Growth of the South-Finnish Forests during the Period of 1961-2010 as Function of Thermal Conditions in Air and Soil

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Abstract

This study investigates the growth of forest stands ($m^3ha^{-1}a^{-1}$) and its temporal variation during the five decades of the period 1961-2010 as measured in the national forest inventories by the Finnish Forest Research Institute, in three regions, comprising the southern half of Finland. This growth was explained by sum of the effective temperatures and winter maximum soil frost depth; the correlation coefficient between the measured and modelled growths for the regions and decades studied being 0.97. It was also shown that the regional differences in soil frost depth are related to the differences between the temperature sum in the air and that in the upper soil layer during the growing season. Further, the residuals of the main test were analyzed for secondary factors. The temporal and regional variation could be accounted for by the relatively low growth in the peatland-forests created by the extensive drainage measures of 1961 1980, the response of the growth-rate to May+June precipitation, and the extensive application of fertilizers in 1968 1980**.** The regional differences and temporal changes in climate are also reflected in the understorey vegetation**.**

Key words: Boreal forests; Forest growth and climate; Snow and forest growth; Soil frost and forest growth

Introduction

Up to the present, the zonation and productivity of boreal forests have been generally explained by a single variable; this can be: the biotemperature, i.e. the sum of mean temperatures above freezing point (Tuhkanen 1984); the traditional sum of effective temperatures in excess of +5 ºC (Beuker et al. 1996); the sum of active temperatures in excess of +10 ºC (Nazimova and Polikarpov 1996); a continentality index as function of latitude and seasonal extreme temperatures (Monserud et al. 1996). Alternatively, a sample of stocastic variables (Metzger et al. 2005) or a qualitative list of factors, such as the traditional sum of effective temperature, the duration of the thermal vegetation period and risks of night frosts and drought in early summer (Mäkipää 2000), have been used. Talkkari (1996) explains, unsuccesfully, however, the regional variation of the growth-rate of forests in the southern half of Finland by monthly means of temperature and precipitation. The circumpolar aspect is generally absent, circumpolar forest vegetation zones (Ahti et al.1968) being seldom presented as identical to climatic zones. For example, this identity is not mentioned in the study of forest vegetation by zones by Tonteri et al. (2005). Furthermore, the 'boreal zone' is generally considered without division into subzones but separating its southernmost subzone, the hemiboreal, from it as another main zone, called also 'boreal-nemoral' (Heikkinen 2005, Metzger et al. 2005, Tikkanen 2005). The pioneer works on the boreal forest vegetation zonation by Ahti et al. (1968) and Tuhkanen (1984) are thus mostly neglected or forgotten.

The idea of these authors, behind of this study, is that the boreal ecoclimatic subzones form an interactive system of forest vegetation and climate. In this system, the productivity decreases stepwise northwards by subzones, as indicated by an equation, in which the most crucial climatic effects are integrated, not stochastically but on a firmly physical basis (Solantie 2005, 2006, 2008). This equation integrates the effects of the sum of effective temperatres, biotemperature, duration of the vegetatinal period and soil temperature. The method places more weight on the air temperature during the daylight hours than the night hours; it also takes temperatures in the range of 0 to 5 ºC into account, but with a lesser weight than that of higher temperatures. By this means, it makes comparisons between continental and maritime climates more accurate, particularly due to the considering thermal conditions not only in the air but also in the ground. The same holds also for comparisons between regions in various latitudes.

The growth in the boreal forests, G ($m^3ha^{-1}a^{-1}$), called the 'growth-rate', can be estimated as (Solantie 2005, 2008):

$$G = G\ (F, L, Lcool), \qquad (1)$$

where: F = the winter greatest soil frost depth, L = the sum of effective temperatures.

The traditional version of L, denoted by Ltrad, is defined as the sum of daily mean temperatures in excess of +5 °C, each of them averaged over the years considered. In this study, an advanced version of L, denoted by Lassim (Solantie 2004), was used instead of Ltrad. Lassim is the sum of hourly temperatures during daylight hours (more exactly, during the period beginning, when the sun altitude reaches 3º in the morning and correspondingly ends at 1º in the evening), multiplied by a constant so as to give values equal to Ltrad on the average over large regions, but being somewhat different at single sites or in smaller regions, e.g. those having particular high or low night temperatures due to the effect of water bodies or their topographic situations. In comparisons between maritime and continental regions, e.g. Siberia vs. the Atlantic coast or inland Eastern Canada vs. the Pacific coast, the effect of air temperature cannot be represented only as function of Lassim but rather as the weighed sum of Lassim and Lcool as Ltotal ~ 0.75 × Lassim + 0.3 × Lcool. Here, Lcool is equal to the usual sum of daily mean temperatures, t, when in the range 0 to +5 ºC; when, however, a daily mean temperature exceeds +5 ºC, a value of +5 ºCd is assignated to that day. In fact, it approximately replaces the use of the duration of the thermal growing season but additionally covers the period from and till the dates of t = 0 ºC, and has the same dimension as L, i.e. as degree-days. So, when considering the thermal effect of air temperature on G as a weighted sum of of L and Lcool, it applies circumpolarly, independent of the degree of continentality, and is, therefore, called the thermal factor of the boreal natural environment. The only exceptions are the hemiboreal and southern boreal forest-steppes and steppes in the driest regions. On the other hand, when comparing regions of about equal continentality, as in this particular study, Lcool is not needed, and the use of Lassim alone is accurate enough. In this case, the equation obtained by a regression analysis explaining G as observed in the 3rd national forest inventory 1951 1953 (Solantie 2005) was applied:

$$G\ (m^3ha^{-1}a^{-1}) = 0.00647 \times Lassim\ -0.0435 \times F\ -1.97 \qquad (2)$$

In this equation (Solantie 2005),

$$F = (40 \times P + (1.4 \times S_0 \times \ln P)^2)^{0,5} - 1.4 \times S_0 \times \ln P - 0.03 \times Lassim \qquad (3)$$

where: P = the frost sum (-ºC d) ja; S_0 = the mean snow depth during the winter (cm), while the last term denotes the effect of heat flux from the ground.

In circumpolar applications, Lassim in Eqs. (2) and (3) is replaced by Ltotal. In this study, Lassim was used instead of Ltrad as a reminder that Lassim is more acccurate than Ltrad for comparisons between different places and regions. It turned out, however, that the differences between Lassim and Ltrad for the regional means in this case were insignificant: for the segment West 16 ºCd, for East-A 9 ºCd and for East-B 12 ºCd; the corresponding values of precisions for G are +0.12, 0.07 and 0.09 $m^3ha^{-1}a^{-1}$, respectively. This, however, could not have been known without testing.

Equation (2) was basically created by explaining the spatial analyse of production capacity of forests on the basis of the national inventory 1951-1953 by Ilvessalo (1960) using climatic data for the period 1961-2000.

