Oil Shale, 2008, Vol. 25, No. 1, pp. 75–93
doi: 10.3176/oil.2008.1.08 ISSN 0208-189X

GROWTH ACCELERATION OF *PINUS SYLVESTRIS* IN BOG STANDS DUE TO INTENSIFIED NUTRIENT INFLUX FROM THE ATMOSPHERE

M. KAASIK[(a)*], T. PLOOMPUU[(b)], R. OTS[(c)], E. MEIER[(d)], H. OHVRIL[(a)], O. OKULOV[(e)], H. TERAL[(a)], L. NEIMAN[(a)], V. RUSSAK[(f)], A. KALLIS[(f)], P. POST[(a)]

[(a)] Institute of Physics, University of Tartu
Ülikooli Str. 18, 50090 Tartu, Estonia

[(b)] Chair of Biology, Tallinn University
Narva Road 25, 10120 Tallinn, Estonia

[(c)] Hugo Treffner Gymnasium
Munga Str. 2, 51007 Tartu, Estonia

[(d)] Institute of Ecology and Earth Sciences, University of Tartu
Ülikooli Str. 18, 50090 Tartu, Estonia

[(e)] Tiirikoja Lake Station, Estonian Meteorological and Hydrological Institute
Narva Str. 108, 49604 Mustvee, Jõgevamaa

[(f)] Tartu Observatory
61602 Tõravere, Tartumaa, Estonia

As the pine trees at ombrotrophic bog grow in the extreme lack of nutrients deposited into the soil exclusively from the atmosphere, any increase of deposition affects the growth of trees remarkably. Radial increments of Pinus sylvestris *in bog stands were studied at 6 sites in the North-Eastern Estonia, 7 sites in remote parts of Estonia, a site in Southern Finland and a site in Lithuania. In total 380 cores from trees aged 80–200 years were used for this study. It was found that after a quite steady growth in 1930–1960 annual increments in the oil shale impact area increased about two-times. Rapid growth lasted about two decades, 1970–1990, when the consumption of oil shale and resulting environmental impacts were largest. Smaller but nearly simultaneous acceleration was found in remote sites. Since the 1990´s, the increments decreased again. Such behaviour is in good agreement with both airborne emissions from the local oil-shale-based industry and global human activities. A strong negative correlation between the radial increment and the atmospheric Bouguer transparency coefficient (an integral indicator of column aerosol content of the atmosphere), measured in Estonia since 1932, was found. Thus, the deposition of nutrient-containing aerosol has probably*

* Corresponding author: e-mail *marko.kaasik@ut.ee*

accelerated the growth of pines in bog stands at large European boreal areas.

Introduction

Positive influence of small and moderate deposition loads of oil-shale fly ash (containing Ca, K, Mg and other mineral nutrients) on the growth of trees in ombrotrophic bog stands is a straightforward conclusion from the fact that the growth is strongly limited by lack of nutrients deposited into peat soil exclusively from the atmosphere.

Dramatic impact of fly ash deposition to entire bog plant community (destruction of *Sphagnum* cover, invasion of numerous non-typical species) in North-Eastern Estonia was mentioned already in the 1970's [1]. Rapid growth of pine trees, changing the look of the bog landscape was described as a part of such transformations [2]. Some recent studies deal with the growth acceleration in quantitative terms. Pensa *et al*. [3] compared both radial increment of pines in bog forest in Voorepera near Kohtla-Järve to 6 sites elsewhere in North-Eastern Estonia and 8 reference sites in other parts of Estonia. They found that radial increment increased rapidly starting from 1960, and the average increment of 1964–1997 was about 4 times larger than during the two previous decades. It was also found that the average recent increment at 7 bog forest sites in the North-Eastern Estonia was larger than the average of reference sites by a factor of 1.5. Radial increment was found the most indicative among different characteristics: shoot length and needle age did not have statistically significant difference compared to reference sites. Ots and Reisner [4] compared the radial increments, needle mass per area and nutrients in needles at the Muraka bog (North-Eastern Estonia) and the Tolkuse bog (Western Estonia) and found radial increment the most indicative characteristic again. At the Muraka bog, since 1964, the increment had changed rapidly with the general tendency of increasing instead of smooth decrease due to ageing of trees, as observed at Tolkuse.

