Dissertationes Forestales 53

Long-term dynamics in growth of Scots pine and Siberian spruce in Komi Republic (European part of Russia)

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Academic dissertation

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ABSTRACT

The main objective was to investigate the long-term growth dynamics of Scots pine (*Pinus sylvestris L.*) and Siberian spruce (*Picea obovata* Lebed.) trees in the Komi Republic, in the currently changing environment.

Positive long-term growth trends of Scots pine and Siberian spruce were identified in the Komi Republic using empirical data from radial growth and height growth analysis in the forest-tundra transition zone, the northern taiga zone, the middle taiga zone, and the southern taiga zone. The statistically significant increase in height increment of 40% for Siberian spruce and 30% for Scots pine was identified for the whole Komi Republic. Within this region statistically significant increases were found in the middle taiga zone for Siberian spruce by 240%, Scots pine 140%, and in the northern taiga for Siberian spruce by 164%. Increases in the radial growth of Siberian spruce in the forest-tundra was 134% while in the northern taiga zone it was 35% over successive 50 year periods from 1901 to 1950 and from 1951 to 2000. In the middle taiga zone a 76% increase in radial growth of spruce was found (over 100 years), whilst in the southern taiga zone the changes were not statistically significant. The increase in radial growth of Scots pine in the northern taiga zone was 32%. In the middle taiga zone the radial growth increase in Scots pine was 55% and in the southern taiga zone the changes were not statistically significant.

During the last 20 years, a temperature increase was recorded by all the meteorological stations in Komi Republic; whilst levels of precipitation have been increasing for the last 40 years ago. This is reflected in the radial increment of Siberian spruce and Scots pine. Thus, climate change could partly explain the increased site productivity. The total variance explained by temperature varied from 22% to 41% and precipitation from 19% to 38%.

A statistically significant correlation between Normalized Difference Vegetation Index (NDVI) data and tree-ring width has been identified for the territory of the Komi Republic. The increased site productivity caused the increase in integrated NDVI values from June to August. This indicates that NDVI can be used as a proxy for estimating the forest growth trends of recent decades for generalization on a large scale. The increased site productivity in the southern and middle sub zones of taiga in the Komi Republic has been shown using NDVI data for 20 years. In the region under discussion, the distribution of the trends in NDVI data changes on a south-west to north-east gradient. NDVI data could be used to increase the spatial resolution of tree-ring width series. The decrease in precipitations was reflected in increase in NDVI. An increase in productivity reflected in NDVI data is maximal on the sites with increased temperature and decreased precipitations. Taking into account the relatively small influence of humans in the Komi Republic compared to Europe, the site productivity during recent decades has also increased in relatively untouched forests.

Keywords: radial increment, dendrochronology, climate change, height increment changes, site productivity, stem analysis.

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Цель работы: изучить долговременную динамику в приросте сосны (*Pinus sylvestris L.*) и ели (*Picea obovata* Lebed.) в изменяющихся условиях окружающей среды Республики Коми.

На основе анализа радиального и апикального прироста образцов, собранных в лесотундре, в подзонах северной, средней и южной тайги, в Республике Коми были идентифицированы тренды в увеличении прироста сосны и ели. В среднем для всей территории Коми статистически достоверное увеличение апикального прироста ели составило 40%,, а сосны - 30%. Самое большое статистически достоверное увеличение апикального прироста было выявлено для ели и сосны в подзоне средней тайги и составило, соответственно, 240 и 140%. В подзоне северной тайги апикальный прирост ели увеличился до 164%. Сравнительный анализ радиального прироста образцов деревьев за периоды 1901 – 1950 гг. и 1951 -2000 гг., показал значительное увеличение прироста древесины ели и сосны. Так, в лесотундре радиальный прирост ели увеличился на 134%, в то время как в подзоне северной тайги не более 35%. В подзоне средней тайги радиальный прирост ели увеличился на 76%. Однако, статистически достоверных изменений в радиальном приросте ели в подзоне южной тайги не обнаружено. При этом радиальный прирост сосны увеличился в подзоне северной тайги на 32%, а в подзоне средней тайги на 55%. Статистически достоверных изменений в радиальном приросте сосны в подзоне южной тайги также не обнаружено.

Анализ данных метеорологических станций Коми позволил выявить статистически достоверные тренды в увеличении как среднегодовой температуры воздуха за последних 20 лет, так и в увеличении годовой суммы осадков за последних 40 лет. Эти изменение климата, являются одной из причин увеличения прироста древесины обследованных деревьев. Статистический анализ данных показал, что 22 - 41% изменений радиального прироста деревьев связано с температурой и 19 - 38% изменений связано с количеством осадков. Установлена статистически достоверная корреляция между вегетационным индексом NDVI и шириной годичных колец. Увеличение прироста древесины вызвало увеличение интегрального значения вегетационного индекса NDVI с июня по август. Статистический анализ показал, что вегетационный индекс NDVI может быть использован для оценки изменения прироста древесины за последние десятилетия, позволяя генерализировать данные на больших площадях. В результате анализа данных вегетационного индекса NDVI за последние 20 лет установлено повышение продуктивности лесов в подзонах южной и средней тайги. При этом максимальное увеличение значений индекса отмечено на участках с увеличением температуры и сокращением осадков. В целом по Республике Коми тренды вегетационного индекса NDVI распределены с юго-востока на северо-запад. Вегетационный индекс NDVI может быть использован для увеличения пространственного разрешения дендрохронологических данных.

Ключевые слова: радиальный прирост, дендрохронология, изменение климата, изменения апикального прироста, продуктивность, анализ роста ствола.

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Eugene Lopatin had main responsibility in regard to all work done in Papers I – V. Prof. Taneli Kolström and Prof. Heinrich Spiecker managed the projects and helped in writing the manuscripts.

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1. INTRODUCTION

1.1. Climate change in the Komi Republic

According to the World Meteorological Organization (WMO, 2004) the global surface air temperature has increased since measurements were first recorded in 1861. During the 20th century the increase was more than 0.6°C. The rate of change for the period from 1976 to the present was roughly three times that of the last 100 years as a whole. Analyses of proxy data for the northern Hemisphere indicate that this increase in air temperature during the latter part of the 20th century is unprecedented during the last millennium. In the northern Hemisphere, the 1990s was the warmest decade and 1998 was the warmest year during the last 1000 years (WMO, 2004). Over the past 40 years, the snow pack has started to melt earlier each spring and the growing season in boreal forests has become longer (Groisman *et al.*, 1994; Brown, 2000).

Global climate change due to the greenhouse effect, strengthened by human induced gas emissions (use of fossil fuels, land-use changes, etc.), has become a clear phenomenon (IPCC 2007). It is predicted that climate change in northern Europe will reflect a doubling of CO_2 concentration by the year 2100. As a consequence, annual temperatures are likely to rise at a rate between 0.1 and 0.4^0C per decade. This effect will be greater in northern Europe than elsewhere, and may result in an increase of $2\text{-}4^0$C in the mean annual temperature and up to 6^0C in the winter temperature (IPCC, 2007). These changes in climatic conditions are likely to enhance the growth of boreal forests in direct response to physiological processes in trees to elevated temperature and CO_2 but also in the long-term through longer growing seasons and enhanced mineralization of nitrogen (Wang *et al.*, 1995; Kellomäki & Väisänen, 1997; Myneni *et al.*, 1998; Beerling, 1999; Mäkipää *et al.*, 1999; Saxe *et al.*, 2001; Stromgren & Linder, 2002).

