 to 15th of August in year i is an obvious example of those.

Despite of these reservations, the result suggests that photosynthesis during spring and autumn has a minor effect on the ring-width variation of Scots pine at the northern timber line.

The physiological basis for the effect of temperature on growth processes is not thoroughly understood. Part of the positive covariance between growth and midsummer temperatures could be of indirect nature. Summer temperatures in Lapland correlate negatively with cloudiness, which in turn affects the availability of radiation and thus photosynthesis (Pohtila 1980). On the other hand temperature is known to influence biochemical reactions. According to Landsberg (1986) the effects of temperature are largely attributable its effects on the activity of enzyme systems.

A possible explanation for the lack of predictive power of spring and autumn temperatures might be that air temperatures do not adequately reflect the growing conditions of trees. The $CO_2$ uptake of pine needles reacts relatively quickly to changes of air temperature. The root systems of trees most likely show a considerably slower response to air temperature, however. In fact, it has been shown that in Northern Fennoscandia $CO_2$ exchange in Scots pine needles usually starts while the ground is still covered by snow (Hari et al. 1994). Effective metabolism in the root systems will begin considerably later. Especially if an unusually thick layer of frost has developed in soil during winter, soil temperatures may remain low for a long period despite of warm air temperatures, retarding the onset of metabolism in roots. This can be one of the reasons why the $CO_2$ uptake capacity of pine needles, as described by

Pelkonen (1981), may be less useful for predicting annual growth of Scots pine in the conditions of northern forest limit.

# Conclusions

The models emphasizing the effect of high midsummer temperatures were able to explain a considerable proportion of the variance of the growth indices. Evidently warm midsummer is an essential prerequisite for above average growth of Scots pine at the northern forest limit. The model predicting annual photosynthetic production of Scots was able to explain the only a marginal share of the variation of the growth indices. The considerable variation in the onset of the photosynthetically active period has evidently a lesser role in determining annual growth.

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*Total of 28 references*

## List of symbols

D = the declination angle
h = time (of day), given in angular distance from the meridian of the observer
I = irradiance
$Ir\%_i$ = radial growth percentage for year i
l = latitude
m = rate of maturation
$P_i$ = photosynthetic production for year i
p = rate of photosynthesis
Sp = seasonal stage of development
$s_e$ = standard deviation of prediction error (observed value – predicted value)
T = temperature
$\beta$ = the solar elevation angle

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