There are only few experimental studies on the impact of excess nutrients on the growth of Scots pines at bog. The measurements made at bogs in nearly natural conditions all over the Sweden show no correlation between the increment of trees and nutrients in the peat [5]. Most probably the impact of small variability in nutrition conditions is obscured by different local factors. Fertilising experiments at drained bog stands in Finland, however, show dramatic impact of excess influx of K, P, N and micro-nutrients (B, Cu, Mn etc.) on the growth of trees [6]. After fertilising the stands with KCl (10–40 g/m^2 of potassium), at sites with sufficient availability of nitrogen the volume growth of trees was 5–7 times larger compared to a non-fertilised reference site. The growth of trees accelerated already after even a single act of fertilisation, achieved maximum in 5–10 years and begun slowly to decelerate afterwards. At the highest load of fertilisers (40 g/m^2 of potassium) the deceleration was not remarkable even after 20 years from the moment of fertilising.

According to the estimated deposition fluxes of fly ash in the past [2] and 6.85% content of K_2O in the ash [7], the cumulative loads of potassium during 1960–2000 in the most polluted bog sites were close to 100 g/m^2, e.g. at Kõrgesoo, just between the Estonian and the Baltic Power Plants (together called the Narva Power Plants). Loads exceeding 10 g/m^2 were found at large areas, up to 30 km from the Narva Power Plants and 10–15 km from Kunda, Kohtla-Järve and Ahtme. Thus, detection of a growth acceleration of trees at extensive bog massifs in North-Eastern Estonia was expected. However, these bogs are not drained and probably the excess of water also limits the growth. Additional limitation is availability of phosphorus – less than 0.2% of P_2O_5 was found in fly ash [7].

Increased influx of nutrients, however, is not a local problem in the oil shale processing region, in some extent it occurs worldwide. The growth of industry, transportation and intense agriculture introduced growing amounts of nitrogen and mineral particles into the atmosphere until the end of the 20th century. The peak of emissions in industrially developed countries (incl. Europe) was achieved approximately by 1980. Afterwards, the environmentally oriented technologies in the Western Europe, and a general economic decline in the Eastern Europe took effect and emissions started to decrease.

Because a detailed and continuous monitoring of background air quality was established only after the problem was recognised, there is a lack of direct observations on the influxes of nutrients before the 1980's, i.e. just during the observed period of growth acceleration [3, 4]. Also, the information about pollution sources is too scarce to provide air pollution transport modelling for entire Estonia or the Northern Europe for these times. Fortunately, there exists a bulk characteristic strongly driven by atmospheric aerosol content – the integral transparency coefficient of the atmosphere, available in Estonia already from the 1930's. Altering of transparency occurs due to an increase in aerosol concentration in the atmosphere, responsible for attenuation of solar light and carrying nutrients. Most of the emitted particles, except from great volcanic eruptions, remain in the lower troposphere.

Comparing the records of atmospheric transparency in different parts of Europe, the tendencies were found similar: a short-term (24 months) dimming of the atmosphere after heavy volcanic eruptions like El Chichòn (1982) and Pinatubo (1991). There was a decreasing general trend of transparency from the 1930's to the 1980's, and restoration in the following years, except two post-Pinatubo years [8].

This paper is intended to clarify the geographical extent and the temporal structure of the growth acceleration of the Scots pines at bog. In comparison with previous studies [3, 4] the study area is larger, extending outside of Estonia, a few hundred kilometres away from the oil shale mining and processing region. Besides forested bogs, a ridge-hollow complex with sparse trees is included, as it is the most deficient in nutrients and thus expected to be the part of bog most sensitive to the influence from the air. The atmospheric transparency (the Bouguer coefficient) is applied for comparison as a quantitative index of aerosol pollution in the past.

Data and methods

Radial increment

The map of research sites is presented in Fig. 1. Coordinates and sample sizes are given in Table 1. Trees were selected randomly, but aiming at representative sample for the ombrotrophic bog as a whole: ridge-hollow bog, edges of bog pools, sparse bog forest. In order to eliminate the local factors affecting the growth, each site was actually an area a few kilometres around the marked point. Height of trees varied from 1.5 to 8 meters, as a rule. In Kõrgesoo site, where growth conditions are comparable to mineral land due to fly ash influx, several trees were found higher than 10 m.