All forests located in northwest Russia, including the regions of Archangel, Karelia, Komi, Vologda, Leningrad, Novgorod, and Pskov, produce a considerable amount of wood, an important raw material for the development of the forest industries and also for socio-economic development in these regions. Annually, northwest Russia produces 35% of the total industrial round wood of Russia, 63% of its pulp, paper, and cardboard, 39% of its plywood, and 27% of its sawn timber. Moreover, the forestry sector is one of the most important employers in the rural areas of the region, with there being approximately 120 000 employees in the industry, and 35 000 in forestry (Gerasimov and Karjalainen, 2005).

Recent findings clearly show that climatic changes are a major driving force behind growth variation, as well as changes in tree mortality (Spiecker, 1995, 1996, 2000; Raitio, 2000; Mäkinen *et al.*, 2001). Understanding how growth trends in the unmanaged forests of northwestern Russia respond to past and future global changes is very important for the development of the European forest sector as a whole. Additionally, forestry and forest industries are the backbones of the economies of the regions making up northwestern Russia. Furthermore, the ratification of the Kyoto Protocol by Russia in October 2004 created renewed impetus to reduce the uncertainty of the role of Russia's forests in carbon exchange with the atmosphere, to create transparent methods for monitoring terrestrial carbon stores and flux, and to inform the decision-making process managing carbon in forest ecosystems as a part of the overall national forest management strategy (Strakhov *et al.*, 2003). A major impediment to understanding terrestrial carbon exchange is the lack of field measurements covering the full range of natural variability of vegetation attributes (Krankina *et al.*, 2005).

There is clear evidence that during recent decades the climate in the Komi Republic has changed (V). Analysis of climate data for the Komi Republic (Table 1) showed that during the last 30 years the temperature increased by 0.48^0C for the entire region. If this trend was consistent over the last century then the increase was around 1.4^0C during the century. Mean annual precipitation during the last 30 years decreased by 2.2%. If this trend was consistent over the last century then the decrease was around 7.3% during the century. But the tendencies within vegetation complexes are different. All vegetation zones showed an increase in mean annual air temperature (Table 1). The mean annual precipitation increased in the middle taiga and the southern taiga. In other vegetation complexes a decreasing trend was identified. Borehole temperature measurements in the Komi Republic (Figure 1) also indicate a strong subsurface warming, reflecting changes in the trends of both surface air temperature and solid precipitation (Oberman & Mazhitova, 2004). Our hypothesis was that the local climate change is reflected in radial growth of Scots pine (*Pinus sylvestris* L.) and Siberian spruce (*Picea obovata* Lebed.) in the Komi Republic.

Table 1. Changes in mean annual air temperature and mean annual sums of the precipitation for 2 subsequent periods (1946-1975; 1976-2005) within the vegetation complexes in Komi Republic (III).

Vegetation complex	Change in mean annual air temperature between 2 periods, °C	Change in mean annual precipitation sums between 2 periods,%
Tundra	0.45	92.81
Forest-tundra transition zone	0.45	92.74
Mountain taiga forests	0.49	97.52
Northern taiga	0.44	97.38
Middle taiga	0.46	102.96
Southern taiga	0.59	103.36
Komi Republic (whole)	0.48	97.79

1.2. Identification of long-term trends in forest growth

The definition of growth trends in this study (I-V) is similar to used in previous research projects (Spiecker, 1996; Untheim, 1996; Kahle *et al.*, 2005). A growth trend can be defined as a persistent change in the average rate of growth. Growth trends within this project are indicated by long-term (more than 30 years) site-induced deviations of observed versus expected growth without taking into account site changes (Spiecker 1996). Long-term trends (period ≥ 30 years) in growth can be defined as a component of annual growth variation dominated by low-frequency variation.

In the Komi Republic there is no available growth rates data because of the lack of permanent research plots for the observation period (1901 – 2000). Because forest growth cannot be analyzed in a direct way, reconstructed radial and height increment of dominant trees is used in this study as an indirect measure of the past changes in the development of site productivity (potential of wood production) (Spiecker, 1999a). There are 3 methodological approaches chosen for the identification of long-term growth trends using the sampled trees (I-IV):

- chronology building,

- comparison of radial increment in similar cambial age at 1.3m height, and

- comparison of height increment in similar cambial age reconstructed from stem analysis

Building chronologies and evaluating long-term changes in forest growth using these chronologies is one of the most widely used methods of identifying forest growth trends (Spiecker, 1996; Mielikäinen & Sennov, 1996; Sinkevich & Lindholm, 1996; Spiecker, 1999b; Grudd *et al.*, 2002).

In papers I, II, IV, V raw radial increment series were also used, trying to avoid any bias introduced by indexation. Radial growth was analyzed within age classes to check whether there were any size differences between the radial increment of trees of the same cambial age in different periods (Briffa *et al.*, 1992; Becker *et al.*, 1994; Lebourgeois & Becker, 1996; Lebourgeois *et al.*, 2000). In this approach the radial increment series are divided into age classes so that only data derived from rings within a specific age range are averaged in succession. This gives tree-growth estimates within which the age of trees is held roughly constant through time (Briffa *et al.*, 1992). Data are averaged year by year, separately, for the two species. Two age classes were considered: 1-50, 51-100, confidence limits for each curve were estimated at p=0.05. Only the series derived from disks and cores where the innermost rings allowed the estimation of pith location and cambial age were included in the analysis.

To determine changes in tree height growth the concept of cohort comparison has been applied: differences in the average height growth curves between trees with different germination dates are used as indicators for changes in forest site productivity over time (Untheim, 1996; Kahle *et al.*, 2005). In this approach, similarly to the radial increment, the height growth series are divided into age classes.

1.3. Long-term forest growth trends in Europe

An attempt to identify forest growth trends in Europe was conducted in 1993-1996 (Spiecker, 1996, 1999b). The main purpose of the project was to analyze whether site productivity in European forests had changed during the last decades. It was possible to observe an increasing growth trend in most cases. However, in some studies (Mielikäinen & Sennov, 1996; Nöjd, 1996; Mäkinen *et al.*, 2001) a decreasing trend was reported at specific sites. The information about forest growth in the Kola Peninsula and Russian Karelia represented Russian studies in this European project. A negative trend was found in the Kola Peninsula which can be explained by the non-ferrous smelter in the area (Nöjd, 1996) while a positive trend was found in the Saint-Petersburg region (Mielikäinen & Sennov, 1996). Studies in Karelia showed that no definite conclusions can be made regarding site productivity changes in the area (Sinkevich & Lindholm, 1996). These study areas represent only 17% of the forest area of northwestern Russia. Previous studies on growth trends, however, were conducted mostly in secondary even-aged forests in Europe (Spiecker, 1996). Studies of growth trends in pristine uneven-aged forests may provide a better understanding of the reaction of forest ecosystems to global climate change. It is especially important for modeling of future forest growth, since usually the effects of forest management are well understood.