The main idea of this study was to apply this method for the growth rates of forests ($m^3ha^{-1}a^{-1}$) in the southern half of Finland during each of the 5 decades 1961-2010, firstly to observe how accurate the Equation (2) is to approximate the temporal variation of climate, and secondly, to study to what degree the residual is random and to what degree caused by 'secondary' effects not involved in Equation (2).

Thirdly, the 'soil frost term' in Equation (2) was particularly tested in this study because it varies greatly between boreal regions having different latitude and continentality of the climate. So, the procedure was carried out separately for three meridional segments in the southern half of Finland, in order to include the effect of soil frost, which has a significant east-west gradient, while the sum of effective temperatures does not. Further, the accuracy of the constant term of Equation (2) became tested.

Here, the method is applied to explain the temporal variation of the growth-rate of Finnish forests during the last 50 years, separately in three regional segments having different soil frost conditions. The related impact of climate on understorey vegetation is also discussed. The idea that the ecoclimatic boreal subzones are also zones of productivity was finally tested (see in Discussion) by comparing the present growth-rates of productive forests in Finland, Sweden and Latvia in each ecoclimatic zone, with each other. The contribution of the various climatic factors to the increase of the growth of forests was also considered in the light of a Canadian study.

Materials and Methods

Annual (hectare) growth of forests on the basis of the climatological modelling

The growth of forest per hectare has been earlier calculated by Equation (2) approximating in its advanced version the growth as a function of the sum of effective temperatures and the greatest soil frost depth in winter (Solantie 2005, 2006, 2008). In this article, the applicability of this method to explain the temporal variation of the forest productivity was tested by estimating the mean annual forest growth averaged for each decade of the period 1961 2010, and comparing this to the results of the national forest inventories. The three meridional segments in the southern half of Finland, for which the procedure was carried out separately, are denoted as West, East-A and East-B. Each of the segments consists of four forest statistical regions (Figure 1).

The procedure also differentiated between productive and all forests, the former defined as those growing faster than 1.0 $m^3ha^{-1}a^{-1}$. Furthermore, the temporal and regional variations in the structure of forests, the effect of the extensive drainage of peatlands, the extensive use of fertilizers in forests in the period 1968 1980 and the precipitation occurring in early summer were also recognised; these factors were studied in order to explain the regional and temporal variation of the differences between the observed and modelled growth values (residuals).

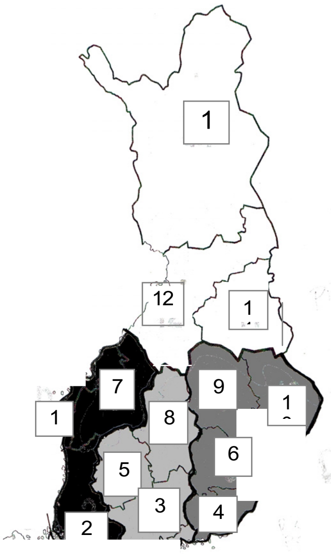

Figure 1. The segments of the southern half of Finland, consisting of the Forest centres (numbered): West (black), East-A (light grey), and East-B (dark grey). Segment West comprises regions 1b, 2 and 7, segment East-A comprises regions 1a, 3, 5 and 8, and segment East-B comprises regions 4, 6, 9 and 10. Regions 1-10, i.e. all three segments together, are referred to as the southern half of Finland

The statistics for the evaluation of snow depths in the segments, based on thousands of observations each year, includes a map of the snow depth on March 15th for the period 1919 1998 and the regional deviations of snow depth for 10-year periods (Solantie 2000). Since around the year 2000, the Finnish Meteorological Institute (FMI) has radically decreased the number of its own observations. In addition, the interest of amateurs in making observations on March 15th, guided by the FMI, has also decreased. For these reasons, the values for 2001 2010 were deduced from the values for 1971 2000 using only the changes in snow depths at observation stations operating throughout the period 1971 2010. The mean snow depths during the winter were approximated by multiplying the values on March 15th by 0.7. The frost sums were calculated for each of the segments for the period 1971 2000 (basic statistics: Drebs et al 2001), and reduced to the decennial means using a sample of stations operating throughout the whole 50-year period studied and giving in the period 1971 2000 practically the same regional means as using all available observation series.

The values of the variables in Equations (2) and (3) by segments and decennia are given in Table 1.

Annual hectare growth of forests on the basis of the national forest inventories

In the forest inventories, carried out over the southern half of Finland, each of them taking 2 to 5 years, the growth values were observed by boring; they represent growth during the five years preceding the observation, and were compiled as regional means and published in the forest statistical yearbooks.

The data sources for decennial growth-rates in the five decades 1961 2010 are given in Table 2, while the

Table 1. The sum of effective temperatures, Lassim (°C d), the winter greatest soil frost depth, F (mm), frost sum, P (-°C d), and the mean snow depth in winter, S_0 (mm), by segments as West, East-A, East-B and the southern half of Finland (consisting of these three segments, shown in Figure 1), denoted here as W, E-A, E-B and **S.F.**

period	Lassim				F				P				S_0			
.	W	E-A	E-B	**S.F.**	W	E-A	E-B	**S.F**	W	E-A	E-B	**S.F.**	210	282	380	**291**
19?98													210	282	380	**291**
61-70	1105	1140	1120	**1123**	369	255	246	**290**	925	980	1250	**1052**	240	310	400	**317**
71?80	1130	1165	1150	**1148**	282	199	187	**223**	700	730	960	**797**	212	258	348	**273**
81?90	1145	1180	1165	**1163**	205	125	112	**147**	795	850	1080	**908**	281	350	456	**362**
91?00	1160	1195	1180	**1178**	232	129	99	**153**	500	520	735	**585**	165	216	327	**236**
01?10	1305	1340	1325	**1323**	293	95	80	**156**	590	625	815	**677**	155	252	339	**249**
61?10	1170	1205	1190	**1187**	276	161	145	**194**	700	740	970	**805**	211	277	374	**287**

values by decades obtained for productive forests are given in Table 3.