1.4. Impact of climate change on forest growth

At boreal latitudes the warmer temperatures may affect the rates of both the growth of trees and ontogenetic development. Air temperature affects the onset, distribution and duration of growth over the spring and summer, and an increase in temperature is likely to affect the timing of bud burst in trees by altering the amounts of chilling and forcing temperatures required to induce bud burst (Kramer, 1994). In the boreal zone the diameter growth correlates with temperature during the growing season (Briffa *et al.*, 1988, 1992, 2004; Lindholm, 1996; Miina, 2000; Linderholm *et al.*, 2003), and therefore an earlier onset of growth is expected under conditions of elevated temperature, with concurrent increases in the length of the growing season and wood production (Beuker, 1994). This would be expected especially when the growth response is not limited by other environmental factors or nutrient availability.

The case studies in the Komi Republic (Drobyshev *et al.*, 2004) show that the latewood width of Scots pine (*Pinus sylvestris* L.) correlates positively with the temperature in April-May and July-August of the current growth season and with the July-August precipitation of the previous year. Earlywood width was positively affected by the precipitation in May and November of the previous year (Drobyshev *et al.*, 2004). This accords with the observation which shows that the growth of conifers in the boreal zone positively correlates with growing season temperatures (Briffa *et al.*, 1988). Physiologically, this results from the fact that in the boreal zone, the carbon gain of the trees is typically limited by the temperature during the growing period. As long as water is not a limiting factor for the radial growth, increased carbon gain in the tree ring should positively correlate with increment. One possible hypothesis could be that increased temperature results in more carbon being assimilated by the tree and as a result trees will grow faster. In this case there are two scenarios for this possible development:

- trees will be larger as there will be changes in height, shape and thickness of stems as a result of carbon accumulation and higher production;

- trees will grow faster but the increased growth could be limited by higher mortality rates with no net change in the production and carbon accumulation.

The experiments of growing trees in chambers with elevated CO_2 and temperature showed that the radial growth of trees is significantly increased in response to elevated CO_2, pointing to enhanced wood production in the future. Wood properties were significantly affected by elevated temperature or elevated CO_2 (Kilpeläinen *et al.*, 2003, 2005). The expected climate change may imply changes in the material properties of wood in the future, because earlywood and latewood width, mean wood density, earlywood density, fiber length and the chemical composition of the wood (extractives and cellulose content) were significantly affected by elevated temperature or elevated CO_2 (Kilpeläinen *et al.*, 2005).

A dramatic change, however, in the sensitivity of hemispheric radial tree-growth to temperature forcing has become apparent during recent decades, and there is additional evidence of major increases in tree-growth in the northern boreal forests (and hence, probably, ecosystem biomass), most clearly over the last century (Briffa *et al.*, 1998a, 1998b). On the other hand, the question has been raised as to whether increasing temperatures disrupt the regulatory mechanisms of trees so that exploitation of the longer growing season remains incomplete and risk of frost damage increases (Saxe, 2000). It has also been suggested that warmer temperatures stimulate the growth of existing meristems/organs so that the duration of the growth phases may be shortened (Morison & Lawlor, 1999).

From the forest management point of view, the changes in tree growth and stand productivity under conditions of changing climate and the consequent changes in the material properties of the wood imply that current forest management practices have to be modified in the future to respond to the expected climate change and to obtain the desired wood quantity (Matala *et al.*, 2003, 2005) and quality (Kilpeläinen *et al.*, 2005).

1.5. Aims of the study

The main objective was to investigate the long-term growth dynamics of Scots pine (*Pinus sylvestris* L.) and Siberian spruce (*Picea obovata* Lebed.) in the Komi Republic, in the changing environment of the last hundred years (1901-2000). The specific objectives were:

I. compare different tree-ring based methods for the identification of long-term trends in the growth of Siberian spruce and Scots pine (paper I);

II. identify the long-term trends in radial and apical growth of Siberian spruce and Scots pine (papers I, II, III);

III. analyze the impact of climate change on radial growth of Siberian spruce and Scots pine (paper IV);

IV. map the changes in forest productivity in the Komi Republic during the period 1981 to 2001 (paper V).

The Komi Republic, which is the largest administrative region of northwestern Russia (forest area of the Republic is 33% of total Northwestern Russia's forest area), was selected for the assessment of long-term forest growth trends. Komi is situated at the eastern boundary of the European part of Russia, in the boreal region, where large areas of natural forest still exist.

The hypothesis of this study is that forest site productivity has changed in the Komi Republic during the last decades as a result of climate change.

2. MATERIALS AND METHODS

2.1. Study area and field sampling

Komi is situated at the eastern boundary of the European part of Russia (Figure 1), in the boreal region where large areas of natural forest still exist. Climatically, the Republic lies within the Arctic, Atlantic-Arctic and Atlantic-Continental zones. The annual average air temperature during the last century varied between $+1^0$C in the southern part of the Republic and -6^0C in the northern part, with the growing season (days with daily average air temperature above $+10^0$C) according to the Russian classification system (Galenko, 1983) being between 10 and 45 days respectively. Annual rainfall decreases from 700 mm in the south to 450 mm in the north. The accumulation of thick snow cover (70-80 cm) is a characteristic for the winter period which lasts between 130 – 200 days (Stolpovski, 1997).

Annual precipitation sums and air temperature means from 18 climate stations were obtained from the Center of Meteorology and Environment Monitoring of the Komi Republic and also from public archives (Vose et al. 1992; Razuvaev et al. 1995) (Figure 1).

The material was collected along a transect from the south of Komi (south taiga sub-zone of boreal forests) to the Arctic spruce timberline (IV). The sampled stands represented similar altitudes. The study's stands were grouped into 'sub-zones' according to their geographical position in the taiga sub-zones of boreal forests (Table 2, Figure 1).

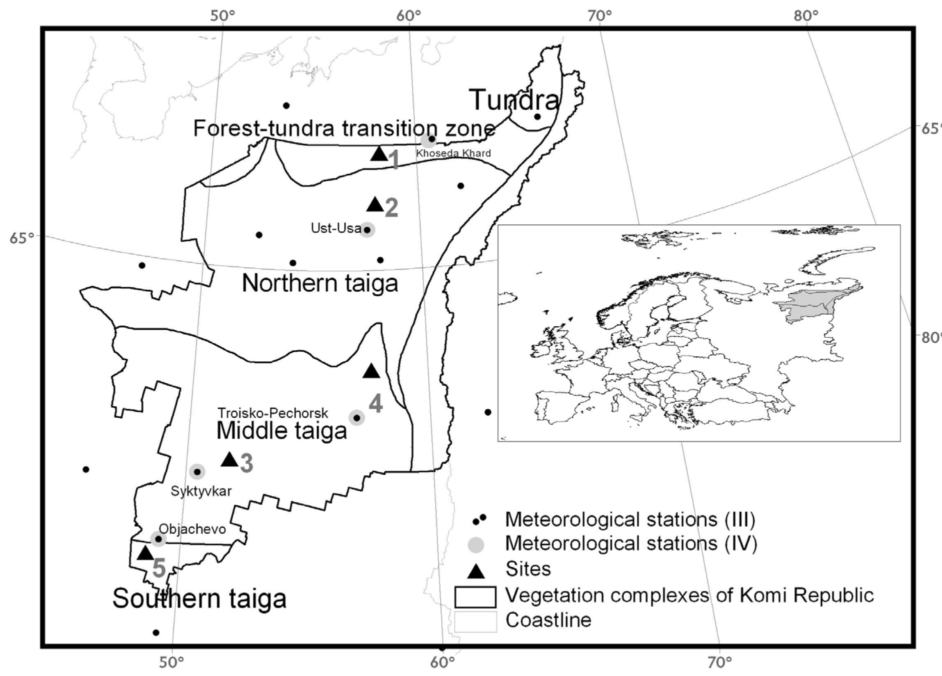

Figure 1. Location of sampled stands and sub-zones of taiga boreal forests. Borders of vegetation complexes according to Kozubov & Degteva (1999). Numbers refer to the sites (see Table 2).

Table 2 Number of trees collected in the Komi Republic in 2003-2005 and used in the studies I – V (sp – Siberian spruce; pi – Scots pine).

Site	Forest zone	Location	I		II		III		IV		V	
			sp	pi	sp	pi	sp	pi	sp	pi	sp	pi
1	Forest - tundra transition zone	66^{0}41'260" N 56^{0}49'142" E	12		16		16		16		14	
2	Northern taiga zone	65^{0}59'697" N 57^{0}48'820" E	14	14	16	20	16	20	16	20	16	20
3	Middle taiga zone (west)	61^{0}44'834" N 50^{0}34'910" E	23	41	40	45	20	25	40	45	40	45
4	Middle taiga zone (east)	63^{0}25'294" N 57^{0}57'597" E					26	21	51	21	51	17
5	South taiga zone	60^{0}33'615" N 49^{0}26'945" E	4	10	30	22	30	22	30	22	30	28
Total			53	65	102	87	108	88	153	108	151	110

During the sampling of the trees coordinates of the sampling sites were measured using GPS (accuracy of 30 m).

The radial and height increment of trees were collected in 2003, measured and used in study I. Then, after preliminary analysis additional trees were sampled in 2004 at the same sites. Additionally collected samples were used in study II. Due to insufficient data for stem analysis (study III) the model trees were harvested in 2005. Then combined dataset from studies I – III were used in studies IV and V.

There is no available prior data, in the Komi Republic, on forest growth because of the lack of permanent research plots within the observation period. As forest growth cannot be analyzed in a direct way, reconstructed radial and apical increment of dominant trees is used in this study as an indirect measure of changes in the development of site productivity in the past (Spiecker 1999a).

In the procedure for site selection the main aim was to find representative site types and at the same time exclude possible forest management or any other human impact in the past. To obtain information about changes in site productivity trees of different ages from comparable sites were selected.

The sites were selected using GIS datasets of forest management units, old forest inventory maps and satellite images TERRA ASTER (scene size 60x60 km) with a spatial resolution of 15 m. Sites with a low productivity index (class 5, according to the classification system for Russian forest productivity) represent 70% of the forest area of Komi Republic (Kozubov & Taskaev 1999). Therefore the analytical approaches used in this study helped to generalize the results from different geographical areas. Differences in site characteristics, such as exposure, soil properties, topography or vegetation development, are assumed to have been averaged out accordingly. To obtain the information about changes in site productivity trees of different ages from comparable sites were selected. The stands were selected according to the following criteria for site conditions:

- spruce or pine dominating stands (proportion of species composition was close to equal);
- low site index (class 5, according to the Russian forest productivity classification system);
- multistoried mature stands represented by trees of 3-5 different age classes.

In most parts of Komi, forest stands are represented by trees of several age classes (Havimo *et al.* 2007). Therefore, sample trees were chosen from trees not dominated by older trees but rather located in openings within the stand. The sample trees were expected to reveal homogeneity in their tree-ring pattern; they showed no obvious signs of near-neighbor competition or forest management. Trees were chosen from different diameter classes, healthy looking with straight, unbroken stems and a regular shaped crown. Mature dominant trees without visible signs of damage were selected as sample trees. A large crown ratio and the occurrence of relatively thick dead branches or large knots in the lower part of the bole have been used as indicators of the dominant crown class status of the tree in the past (Kahle et al. 2007). The selected trees represented similar site conditions but different tree ages. The sample trees in the stands were expected to have a common growth trend, which was influenced by a large portion of climatic effects and other factors which differ among individuals and from site to site. At each site an averaging process, during the building of the mean radial and apical growth curve, helped to minimize the influence of other factors.

Prior to felling, for visual assessment of the tree ring pattern, the core of the tree was extracted with an increment borer. This allowed the exclusion of trees affected by competition in the past. Disks were cut at 1 or 2 meter (or a few centimeters higher or lower if a branch or something else made ring measurement difficult) intervals from the stem using a chain saw. The north direction was marked on the disks.

To determine changes in tree radial growth the concept of cohort comparison was also applied: differences in average radial growth curves between trees with different germination dates were used as indicators for changes in forest site productivity over time. The radial and apical growth series were divided into age classes so that only data derived from rings within a specific age range were averaged. This gives tree-growth estimates within which the age of trees is held roughly constant over time (Briffa *et al.* 1992). The target ages of the stands to be selected were 50 years for the young (1951-2000) and 90 years for the older (1901-1950) trees and age limits should be between a minimum of 30 and maximum of 130 years. These age limits were set in order to exclude juvenile and senescent developmental stages during which trees might be less responsive to environmental stimuli (Kahle *et al.* 2007).

2.2. Remote sensing data

The Normalized Difference Vegetation Index (NDVI) extracted from remote sensing is an excellent tool for monitoring vegetation status and its temporal dynamics. However, the creation of NDVI temporal series is problematic due to difficulties related to the non-uniformity of satellite time-series that can restrict satellite use for the temporal analysis of vegetation cover. Nowadays, different NDVI global data series of contrasted calibration reliability are available from AVHRR data (PAL and GIMMS NDVI) that have been widely used in ecosystem monitoring (Mikkola 1996; Gaston et al. 1997; Young & Anyamba 1999; Pelkey et al. 2000; Lovell & Graetz 2001; Young & Wang 2001; Lafont et al. 2002; Al Bakri & Taylor 2003; Dong et al. 2003; de Beurs & Henebry 2004; Tateishi & Ebata 2004; Vicente-Serrano et al. 2004).

The PAL-NDVI database (available at http://daac.gsfc.nasa.gov), with monthly NDVI data from 1981 to 2001, was used for mapping the changes in site productivity (V). The calibration of this series has been meticulous, and much effort has been expended to develop post-launch calibration coefficients, which were tested in areas without vegetation cover where high NDVI temporal stability is assumed. Moreover, the homogenization of the series has been checked with good results (Kaufmann *et al.*, 2000). The spatial resolution of the PAL-NDVI database (8 km grid cell size) is generally enough for estimating the changes in site productivity in conditions where the logging activities could be carried out. Nowadays the maximum allowed area of clear-cut in Russia is 50 ha, which is less than 1% of the PAL-NDVI pixel. Forests dominate Komi covering more than 80% of the land, therefore, the NDVI values of individual pixels reflect the value of the forest cover with a very high probability.