Table 2. Metadata for the growth rates by decades: The periods of measurements and the corresponding growth years covering the period of 1 to 5 yrs preceding the measurements in situ, by national forest inventories, and the source of the basic data comprising the forest area and annual total growth determined by the Forestry Centres

Decade	Forest inventory and measurement years	Growth years	Basic data: Annual volume of the Yearbook, pages
1961-1970	V 1964-1968	1959-1967	1972, p. 71; 1983, p. 82
	VI 1971-1976	1966-1975	1980, p. 55; 1983, p. 82
1971-1980	VII 1977-1981	1972-1980	1988, p.57, 86
1981-1990	VIII 1986-1991	1981-1990	1993-1994, p. 56, 72
1991-2000	IX 1996-2000	1991-1999	2005, p. 44, 65
2001-2010	X 2004-2008	1999-2007	2009, p. 45, 70
	XI 2009-2011	2004-2010	2012, p. 49, 71

Table 3. Mean growth-rate of productive forests ($m^3ha^{-1}a^{-1}$) as modelled and **measured**, and their differences (residuals)

Decades		West	East-A	East-B	Mean
1961-1970	Modelled	3.79	4.51	4.45	4.25
	Measured	**3.42**	**4.47**	**4.23**	**4.04**
	Meas.-Mod.	-0.36	-0.04	-0.22	-0.21
1971-1980	Modelled	4.33	4.91	4.88	4.71
	Measured	**4.25**	**5.06**	**4.59**	**4.63**
	Meas.-Mod.	-0.08	+0.15	-0.29	-0.08
1981-1990	Modelled	4.77	5.33	5.29	5.13
	Measured	**4.64**	**5.71**	**5.27**	**5.21**
	Meas.-Mod.	-0.13	+0.38	-0.02	+0.08
1991-2000	Modelled	4.75	5.42	5.46	5.21
	Measured	**4.60**	**5.80**	**5.46**	**5.29**
	Meas.-Mod.	-0.15	+0.38	+0.00	+0.08
2001-2010	Modelled	5.42	6.51	6.47	6.13
	Measured	**5.59**	**6.65**	**6.62**	**6.29**
	Meas.-Mod.	+0.17	+0.14	+0.15	+0.16
1961-2010	Modelled	4.61	5.34	5.31	5.08
	Measured	**4.50**	**5.54**	**5.23**	**5.08**
	Meas.-Mod.	-0.11	+0.20	-0.08	0
Change from 1961-1970 to 2001-2010	Modelled	1.63 or 42%	2.00 or 43%	2.02 or 44%	1.88 or 44%
	Measured	**2.17 or 63%**	**2.18 or 49%**	**2.39 or 57%**	**2.25 or 56%**

According to the traditional practice of the Finnish Forest Research Institute, forests are divided into two types, on the one hand, productive, and, on the other hand, poorly productive, the latter being, where the annual growth is less than 1.0 m^3ha^{-1}. This division marks the limit of commercial forestry. Poorly productive forests also become more common northwards. Considering the productivity of total land areas, poorly productive forests are thus also significant in an ecological context. The share of poorly productive forests obviously decreases with climatic warming, but in Finland their share during the 50-yr period studied was mainly determined by forestry measures. In the southern half of Finland, poorly productive forests consist mainly of pine bogs, and due to the effect of extensive drainage measures, their share is small and has decreased during the period considered from 8 to 3 %. For comparison, in Lapland (region 13 in Figure 1), consisting mainly of the norhern boreal zone, the respective share has been steady at 25 %. The growth rate of productive forests thus to a great extent reflects the impact of climate on the growth rate in all forests. For these reasons the growth rates in Table 3 are given for productive forests, and in Table 4 as the differences in the growth rates between productive and all forests.

In the forest statistical yearbooks, growth statistics are given for all forests. By approximating the growth in poorly productive forests as 0.75 $m^3ha^{-1}a^{-1}$, and knowing their area by decades, the growth for productive forests could be deduced. Finally, the modelled values, given by Equation (2), were adjusted to those observed, by changing the constant term in the equation so that the all-over average of the modelled values equalled to that of the observed; this was done separately for all and for productive forests. By so doing, Equation (2) was made more accurate. Because the share of poorly productive forests is so small, in any case below 1.0 m^3ha^{-1}, the accuracy of the assumed value of their growth-rate is not so important. For example, if we were to approximate it by 0.25 instead of 0.75, the mean growth rate of all forests during the period 1961 2010 would decrease by 0.04 in segment West, 0.02 in East-A and 0.01 in East-B, i.e. insignificantly. In Table 3 the growth in the regional segments is given for productive forests, while the differences between the growth in productive and all forestsis is shown in Table 4.

Table 4. The share of poorly productive forest area inthe total forest area by segments and periods / the difference in the growth-rates between productive forests and all forests, i.e. productive + poorly productive ($m^3ha^{-1}a^{-1}$)

Seqment	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	Mean 1961-2010
West	0.12/**0.31**	0.08/**0.27**	0.06/**0.25**	0.07/**0.26**	0.05/**0.24**	0.07/**0.27**
East-A	0.06/**0.23**	0.04/**0.16**	0.04/**0.18**	0.05/**0.25**	0.03/**0.15**	0.04/**0.19**
East-B	0.06/**0.22**	0.03/**0.12**	0.04/**0.17**	0.02/**0.11**	0.01/**0.04**	0.03/**0.13**
Mean	0.080/**0.25**	0.048/**0.18**	0.046/**0.20**	0.047/**0.21**	0.027/**0.14**	0.050/**0.20**

Supplementary effects

A study was also made as to the residuals, i.e. the differences between the measured and modelled growth-rates, are accounted for by other, secondary factors not involved in Equation (2). Considering means over the southern half of Finland, changes in the age class distribution were studied, i.e. the validity of the preliminary assumption that the distribution has been rather stable was tested.

Since the 1960s, forestry measures, both intensive and extensive, have been undertaken to increase forest productivity (Kuusela and Salminen 1991, Finnish Satistical Yearbook of Forestry 2012). The effect of the extensive application of fertilizers carried out 1968-1980, over an area of 21,500 sq. km, i.e. 10 % of all Finnish forests, was obvious, albeit not very great. For better certainty, the period 1971-1980 was excluded, when studying the two other factors described below, i.e. the effects of precipitation and drainage.

The huge national drainage measure, whose aim was to change poorly productive peatland forests into productive forests, began sharply in the 1950s, was at its peak during the 1970s and 1980s, and ceased in the 1990s; during this period, 18 % of the Finland land area was drained. A lot of peatlands became classified as productive soon after successful drainage; these forests were described as 'transforming'. The term 'transforming' means that these forests are undergoing or recently have undergone a change from poorly productive to productive, while still having a growth-rate lower than average. The effect of drainage can be related to the proportion of such forests. When their growth-rate attained the mean of forests on mineral land in the corresponding fertility class around 1990, they were termed 'transformed'. The mean age and area of transforming forests increased in the 60s, and then remained practically unchanged until the mid-90s; the addition of newly-drained peatlands into the 'transforming' stage was about equal to the transfer into the 'transformed' stage. In the early stage of drainage, i.e. in the 1960s, practically all transforming forests were freshly-drained, having a lower growth-rate than later. Albeit the proportion of such area was then lower than in 1971-2000, the negative effect on G was obviously about the same. Therefore, the effect of drainage on G was more or less unchanged over the period 1961-2000. Growth-rates in transforming forests were also lowered in certain cases because dry peat is an effective insulator, enhancing the risk of night frosts in summer, particularly in wide transforming areas (Solantie et al. 2002); there, the melting of soil frost was also delayed. The proportions (%) of transforming forest areas (Tr) by decades during the period 1981-2010 were available from the Finnish Statistical Yearbooks of Forestry by regions, but over the period 1961-1980 only for the southern half of Finland as a whole (Hökkä et al. 2002); in this period, the mutual relations between the values in individual segments to the means in the whole area were assumed to be the same as those in the period 1981-1990.