Mean monthly NDVI sums from June to August were used for calculating the correlation coefficients between NDVI and standardized tree-ring series for the period 1982 to 2001 (V).

2.3. Data analysis

The approach chosen in this study was to combine both dendrochronological and geostatistical methods. Using dendrochronological methods (I-IV) growth trends during the last century were studied. The distribution of trends in site productivity changes during last the 20 years of the study period was mapped using remote sensing images (V).

There are two methodological approaches chosen for the identification of long-term growth trends using the measurement of tree rings from the sampled trees (I, II):

- chronology building,
- comparison of radial increment in similar cambial age

Building chronologies and evaluating long-term forest growth trends using those chronologies is one of the most widely used methods of identifying forest growth trends (II). The comparison of radial increment in similar cambial age allowed the verification of whether there were any size differences between the radial increment of trees of the same cambial age in different periods (II). Two age classes were considered: 1-50, 51-100, confidence limits for each curve were estimated at p=0.05 based on the number of sampled trees using Microsoft Excel. The radial increment series were also summarized for the two equal periods to estimate changes in long-term cumulative increment (Table 2, II). The statistical significance of the differences between the curves was tested by comparing the confidence limits for means estimated at $p=0.05$ based on the number of measured tree rings (Figure 6, Figure 7, II).

The aim of the height growth assessment (III) was to obtain information about the speed of height development of trees starting to grow during different periods of time. The approach applied here was the reconstruction of diameter and height growth by means of a stem analysis technique. It was possible to reconstruct the height of trees at similar cambial year but different absolute year of germination. The comparison of reconstructed height growth curves will give us information about the speed of height development. Mean apical growth curves were calculated for 4 zones of boreal forests on 2 subsequent 50-years periods starting from 1900, confidence limits for each curve were estimated from standard deviation at $p=0.05$ (III).

The method used to identify major climatic factors influencing the radial growth of Siberian spruce and Scots pine along a latitudinal gradient in northwestern Russia is dendroclimatic analysis (IV). To identify long-term climate trends within the forest zones, the absolute differences between mean annual values for subsequent 30 year periods were calculated (III). The period of 30 years was selected due to the availability of meteorological data, based on the balance between the number of stations and length of records. Then the differences were spatially interpolated using ordinary Kriging method (III). The mean values of the differences within boundaries of forest zones where calculated using ArcGIS Spatial Analyst (Table 1).

Trends in PAL-NDVI pixels were identified by means of nonparametric correlation coefficients (p-Spearman) using annual sums of NDVI values from June to August (V). The values of p indicate whether there are significant trends in the development of vegetation. Positive and significant values indicate an increase in the vegetation biomass, and negative values indicate a regressive trend. Trends were considered significant when $p < 0.1$. The trends were assessed in PAL NDVI database for the territory of the Komi Republic (subset of 17 995 pixels).

The tree standing volume annual increment of Siberian spruce and Scots pine (Table 3) was estimated only for the subzones of taiga with a statistically significant increase in apical increment. The single tree volume was calculated by applying the simplified formula $v=g*h*0.5$, where g – basal area, h – height, 0.5 – form factor (Köhl et al. 2006).

3. RESULTS

3.1. Methods for long-term forest growth trends identification

As there were no comparable forest inventory data (based on constant forest area and species composition) available with an annual resolution for the last 100 years, the dendrochronological approach was chosen to identify long-term forest growth trends in the Komi Republic.

From the methodological point of view, for identifying changes to site productivity, the comparison of height increment is the better approach, because height growth of dominant trees is relatively independent of stand density (Lanner, 1985; Magnussen & Penner, 1996). However, at the same time the height increment of the current year is more strongly correlated with the radial increment of the preceding year (Mäkinen, 1998) i.e. height growth probably contains a one year bias partly due to the fact that height growth generally stops much earlier in the growing season than radial growth. The disadvantage of this method is the high financial costs for collecting and measuring sufficient samples, as well as the fact that it is a destructive method.

The interpretation of trends in tree-ring series is neither easy nor unequivocal. The main problem with their interpretation is the method of indexation (Innes, 1991). The method for identifying long-term growth trends through building chronology with standardization of raw tree ring measurements for the whole sub zone of taiga contains some limiting factors. At present it is impossible to find an ideal curve that removes variation in the radial increment caused by ageing, competition, stand dynamics reflected in tree rings while at the same time preserving the long-term climate change signal. Furthermore, it is even more difficult to find an individual curve for each separate factor. However, the method could be used in case the number of sampled trees is high and those limits could be minimized due to the process of averaging. In this study the attempt to remove low frequency variation caused by the above mentioned factors was achieved, but with the understanding that standardization partly removes the long-trend growth trends which belong to low- and medium-frequency growth variation i.e. periods of more than 30 years.

The method for calculating the sums of radial increment for the equal intervals (II, Table 2) contains a potential bias, which is dependent on the size of the estimation period (i.e. in case of global warming the selection of different time intervals will influence the result), age structure of sampled trees, and the bioecological properties of the tree species. Calculating the sum of the annual radial increments for the same periods (II, Table 2) is far from an ideal indication of the total biomass production, not taking into account the possible changes in total wood density which could compensate the volume changes. The combination of methods for estimating long-term growth trends (II, Table 3) should be used in the future with emphasis on estimating height increment and evaluating ring density.

3.2. Long-term forest trends in growth of Siberian spruce and Scots pine

Using radial (I-II) and height growth (III) it was possible to attain positive long-term trends of growth in Scots pine (*Pinus sylvestris* L.) and Siberian spruce (*Picea obovata* Lebed.) in the Komi Republic. The increase in the radial growth of Siberian spruce in the forest-tundra was 134% and 35% in the northern taiga zone (this was calculated comparing the long term mean growth for 50 year periods of 1901 to 1950 and 1951 to 2000). In the middle taiga zone a 76% increase in radial growth was found, whilst in the southern taiga zone the increase of radial growth was measured to be 53%. The increase in radial growth of Scots pine in the northern taiga zone was 32%. In the middle taiga zone the radial growth increase was 55% and in the southern taiga zone 37%.

The apical growth of Scots pine (108 trees, 529 disks) and Siberian spruce (88 trees, 423 disks) was analyzed using stem analysis techniques (III). Mean apical growth curves were calculated for 4 zones of boreal forests for 2 consecutive 50-years periods starting from 1900. A statistically significant increase in height increment of 40% for Siberian spruce and 30% for Scots pine was identified for the whole Komi Republic. Within this region statistically significant increases were found in the middle taiga zone for Siberian spruce by 240%, Scots pine by 140% while in the northern taiga Siberian spruce increased by 164% (III, Figure 2).

Changes in radial and apical growth are presented in Table 3. Using collected samples we estimated that the statistically significant annual increment of single tree standing volume of Siberian spruce in the northern taiga zone increased by 6% and in middle taiga zone by 19%. The annual increment of single tree standing volume of Scots pine in the middle taiga zone increased by 9%. It is not possible to make conclusions about the long-term changes in volume increment in the forest-tundra zone and southern taiga zone using the collected samples.