The response of the growth of Norway spruce to early summer precipitation was shown by Mielikäinen (1996a, 1996b), and the similar behaviour of Scots pine by Henttonen (1984) and Lindholm et al. (2000). This effect was calibrated to be zero in a 'special period', during which precipitation was close to its mean values for 1911-2010, i.e. comprising the 1960s, 1980s and 1990s (Reuna and Aitamurto 1994, Hyvärinen and Korhonen 2003, Korhonen and Haavanlammi 2012).

During the 'special period' the effects of drainage on G in the various segments could be approximated as being equal to the mean residuals during it**.** The approximation could be verified, because the effect of drainage for the southern half of Finland could be observed by multiplying the share of peatland forests by the difference in the growth rates between these (Hökkä et al. 2002) and all forests. During the period 2001-2010 the effects of drainage by segments, then being appreciably smaller, were related to the shares of transformings during this period compared to those earlier. The effect of precipitation could then be obtained differently for each decade as the differences between the residual and the effect of drainage, except for 1971-1980, during which this difference also includes the effect of fertilizer use. The effects of precipitation on G by segments and decades were then related to precipitation; in this way, the effect of precipitation for the period 1971-1980 could also be approximated, the effect of fertilizer use thus roughly estimated by subtracting the effects of precipitation and drainage from the 1971-1980 residual.

Results

The values of variables in the climatic modelling

The values of the variables involved in Equation (2) and (3) in Table 1 are considered. The sum of effective temperatures (Lassim) changes mainly in a south north direction; differences between the meridional segments are therefore small. The frost sum (P) increases towards the north-east; because the mean latitude of the East-A segment is slightly lower than those in West and East-B, P increases more steeply over the eastern step (from East-A to East-B) than over the western (from West to East-A). Considering further that the mean snow depth, S_0, resisting soil frost, increases from west-south-west to east-north-east, soil frost, F. is shallowest in East-B and deepest in West, and its changes are steepest over the western step.

Over the decades, Lassim has increased continuously, taking a great leap over the turn of the millenium. Both P and S_0 are double-peaked, with peaks in 1960s and 1980s. Because the higher peak in P occurred in the 1960s but that of S_0 in 1980s, F was clearly the greatest in the 1960s. In both East-A and East-B F has continuously decreased, first rapidly but later slowly, while in the West segment F decreased to a minimum in the 1980s, and thereafter increased again.

The growth-rate of forests by measurements and modelling

On average Equation (2) gives slightly smaller growths than measured, in all forests by 0.04 and in productive forests by 0.24 $m^3ha^{-1}a^{-1}$. For comparison between observed and modelled growths, the constant term in Equation (2) for all forests is therefore recalibrated to be -1.93 and that for productive forests to be -1.73, instead of -1.97. The recalibrated values of the constants have been used to produce the modelled values of Table 3**.** The regional analysis of forest productivity by Ilvessalo (1960), originally used as the basic material for Equation (2) (Solantie 2005), thus fits excellently, with only minor adjustments of the constant term, as given above, to agree with the forest growth during the five decades studied and with the trends during it, as can be seen from Table 3.

The correlation coefficient between the measured and modelled values in productive forests is 0.982. The standard deviation of the 15 differences between the measured and modelled growths in productive forests is 0.22 $m^3ha^{-1}a^{-1}$ (Table 3). Considering that the measured values also have their own errors, these differences represent the upper limits of the errors in the modelling. The standard errors of the measured growth-rates by the Forestry Centres were on average 0.10 $m^3ha^{-1}a^{-1}$ (Heikkinen et. al. 1998 2001). Each segment consists on average of 3.7 by the Forestry Centres; consequently, the corresponding error for a growth-rate in a segment is 0.05 $m^3ha^{-1}a^{-1}$, and the standard error at the modelled values is as $(0.22^2 - 0.05^2)^{0.5} = 0.214$ $m^3ha^{-1}a^{-1}$. The differences between the observed and measured values are therefore practically equal to the errors of the modelled values. The growth-rates in Table (3) and the contributions to them by various effects (below) are accurate to 1 decimal place. Also, to be such when summed, they are, however, given to 2 decimal places.

The growth differences between the productive forests, G, and all forests, Ga, in Table (4) has a mean value of 0.20 $m^3ha^{-1}a^{-1}$. Considering that $G - Ga = pp \times (G - 0.75)$, it is practically proportional to the share of poorly productive forests, denoted by pp (Table 4). In the southern half of Finland, practically all forests are used economically so that forests, where the growth-rate is appreciably reduced due to high age, are exceptional there; the share of > 141-yr aged forest stands was in 1963-1970 1.0 % and in 2009-2011 1.6 %. Most of the poorly productive forests consist of virgin and recently-drained peatlands, as in segment West, where the share of poorly productive forests, practically all of them on peatlands, is greatest. The temporal development of this difference behaved accordingly. From the 1960s to the 1970s, the differences decreased clearly, and then remained at about the same level, until they decreased again around the change of the millenium. Poorly productive forests were still abundant in the early stage of the huge national drainage measure, i.e. in the 1960s. At that time freshly-drained peatlands, initially waste lands became transformings and were classified as poorly productive forests; their area increased rapidly. In the next stage, this process continued, but contemporaneously part of the transforming forests became classified as ‘productive’. After the drainage measure came to an end, only the latter change continued. The abundant application of fertilizers on poorly productive forests in the 1970s may have contributed to the sharp decrease of poorly productive forests from the 1960s to the 1970s. Note also that in segment East-A, where almost-bare rocks comprise a greater share of poorly productive forests than in the other two segments, the share of poorly productive forests was least but decreased slowliest.

The good accordance between the modelled and measured values shows that most of the increase in the growth-rate in forest stands in the southern half of Finland during the period 1961-2010 is caused by a change in the climate. On the average, the growth-rate of the modelled values in the productive forests increased over the period by 44 % or 1.88 $m^3ha^{-1}a^{-1}$ and that of the measured values by 56 % or 2.25 $m^3ha^{o-1}a^{-1}$. The corresponding increase in modelled values in all forests was 50 % or 1.99 $m^3ha^{-1}a^{-1}$ and that of measured values 65 % or 2.36 $m^3ha^{-1}a^{-1}$. The residual, i.e. the difference between the observed and modelled values, increased during the period; the correlation coefficient between time and the mean residual in the three segments being 0.96, and the trend 0.009 $m^3ha^{-1}a^{-2}$, indicate the effect of some supplementary factors, albeit not major ones.

Supplementary effects involved in the residual of the main climatic modelling

Table 5 gives the age structure of forests in the southern half of Finland according to the forest statistical yearbooks.

Two main temporal changes in the age class distribution can be noted. The increasing trend in the age class 21-40 until the end of millenium, and in the age class 41-60 after that, is caused by the extensive forest regeneration measures in the 1960s and 1970s. The decreasing trend in the age class 61-80 is obviously caused by the fact that stands attained the proper stage for felling earlier than before due to increased growth. In accordance with this, the proportion of forest in the development stages of young thinning

Table 5. The age class distribution in the forests of the southern half of Finland by inventory periods (%)

Period	<20 yr	21-40 yr	41-60 yr	61-80 yr	81-100 yr	<100 yr
1964-1968	17	13	17	28	16	9
1971-1976	21	15	18	23	14	9
1977-1981	21	16	17	20	15	11
1986-1991	19	20	16	17	15	13
1996-2000	20	22	17	16	13	13
2004-2008	22	23	18	14	11	12
2009-2011	20	22	22	14	11	11

stands or younger growth, comprised in 1971-1976 49.2 %, in 1986-1991 50.6 % and in 2009-2011 50.1 % of the total area of productive forest stands in the southern half of Finland (Yearbook of Forest Statistics 1983, Yearbook of Forest Statistics 1993 94, Finnish Statistical Yearbook of Forestry 2012).

The volume share of pine in forest stands in the southern half of Finland from the 1960s till 1996-2000 remained stable at 39 to 41 %, but since then has increased to 44 % in 2009-2011. On the other hand, the share of spruce was also stable at 42 to 43 % till 1996-2000, decreasing to 35 % by 2009-2011. The main reason for this is the response of forest stands on peatlands, consisting mainly of pine, to the extensive and successful drainage measures. The relative annual growth of spruce in the southern half of Finland in 1996 2000 was 4.10 % by volume and that of pine 4.00 %, while in 2009 2011 the respective values were 4.37 % and 4.46 % (Finnish Statistical Yearbooks of Forestry 2005 and 2012). The growth-rates for pine and spruce are thus about equal, while the growth of pine has overtaken that of spruce, in accordance with the analysis of the effect of drainage above.

When considering the effect of drainage on the growth-rate (Table 7), the relative shares of the 'transforming' and 'transformed' peatlands in the forest area are the most important basic statistics (Tables 6 and 8).

The effect of drainage on the growth rate, Dr, in the decades of the 'special period,' approximated by the mean residual during this period, was -0.21 in West, +0.24 in East-A, and -0.08 in East-B. The 'transforming' proportions of the forest area (Tr) in these segments in 1961 2000 are 11.1, 6.6 and 9.7 %, respectively. We obtain the following linear dependence:

$$\text{The effect of drainage} = 0.90 - 0.10 \times \text{Tr} \qquad (4)$$

The effect of drainage for the southern half of Finland in the 80s was also calculated on the basis of the growth-rates in drained peatlands. The growth-rate in all peatland forests during the 80s was 0.7 $m^3ha^{-1}a^{-1}$ lower than in all productive forests (Hökkä et al. 2002). Multiplying the latter value by the share of peatland forests in all forests (0.19), we obtain the effect of drainage in the southern half of Finland at its peak in 80s as 0.13 $m^3ha^{-1}a^{-1}$, i.e. practically the same as the value of 0.04 above. Equation (4) was applied also to obtain the effect of drainage also for the periods 2001-2010 and 2009-2011. The rapid increase of the proportion of transformed peatlands at the expense of transforming since the turn of the millennium and the consequential positive effect of drainage can be noted in Tables 6, 7 and 8.

The decennial precipitation values, Pr, for the period 1911-2010, based on the data by Reuna and Aitamurto (1994), Hyvärinen and Korhonen (2003) and Korhonen and Haavanlammi (2012), are given by segments in Table 9, and the effects of Pr on G 1961-2010 in Table 10; these were obtained as follows.

In the three decades comprising the 'special' period (the 1960s, 1980s and 1990s), May+June precipitation was on average the same as in 1911-2000, but in 1961 1970 it was appreciably lower and in 1981-2000 somewhat higher. The effects of Pr on G during the former 'dry' and the latter 'wet' partial periods were obtained by subtracting the mean effect of drainage during the special period from the residuals during the 'dry' and 'wet' partial periods. The response of G ($m^3ha^{-1}a^{-1}$) to Pr (mm) as dG/dPr is in West 0.01, in East A 0.03 and in East-B 0.02 and, on average 0.018. This accords with the fact that the evapotranspiration in forests (Hyvärinen, Solantie et al. 1995), the volume of growing stands and the share of spruce are the highest in East-A and the lowest in West, and also

Table 6. Transforming peatlands as a share of the total forest area by segments and periods

Segment	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	1961-2000	1961-2010	2009-2011
West	0.066	0.122	0.131	0.123	0.103	0.110	0.109	0.062
East-A	0.040	0.074	0.079	0.070	0.053	0.066	0.063	0.029
East-B	0.060	0.112	0.120	0.095	0.061	0.097	0.090	0.045
Mean	0.055	0.103	0.110	0.096	0.069	0.090	0.086	0.045

Table 7. Transformed peatlands as a share of the total forest area by segments and periods

Segment	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	1961-2010	2009-2011
West	0.035	0.052	0.071	0.093	0.180	0.086	0.188
East-A	0.022	0.033	0.044	0.069	0.106	0.056	0.118
East-B	0.023	0.035	0.046	0.075	0.143	0.064	0.152
Mean	0.026	0.039	0.052	0.078	0.140	0.068	0.151

Table 8. The effect of drainage on the growth-rate of forests ($m^3ha^{-1}a^{-1}$)

	1961-2000	2001-2010	2009-2011
West	-0.21	-0.13	+0.28
East-A	+0.24	+0.37	+0.61
East-B	-0.08	+0.29	+0.45
Mean	-0.04	+0.21	+0.45

Table 9. Statistics of May+June precipitation by segments (mm) as weighed means of basin values

	1911-1920	1921-1930	1931-1940	1941-1950	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	61-70, 81-00	1911-2010	St. dev
West	83.5	105.0	**74.5**	89.0	85.5	76.5	79.0	97.0	97.0	**107.0**	90.2	89.4	12
East-A	93.3	**122.1**	86.7	96.2	97.5	86.5	**84.2**	105.3	95.5	117.1	96.8	98.4	13
East-B	94.5	**122.0**	95.5	99.0	89.5	95.0	**94.5**	106.0	108.5	116.5	103.2	102.1	11
mean	90.4	**116.4**	**85.6**	94.7	90.8	86.0	85.9	102.8	100.3	113.5	96.7	96.6	11

East-B = 0.5 x Saimaa (above Tainionkoski, below Konnus, Karvio and Jakokoski) + 0.5 x Kallavesi (above Konnus and Karvio)

Table 10. The effect of precipitation on the growth-rate of forests (m^{3}ha^{-1}a^{-1}mm^{-1})

Segment	1961-1970	1971-1980	1981-2000	2001-2010	Mean 1961-2010	Mean in the 60s, 80s and 90s
West	-0.15	-0.12	+0.07	+0.30	+0.03	0
East-A	-0.28	-0.35	+0.14	-0.23	-0.12	0
East-B	-0.14	-0.15	+0.07	-0.14	-0.06	0
Mean	-0.19	-0.21	+0.09	-0.05	-0.05	0

with the fact that, according to tree-ring-studies, the response of growth to early-summer precipitation decreases northwards (Lindholm et al. 2000), i.e. towards a harsher climate. Applying these values to the small differences between Pr (1971-1980) and Pr (1961-1970), we obtain the effects of Pr (1971-1980) on G. Subtracting the effects of Pr and Dr from the residual, both as means over the 3 segments, the result, 0.15 m^{3}ha^{-1}a^{-1}, approximates the effect of fertilizer application in the 70s, amounting to 1.5 m^{3}ha^{-1}a^{-1} on the fertilized sites.