Table 3. Statistically significant long-term growth trends in growing stock increment per tree of Siberian spruce and Scots pine in the Komi Republic estimated for the equal intervals.

Forest zone	Parameter	Northern taiga zone	Middle taiga zone (west)
		Site 2	Site 3
Siberian spruce	D, cm 1901-1950	5.842	10.116
	H, m 1901-1950	4.000	6.000
	V, m3 1901-1950	0.005	0.024
	D, cm 1951-2000	7.872	17.822
	H, m 1951-2000	9.300	21.000
	V, m3 1951-2000	0.023	0.262
	V mean annual change, %	**6.4**	**19.7**
Scots pine	D, cm 1901-1950		11.964
	H, m 1901-1950		7.000
	V, m3 1901-1950		0.039
	D, cm 1951-2000		18.524
	H, m 1951-2000		17.000
	V, m3 1951-2000		0.229
	V mean annual change, %		**9.6**

3.3. Impact of climate change on forest growth

The identification of major climatic factors influencing radial growth along a latitudinal gradient in northwestern Russia using dendroclimatic analysis showed that changes in temperature and precipitation are reflected in the radial increment of Siberian spruce and Scots pine (III). Thus, climate change could partly explain the increased site productivity. The total variance (Figure 2) explained by temperature varied from 22% to 41% and precipitation from 19% to 38%. The significant climatic parameters for radial increment in the Komi Republic were identified, but the relations between temperature and precipitation in explained variance changes over the time (III). Taking into account that the trees were samples from remote pristine forests we conclude that the main causes of increased height increment are decreased precipitation (7.3% during the 20th century) and increased temperature (1.4^{0}C during the 20th century).

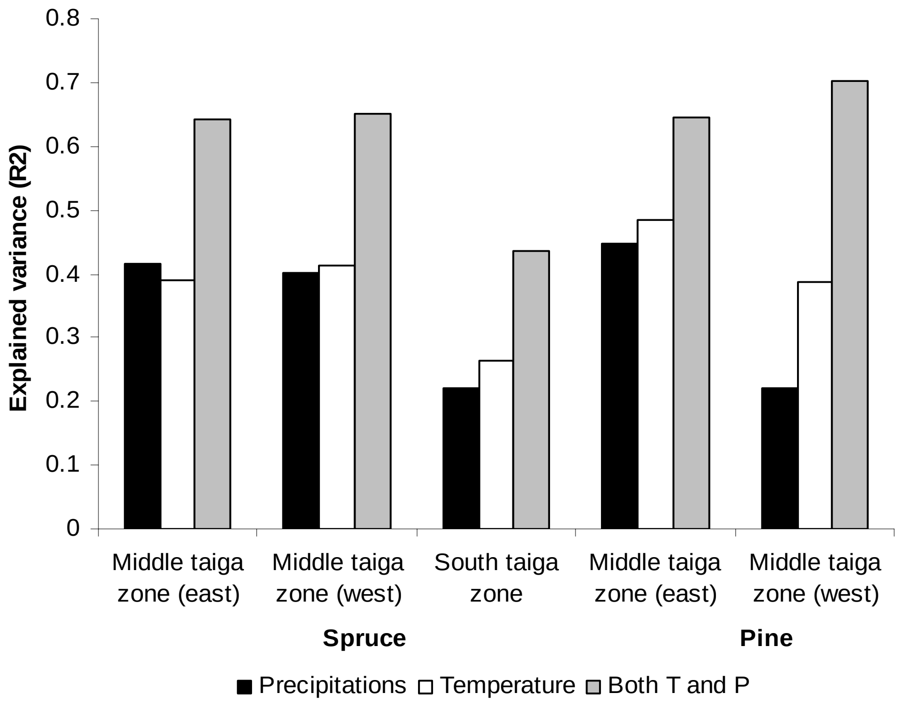

Figure 2. Amount of variance (R^2) explained by temperature (T) and precipitations (P) for the period 1954-2003.

3.4. Spatial distribution of changes in site productivity

In this work the evolution of the vegetation in the Komi Republic from 1982 to 2001 was analyzed using NOAA AVHRR PAL time series. A statistically significant correlation (adjusted R^2=0.44-0.59) between NDVI data and tree ring width (261 living trees) was identified for the Republic. The increased site productivity is reflected in the increase of integrated NDVI values from June to August. This allows the NDVI to be used as a proxy for estimating forest growth trends for recent decades. A positive and significant trend in the NDVI data was identified from 1982 to 2001, coinciding with an increase in site productivity in the study area (Figure 3). The decrease in precipitation coincides with an increase in site productivity (highest r^2 was 0.71). The increase in productivity reflected in the NDVI data is highest on the sites with increased temperature and decreased precipitations. In the Komi Republic the distribution of the trends in NDVI data changes on a south-west to north-east gradient. NDVI data could be used to increase the spatial resolution of tree ring width series. Taking into account the relatively small role of human activity in the Komi Republic compared with Europe, the site productivity during recent decades also increased in the relatively untouched forests (V).

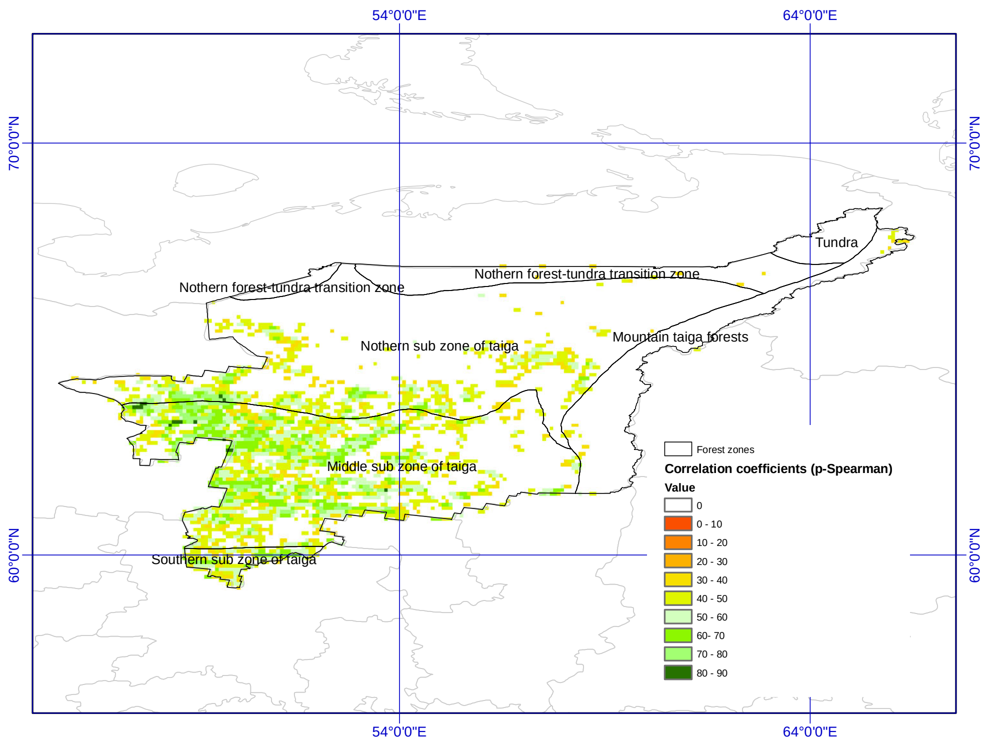

Figure 3. Spatial distribution of trends in NDVI data from 1982 to 2001.