Let us consider the effect of Pr in the period 2001 2010 on average for the three segments as the difference between the residual (+0.16) and the effect of Dr (+0.21). This effect of Pr = 113 mm as -0.05 was the same as that of Pr = 94 mm, when interpolated between the pairs of values in Tables 7 and 8 between the 'dry' and 'wet' periods, i.e. 1960s and 1981-2000.

Discussion

The good accordance between the modelled and measured growths of forests per hectare in each of the three meridional segments during the last five decades shows that climate determines most of the spatial and temporal variations in this mean growth, especially as most of the differences between the modelled and observed values, albeit small, could be explained by secondary factors, i.e. drainage, May+June precipitation, and fertilization in the 70s. The effect of the structure of forest in respect of age and tree species proved to be insignificant.

The effects of drainage according to Equation (4) in the southern half of Finland for the periods 1961-2000, 2001-2010 and 2009-2011 are -0.04, +0.21 and 0.45 m^{3}ha^{-1}a^{-1}, respectively. The rapid increase of the drained areas accords with the fact that transformed peatlands in 1996-2004 comprised 34 % of the total area of 'transforming' and 'transformed' but in 2009-2011 this proportion was already 77 %. The mean growth-rate in drained spruce swamp forests during the 80s was 2.2 m^{3}ha^{-1}a^{-1} higher than in drained pine bog forests (Hökkä et al. 2002). So, in East-A, where the share of peatlands in the total area of forests and mires is the lowest, 19 % in 1980 (Yearbook of Forest Statistics 1988) and the share of rather productive spruce swamps in peatlands is the highest (44 %), the effect of drainage (Table 8) in the period 1961-2000 was constantly positive. On the other hand, in West, where climate is harshest, the share of peatlands is the highest (33 %), and the share of spruce swamps in peatlands is the lowest (27 %), the effect remained negative till around 2007. In East-B the effect of drainage, both in respect of the magnitude and turning to positive, was between those in East-A and West.

The method supposes that the effect of the mean May+June precipitation 1911-2010 as 96.7 mm on the growth of forests is 0. Precipitation in the 60s and 70s was 11 mm lower, in the 80s and 90s 5 mm higher and in 2001-2010 17 mm higher than that 100 yrs mean (Tabe 9). It proved out, that the effect of precipitation (m^{3}ha^{-1}a^{-1}) in 60s and 70s was -0.2, in the 80s and 90s +0.1 while in 2001-2010 -0.05 (Table 10); so, the optimum, i.e. the maximum effect, corresponds to 5 to 10 mm higher amounts of precipitation than the long period mean. The increase of precipitation in early summer from the 60s to the 80s is the obvious reason for the simultaneous rise of the residual, particularly in segment East-A. The mean rise of the residuals over the turn of the millenium reflects the increased growth in peatland forests, while the differences in the residuals for the period 1961-2010 between the segments reflect the corresponding differences in the effect of drainage. Thus, by considering the effects of precipitation and drainage, we can understand why the measured increase of growth-rate during the period 1961-2010 was somewhat greater than that given by Equation (2). The mean increase over the period of the residual from the modelling of the growth-rate in productive forests, i.e. 0.37 m^{3}ha^{-1}a^{-1}, or 16 % of the observed increase in the growth, can be accounted for roughly as follows: 0.16 $m^3ha^{-1}a^{-1}$ is due to the increase of precipitation and 0.21 to the consequencies of the successful drainage.

The fact that the climate in segment West is harsher and the growth-rate of forests is lower than in East-A or East-B, is also reflected in the ecological features of forests connected with the growth of trees. The middle boreal zone comprises only 15 % of segments East-A and East-B but 47 % of segment West, extending here farther south. During the 50-year-period studied, the boundary between the ecoclimatic regions corresponds on average to a growth of 4.5 $m^3ha^{-1}a^{-1}$ in productive and 4.3 $m^3ha^{-1}a^{-1}$ in all forests. Using the classification generally used in Finland since the 1940s (Ilvessalo 1940), the proportions of most productive forests (herb-rich and herb-rich heath forests) in East-A, East-B and West are 35, 32 and 13 %, while shares of the least-productive forests (sub-xeric and xeric forests) are 17, 21 and 30 %, respectively (Finnish Statistical Yearbook of Forestry 2012); note that xeric and sub-xeric forests regulate evapotranspiration more in order to save energy than to save water.

During the cold 60s, middle boreal conditions extended down to 62°N, while in the period 2001-2010 hemiboreal conditions extended up to this line, and southern boreal conditions now prevailed in the area that had had middle boreal conditions in the 60s. During the last 50 years, the growth-rate of forests has increased by 60 % and the mean hectare yield of the main cereal species during the period 1971-1980 to 2000-2011 by one-third (Solantie 2012). This climatic change and the consequent increase in productivity is due more to normal climatic fluctuation than to the ongoing global climatic change. For this reason, possible periods of lower productivity in the future should not be discounted.

The detailed map of Ilvessalo (1960) of the growth of productive forests corresponds astonishing closely to the average measured forest growths by segments during the period 1961-2000, showing the excellent quality of his work. The measured means in West, East-A and East-B are 4.23, 5.26 and 4.79, while the corresponding values, integrated by the author from Ilvessalo's map, are 4.1, 5.05 and 4.8, respectively; i.e., 97 %, 96 % and 100 % of that measured.

The great importance of May+June precipitation for the growth of trees, especially spruce, accords with the fact that in Finland water storage in the ground decreases rapidly in early summer, as precipitation is then low but while evapotranspiration in June reaches its annual maximum (Solantie 1987). Spruce also occurs in sites having clay or silt soils that retain moisture well. In the middle boreal zone, spruce suffers more from cold ground and night frosts, common also even in summer (Saku and Solantie et al. 2011), than from drought; therefore, the share of pine in this region is greater, with the exception of hill sites in the county of Kainuu; there, soil frost is shallow due a particularly thick snow cover, and the risk of night frosts is small due to forest being mostly situated above the cool low-lying air layer.

Ring-width studies of Scots pine in the strict nature reserves and long-term permanent plots of the Finnish Forest Research Institute do not reveal any long-term trend in annual growth in the southern half of Finland during the 20th century (Mielikäinen and Timonen 1996); on the other hand, examples of responses of the growth on permanent plots on climate exist (see at the end of Discussion). However, these results are not contradictory to the influence of climate on forest growth discussed in this chapter (Mielikäinen, pers. com.). Forests may have reacted to the better climatic conditions mainly by producing more stems, i.e., raising the stem density, while Mielikäinen and Timonen normalised their growth-rates to correspond to an unchanged forest density. Note also that the forest density decreases stepwise northwards. Other forestry measures were also carried out, in addition to the drainage of peatlands and application of fertilizers in the 1970s that may have influenced the growth and structure of the forests. Such factors include thinning-out and the quality of the saplings raised in nurseries. These questions, however, demand specific study and are here left open.

The structure of the forest understorey vegetation also changes by climatic zones and follows changes of climate. In forests on mineral soils, the coverage of dwarf shrubs in the Finnish southern boreal zone in 1985 was 19 %, in the middle boreal 33 % and in the northern boreal 42 %, respectively (basic data: Tonteri et al. 2005). The corresponding coverages of grasses are 16 %, 8 % and 5 % and those of herbs and ferns 10 %, 4 % and 2 %. The changes in vegetation over the period 1951-1953 to 1995 also reflect the movement of the zones due to climatic impact. The share of the dwarf shrubs of the cover of all forest understorey vegetation on mineral lands in Finland decreased from 37 % to 29 %, while the corresponding share of grasses increased from 6 % to 7 % and that of herbs and ferns from 5 to 6 % (Reinikainen et al. 2000), in spite of lesser light. The frequencies of forests in the various fertility classes have correspondingly changed somewhat (Tomppo 2000).

The cover of dwarf shrubs increases and that of trees decreases stepwise northwards, mainly because vegetation increasingly tries to transform solar radiation into sensible heat when progressing northwards.

The increase in the cover of xeromorphic dwarf shrubs across the boundary between the s. and m. boreal zones saves more energy by lower evapotranspiration than it loses by a slightly higher albedo (Solantie 2003, Venäläinen et al. 1998). Sparser stands in the middle boreal zone, however, cause a greater night-time loss of heat in surface inversion situations, favouring Scots pine and dwarf shrubs, resistant to frosts. On the other hand, the milder southern boreal and hemiboreal climates provide a good prerequisite for denser tree stands, although single trees suffer from rivalry, shadowing and a decreased shield of snow cover against soil frost. Dense and tall stands lessen the risk of night frosts during the warm season, thus favouring herbs and fens.

The depth of soil frost is used in the basic equation of the boreal natural environment (Equation 2) because of its relation to the thermal conditions in the root zone and the depth and size of the root system. Considering that the frost sum correlates positively with the depth of soil frost, the positive correlation of +0.2 between the the growth of pine at Punkaharju in East-B and monthly mean temperatures from December to April, obtained by Helama and Lindholm (2003) on the basis of ring-width studies, is in accordance with the results of this study. In higher-situated regions, where abundant orographic precipitation and a thick snow cover keep the ground practically free of soil frost, forests are more productive than expected on the basis of the cool and short growing season. For example, the Livonian highland in Latvia belongs to the hemiboreal zone despite its situation at over 200 m a.s.l. On logged sites, the young plants of deciduous trees, allowing snow to fall evenly to the ground, appear first, thus shielding the spruce saplings. In time, the spruce branches steer the falling snow into an edging collar, forming a shield of thick snow cover over the outer roots.

Solantie (2003) studied the difference between the mean temperatures at 200 cm above the ground level (Tair) and 20 cm below it (Tsoil), and the part of the flux of sensible heat received by the uppermost 50 cm soil layer, using soil temperature statistics for 1971 1990 at various stations (Heikinheimo and Fougstedt 1992). After the melting of soil frost, soil is the coldest in relation to air in June. Because the heat flux to the ground is greater the higher Tair Tsoil is, the soil in regions of deep soil frost warms up rather rapidly, so that by August the values of Tair Tsoil in regions of deep and shallow soil frost become equal. In any case, in summer Tair Tsoil is lower the deeper soil frost has been, especially in June.

The difference in temperature sums between that in soil (Lsoil) 20 cm below the ground and that in air (Lair) up to the end of August decreases by 3.8 °Cd for each cm of F (Solantie 2003). Noting that F in the period 1961-2010 in segments East-A and East-B combined was 12.3 cm smaller than in West (Table 1), the respective difference in Lsoil Lair is 47 °Cd. A study of the spill-water temperatures in underground pipes all around Finland in 1997-2002 includes statistics of the median duration of the period of water temperature above 12 °C by counties (Rantanen et al. 2003). The results, 149 d in East-A, 139 d in East-B and 130 d in West, provide additional evidence of the regional differences in soil temperatures during the growing season. Trees in regions of deep soil frost concentrate their roots in the surface layer, where soil frost melts first, while in regions, where soil frost occurs only in the surface layer; roots find favourable conditions deeper in the ground. Correspondingly, the mass of roots is greater in regions of shallow soil frost; the mass of tree stands and their annual growth, being related to the root mass, are correspondingly greater. This accords with the results of the experiments carried out by Repo et al. (2013). In plots, where snow cover was removed in winter, in the period of 3 years after the experiment the production of new roots above a depth of 15 cm was higher, but beneath this level lower, than in adjacent plots under natural snow cover. Additional evidence of the adaptation of tree root systems to soil frost is given by the observation that the minimum wind speed averaged over a period of 10 min. to cause massive blow-downs in the middle boreal zone under conditions of unfrozen soil and the passage of cyclones is 14 ms^{-1}, while in the southern boreal zone the corresponding limit is 17 ms^{-1} (Solantie 1983). The rivalry of trees with dwarf shrubs in regions of deep soil frost and shallow root systems is stronger than in regions of shallow soil frost, and in the the former case dwarf shrubs use a greater share of the total growth potential for vegetation at the expense of tree stands.

Soil frost is also significant for lower forest vegetation. In regions of deep soil frost and thin snow cover *Vaccinium vitis idaea* is more common than *Vaccinium myrtillus*, and vice versa in regions of shallow soil frost and thick snow cover (Solantie and Drebs 2006; basic data: Reinikainen et al. 2000). The obvious reason is that superterranean parts of *Vaccinium myrtillus* cannot stand temperatures below -32 ºC and remain alive without a snow shield (Solantie 1980), while the stands of *Vaccinium vitis idaea* in regions of deep soil frost are particularly robust in carrying snow load and forming insulating air pockets.

Let us consider the present growth-rate in productive forests G ($m^3ha^{-1}a^{-1}$) by ecoclimatic zones in Finland (Finnish Statistical Yearbook of Forestry 2012) and Sweden (Swedish University of Agricultural Sciences, Dept. Forest Resources Managment 2014) that comprises all the subzones of the boreal main zone. The ecoclimatic zonation for Finland and Sweden are those determined by Ahti et al. (1968) and Sjörs (1967), almost identical. Some of statistical counties comprise parts of various zones; regions comprising areas from two or three zones, were classified according to the dominating zone.