4. DISCUSSION

4.1. Contribution and synthesis of the research

The long-term growth dynamics of Scots pine (*Pinus sylvestris L.*) and Siberian spruce (*Picea obovata* Lebed.) in the Komi Republic in the currently changing environment was studied on different spatial and temporal scales. The tree-ring based methods for the identification of long-term trends in the growth of Siberian spruce and Scots pine were compared (II). Based on this result the statistically significant trends in radial and height increment were identified. This allowed the estimation of the changes in mean annual volume increment. The increase in standing volume in the middle taiga is 19% for Siberian spruce and 6% for Scots pine, in the northern taiga 9% for Siberian spruce. Then the impact of climate change was identified, showing that the influence of temperature and precipitations on the changes of Scots pine and Siberian spruce growth varies from 19% to 41%. Using the collected samples it was shown that climate change caused 60% of the mean annual volume increment in the middle taiga.

The causes of the increased volume are decreased levels of precipitation (7.3% during the 20th century) and increased temperature (1.4^{0}C during the 20th century). The causes of the increased growth of conifers were also confirmed by independent remote sensing observations from satellites.

This research allowed the identification of the dynamics in conifers' growth in the Komi Republic and the share of climate change in those changes. This information could be used for modeling the growth of Scots pine and Siberian spruce stands in the middle taiga zone of northwestern Russia. Based on results of the modeling and the analysis of current forest management rules the proposals for the adaptation of forest management practices could be developed in order to achieve sustainable forest management within this region. The results of this study could be also used for clarifying the role of northwest Russia's forests in carbon balance under different scenarios.

4.2. Relevance

The topic of the research is relevant for many reasons. First, the importance of northwestern Russia for the wood and wood based products supply for Europe. In 2002, in northwest Russia, approximately 40.3 million m^3 was harvested, of which 35% was exported (Gerasimov & Karjalainen, 2006). Secondly, there is still uncertainty regarding the role of Russia's forests in carbon exchange with the atmosphere (Strakhov *et al.*, 2003) and its dynamics due to climate change. A major impediment to understanding terrestrial carbon exchange is the lack of field measurements covering the full range of natural variability of vegetation attributes (Krankina *et al.*, 2005). Thirdly it helps to improve the understanding of tree growth in unmanaged boreal forests under the changing climate conditions. Finally, the knowledge of the absence or presence of trends could be used by companies in the decision-making process regarding the leasing of forests for 99 years. Therefore, there obviously was a need for information about forest growth trends in the Komi Republic.

4.3. Validity and reliability

The validity of the research can be evaluated by comparing the results to those obtained in earlier studies. Forest growth trends in Europe (Spiecker et al., 1996) combined with the results on radial increment from our studies are shown in Figure 4. Comparisons of trends in the Komi Republic with trends at the same latitude (i.e. Finland, Sweden, and Norway) show that there are different forest growth trends from this study. The explanation for this difference could be the different climate conditions. In Europe increasing (Spiecker, 1996; Kahle *et al.*, 2005) and decreasing (Mielikäinen & Sennov, 1996; Nöjd, 1996; Mäkinen *et al.*, 2001) growth trends have been reported. In our study no statistically significant ($p<0.05$) negative trends in height growth were found. For the whole region an increasing trend in height increment was identified.

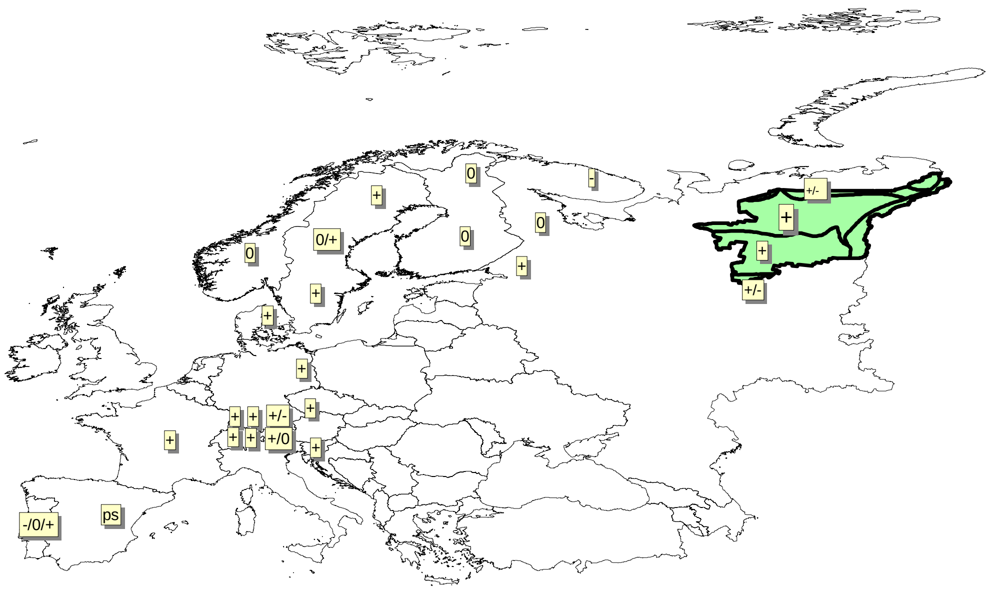

Figure 4. Map showing the long-term forest growth trends in Europe according to Spiecker et al. (1996) and this study in the Komi Republic. "Trend": + positive, - negative, 0 – no trend, ps – preliminary study.

The absence of statistically significant trends in height growth in the southern taiga zone, the forest-tundra transition zone and for Scots pine in the northern taiga could be explained by a relatively low number of samples necessary for the clear estimation of confidence intervals. It was shown for northwestern Russia that limited availability of nutrients, such as Ca, may constrain the response of trees to a more favorable climate (Lawrence *et al.*, 2005). Therefore possibly decreased soil fertility could also explain the absence of changes in forest growth.

The response of high frequency variation in radial increment of pine to summer temperatures was reported for different sites in northern Europe (Lindholm, 1996; Kalela-Brundin, 1999; Lindholm & Eronen, 2000; Miina, 2000; Kirchhefer, 2001; Helama *et al.*, 2002; Linderholm *et al.*, 2003). This pattern was also found in our study (i.e. Scots pine in western part of the middle taiga zone), but without the strongest response to the July temperature. The possible explanations are the selection of sites in multistoried forests and the influence of the continental climate. The general decrease in the amount of variance explained by climate is in accordance with the findings on reduced correlations between growth and temperature in subarctic Eurasia (Vaganov *et al.*, 1999).

Several studies (Riebsame *et al.*, 1994; Myneni *et al.*, 1998; Vicente-Serrano *et al.*, 2004) have shown a recent increase in vegetation cover in different ecosystems around the world adducing that the principal cause is the rise in temperature and precipitation. In the Komi Republic the increase in productivity reflected by the NDVI data is highest on the sites with increased temperature and decreased levels of precipitation (adjusted R^2=0.71). The absence of a statistically significant correlation between NDVI and temperature in the Komi Republic could be explained by a excess of precipitation in the boreal forest zone. The territory of Komi is characterized by surplus moisture, mean annual evapotranspiration is significantly lower than annual rainfall (Galenko, 1983).