The northern boreal zone, excluding subarctic areas of birch forests: G = 2.9 in Finnish Lapland and 2.7 in Swedish Norrbotten

Middle boreal zone: G = 4.13 in the Finnish counties Pohjois-Pohjanmaa and Kainuu, and 4.09 in the Swedish counties Västerbotten, Jämtland and Dalarna.

Southern boreal zone: In the Finnish area of thick soil frost (West), G = 5.52, and in the areas of thin soil frost, G = 6.70 (in East-A 6.70 and in East-B 6.71), on the average 6.12. In the Swedish area of thick soil frost (Västernorrland) G = 5.5, in the area of thin soil frost (Wärmland) G = 6.8 and in the area of moderate soil frost (Gävleborg) G = 6.2; so, on average in Swedish southern boreal counties G = 6.09.

In the Swedish counties Västmanland and Örebro, at the northern edge of the hemiboreal zone, G = 6.62.

In the hemiboreal mainland counties in Sweden, i.e. Uppsala, Stockholm, Södermanland, Östergötland, Väster Götaland, Jönköping, Kronoberg and Kalmar, on average, G = 6.88.

In the counties of temperate climate, i.e. Halland, Blekinge and Skåne, G = 7.88.

So, the growth-rates in both countries follow exactly and equally the ecoclimatic zonation, and soil frost at least within the southern boreal zone. The reason for this almost complete equality of forest-growth in the same ecoclimatic zones in these two neighbouring countries is expected because the climatic fluctuations as well as the bedrock and structure of soils and the utilisation history of forests during the 50 last years in the respective regions are practically identical.

The only exceptional region in Sweden is the hemiboreal Gotland, where G is as low as 3.5 due to its particularly thin soil layer. In Latvia, all of it consisting of hemiboreal ecoclimatic zone, the present mean value of G, according to the second national forest inventory by the Latvian State Forest Institute ‘Silava’ (Dr. Aigars Jansons, pers. com.), is as high as 7.91, i.e. 15 % higher than in the respective area in Sweden. The main reason is that in Latvia there are practically no stony and rocky areas, common in the southern Sweden.

The increase of the growth-rate of forests (stemwood) over the period 1956 2001 was noticed and studied in British Columbia by Wu et. al. (2014) in permanent plots, eliminating the effect of increasing age of the stands. They found that air temperature, particularly the duration of the thermal growing season (i.e. Lcool), was a factor explaining most of the increase of growth, in maritime areas 58 % and in interior (rather maritime as well), 48 %. The corresponding proportions of solar radiation were 12 and 7 %, and those of precipitation and vapor pressure in both areas 35 %. The respective proportions of the effects of atmospheric CO_2 and deposit of N together, were 32 and 23 %. Ignoring the effect of soil temperature, the authors did not mention that the circulation and utilisation stage of nitrogen depend on soil temperature, regulating greatly the activity of microorganism in the ground.

Conclusions

Boreal forests are mutual interactive systems of vegetation and climate, i.e. ecoclimatic zones. This study confirms the hypothesis that albeit forest producitivity generally follows the changing climate, the geographical structure of the ecoclimatic zonation, the structure of forest vegetation and the relations of the forest productivities between various regions remain practically unchanged, while the boundaries between the neighbouring boreal subzones glide according to the climatic fluctuation. Explaining the growth rate of the productive forests in the southern half of Finland by the thermal factors in air and soil by Equation (2), the steady growth of the residuals indicates the contribution of additional factors. Of such factors, the effects of early-summer precipitation, the drainage of peatland forests, the application of fertilizers in the 1970s and the age structure of the forest stands were studied; it was found that the residuals could be satisfactorily accounted for by these factors. However, open questions still remain; these include, e.g.: the influence of the breeding of plants and the effect of forestry measures on the stand density, especially optimally-timed thinning, and through it to the increase of these improved growth rates. These factors can explain the residuals only at the expense of the effects of the studied factors. Albeit the effects of the considered factors on residuals are rough and may be overestimated, the possible effects of other, yet-to-be-studied factors cannot be significant, particularly with reference to the small size of the residuals.

The development of forest vegetation was also in accordance with the climatic impact on the growth of forest stands. Another open question is the disagreement between the observed increased growth rate of the Finnish forests and the almost unchanged growth of strictly virgin stands in experimental plots. In any case, the forestry measures carried out during the 5 previous decades have been successful, albeit not raising the annual growth per hectare, but by converting most of the poorly productive peatland forest areas and even a part of open peatlands into productive forests; in the 60s, productive forests comprised 68.0 % but in 2009-2011 71.9 % of the total land area of the southern half of Finland (Yearbook of Forest Statistics 1983, Finnish Statistical Yearbook of Forestry 2012).

This study concerned a region consisting mainly of southern boreal areas and to some extent also of middle boreal areas. The main boreal ecoclimatic zone, however, also comprises the hemiboreal subzone south of the southern boreal one, as well as the middle and northern boreal north of it. In the circumpolar hemiboreal subzone, roughly half of the land area consists of cultivated fields, reclaimed on the most productive soils originally covered by deciduous stands. This subzone was thus originally a sort of transition between the boreal and nemoral main zones, while in the present forests the boreal character is accentuated, and the growth rate of the forests may be somewhat below the natural level. Concerning the southern boreal zone, it is circumpolarly the subzone, in which forestry plays a more important role in the economy than in the other subzones. Most of the middle and northern boreal forests are virgin, with exception of those in the Nordic countries and especially in Finland. It would be useful to compare the growth of forest stands in Finland to that in the virgin forests of northern Russia, Siberia and Canada in order to elucidate the impact of forestry methods on the growth of forests. One problem is, however, the difficulty in making climatic and forestial observations having a sufficiently good resolution in these particular regions due to the lack of infrastructure in such huge, practically unpopulated wilderness areas. Only in the northern Europe there are good conditions and traditions for maintaining dense networks of observations, also those, which are troublesome and expensive to automatise or to replace by remote sensing. Especially, the crucial importance of soil frost for boreal vegetation emphasizes the need for a dense insrumental network to carry out snow depth, soil frost and soil temperature measurements, for which this article is a piece of evidence. For these reasons, Northern Europe, from Lithuania and southern Sweden up to Lapland, is the best-suited area in the world, where the productivity and vegetation of boreal forests and the related climatic factors can be most easily and least costs observed and studied over all of the boreal subzones. In this article, the method crystallized in Equation (2), is meant to be a practical tool for estimating forest productivity in the boreal ecoclimatic zone; also, it is demonstrated that this method is able to work successfully in estimating fluctuation as well as to represent the impact of different soil frost depths on forest productivity in neighbouring regions like Sweden and Latvia.

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