The retrospective analysis of the diameter and height growth of trees is a method which is commonly used in forest growth trend studies. However, not many studies have been conducted in untouched boreal forest stands. Reconstructing the long-term growth of, and productivity, in pristine boreal forests is a research challenge, since most of these forests are uneven-aged and highly structured. Research concepts developed for the retrospective growth analysis in even-aged forests can only be applied under these conditions if certain prerequisites are fulfilled and certain assumptions are valid. The selection of sample trees is a rather crucial step in the analysis of growth trends (I, II, III). The result of the growth trend analysis is biased if the old sample trees, which are used as a growth reference for the young sample trees, have a different growth history with respect to, for example, the development of crown class and competition status than the younger sample trees.

Since the trees have been selected according to their current crown and competition status the probability is high that some of the older sample trees are “social climbers” which started with low growth rates and whose growth accelerated their later. To reduce this probability prior to felling, for the visual assessment of the tree ring pattern, the core of the tree was extracted with an increment borer. This allowed the exclusion of trees affected by competition in the past and preserving the trees with a similar development history.

The general weakness of this research (I - IV) is the low number of sampled trees. Ideally it would be good to have at least 200 trees (based on Expressed Population Signal statistics, IV) per taiga zone of each species, from which disks will be cut at 1 m intervals and at the same time equally distributed between age classes. This would result in processing at least 33 600 tree disks. Nevertheless, this is a typical weakness in studies on forest growth in relatively remote territories.

4.4. Possibilities and limitations for generalization

The limits of this study for the climate reconstruction are the potential bias due to the different ages of the sampled trees. It was shown that the climatic signal is maximized in older trees and the higher amount of noise is present in younger trees (Carrer & Urbinati, 2004). But from the standpoint of forest management, for the purpose of understanding factors influencing radial increment of trees in the forest, represented by different age classes, this bias is not important. Another limit of using tree rings is the spatial representativeness of the selected stands for different taiga sub zones. It is important to understand changes in forest productivity not only on a temporal scale, but also in spatial terms. Currently, due to the low accessibility and huge size of the territory, it is impossible to create systematic sample plots in the Komi Republic. Therefore, to make conclusions about spatial response distributions requires the use of other methodological approaches.

The limitations of tree-ring analysis for the assessment of the growth trends for such a relatively large territory were solved by using a combination remote sensing data and tree-ring analysis. This also led to the understanding that the major increase in growth is within the middle taiga zone (V). The disadvantage of this approach is the relatively short time series of remote sensing data and using this information one can draw conclusions more on medium-term trends (20 years) than for long-term trends (30 years and more).

Additionally current models of vegetation dynamics using the NDVI time series perform poorly for high-latitude environments. This is partly due to the specific attributes of these environments, such as the short growing season, long periods of darkness in winter, persistence of snow cover and dominance of evergreen species, but also to the design of the models (Beck *et al.*, 2006). It was shown in previous studies (Rees *et al.*, 2002) that NDVI is a poor indicator of taiga forests where dark coniferous trees dominate and where space borne imagery acquired from sparse forests of predominantly narrow-crowned columnar trees tend to be dominated radiometrically by the understorey. Therefore, the changes in site productivity in the northern taiga zone and the Ural Mountains are not statistically significant, however, our tree-ring based studies (Paper I-IV) showed the significant increase in site productivity in the northern taiga zone. Therefore, we conclude that NDVI data could be used on a large scale for identifying the growth trends in the southern and middle taiga sub-zones.

Recently, however, a new method for monitoring vegetation activity at high latitudes using Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI was presented (Beck *et al.*, 2006). This method estimates the NDVI of the vegetation during winter and applies a double logistic function, which is uniquely defined by six parameters that describe the yearly NDVI time series. Therefore we think that it is possible to use NDVI as a proxy for the estimation of changes in site productivity, applying different models for NDVI calculation for the northern taiga and forest tundra transition zone than for the southern and middle taiga. Combining data from AVHHRR sensor with MODIS could provide series of NDVI spanning 27 years.

Another limitation of NDVI as a proxy for the whole region is the relatively low correlation coefficients between tree-rings and NDVI (compared with Wang *et al.*, 2004). This could be due to the fact that growth measured at an individual site may not represent the growth patterns of an entire region. In the Komi Republic it is a mixture of spruce and pine. The mixture effects among them, therefore, will make the NDVI data lose the ability as a proxy for the estimation of forest growth according to the species.

Utilities of the summer NDVI sums could be problematic, because the NDVI will be saturated during the summer season in some dense forest regions, which will make the NDVI lose the ability to identify the changes of biomass. The forest canopy density in Komi is relatively low, compared with broadleaved and tropical forests. The temporal NDVI data (Paper V, Fig. 5) show the fluctuations on an inter-annual scale, which never reach the maximum NDVI value. Consequently in the boreal forest zone, changes in NDVI reflect changes in forest growth.

4.5. Needs for further research

To improve the knowledge on forest growth in Northwestern Russia further research is needed. This research tried to document and map the historical changes in forest growth. But in order to project the future development and implementation of adapted practices to forest management the following questions should be answered:

1. What are the changes in wood anatomy structure of tree rings formed under different climate conditions and how this could influence the wood quality?

2. Are there any differences between the response of individual trees and groups of trees to changing climate?

3. What will be the wood balance in northwestern Russia in the future under the different climate change scenarios?

4. What kind of measures should be implemented in forestry legislation in Russia to maintain sustainable forest management under the global climate change?

5. Is it possible to map forest growth trends using medium resolution satellites (e.g. Landsat) where the image have existed since 1974?

6. What are the trends in tree mortality?

5. CONCLUSIONS

I. Statistically significant increase in height increment of 40% for Siberian spruce and 30% for Scots pine was identified for the whole Komi Republic (33% of Northwestern Russia forested and 4% of whole Russia forested area) during the last 50 years.

II. Climate change could partly explain the increased site productivity. The total variance explained by temperature varied from 22% to 41% and precipitation from 19% to 38%.

III. The main causes of increased height increment are decreased precipitation (7.3% during the 20th century) and increased temperature (1.40 °C during the 20th century).

IV. The statistically significant increment of standing volume of Siberian spruce in the northern taiga zone increased by 6% and in the middle taiga zone by 12%. The increment of standing volume of Scots pine in the middle taiga zone increased by 7%. It is not possible to make conclusions about long-term changes in volume increment in forest-tundra zone and southern taiga zone using the collected samples.

V. A statistically significant correlation between NDVI data and tree-ring width has been identified for the territory of the Komi Republic.

VI. The NDVI can be used as a proxy for estimating the forest growth trends of recent decades for generalization on a large scale.

VII. In the Komi Republic, the distribution of the trends in NDVI data changes on a south-west to north-east gradient.

VIII. Taking into account the relatively limited influence of humans in the Komi Republic compared to Europe, the site productivity during recent decades has also increased in relatively untouched forests.

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