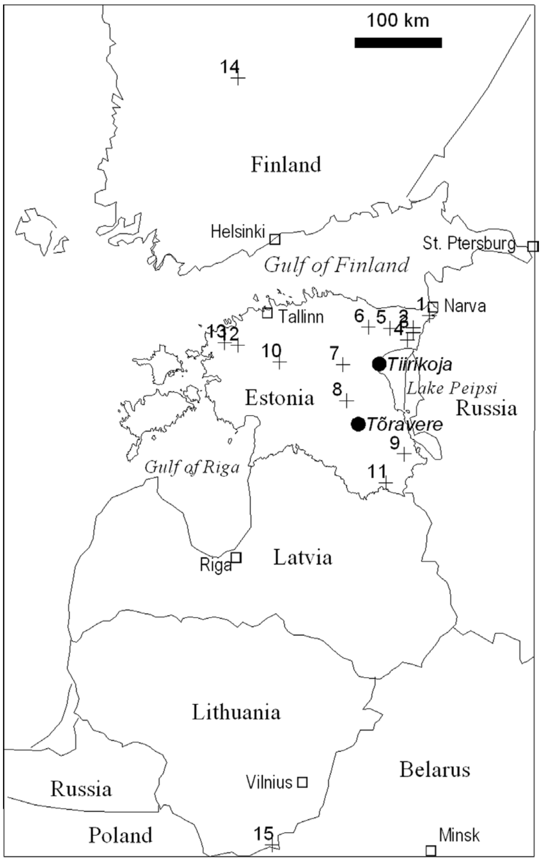


Fig. 1. Bog sites, where coring was carried out (crosses) and monitoring sites of atmospheric transparency (dots). Numbers of bog sites, see Table 1.

Table 1. **Coordinates of research sites and numbers of cored trees**

Name of bog	Latitude (N)	Longitude (E)	Number of trees
North-East Estonia			
1. Kõrgesoo	59°19'	28°02'	15
2. Puhatu, North	59°13'	27°41'	64
3. Puhatu, Central	59°10'	27°40'	28
4. Agusalu	59°05'	27°33'	24
5. Ratva	59°13'	27°13'	23
6. Sirtsi	59°15'	26°47'	18
Other parts (background) of Estonia			
7. Endla	58°53'	26°23'	58
8. Laeva	58°31'	26°16'	14
9. Meenikunno	57°56'	27°19'	32
10. Keava	58°56'	24°58'	29
11. Kellamäe	57°39'	26°56'	22
12. Orkjärve	59°07'	24°08'	14
13. Suursoo	59°09'	23°53'	8
Abroad			
14. Siikaneva & Lakkasuo (Finland)	61°51'	24°17'	56
15. Čepkeliai (Lithuania)	54°01'	24°53'	37

Drill cores were taken through the tree stem in direction East-West. Due to low height of trees, the cores were taken at height of 30–50 cm from moss surface. The cores were scanned and year rings were measured using the *Windendro* software. Both sides of the core were taken into account, thus the statistical sample of sizes is twice the number of trees given in Table 1. In this study only trees of age 80–200 years at drilling height (reference year 2001) are taken into account. The lower age limit was chosen so that all considered trees were growing already before the strong human impact took place and there exist sufficiently long time series before that. The share of younger trees, excluded from further analysis, was less than a half on average, but reflects growth conditions: at Kõrgesoo site 70% of cores were excluded due to young age, despite conscious on-site selection of older trees.

Pines older than 200 years were excluded from the main sample, because they might be too old to give any significant response to improved growth conditions. In total, 18 such trees were drilled, including two about 400 years old trees (one in Finland and one in Laeva bog, Central Estonia). Other 16 trees of this category were found 201–240 years old. This sample was applied to estimate the undisturbed growth deceleration due to ageing, as at least first 150 years these trees grew without significant airborne human impact (direct influences, such as drainage, were excluded choosing the sites). The exponential fit of growth (Fig. 2) gives yearly increment r (mm) depending on age a as

$$r = 0.56e^{-0.0058a} \tag{1}$$

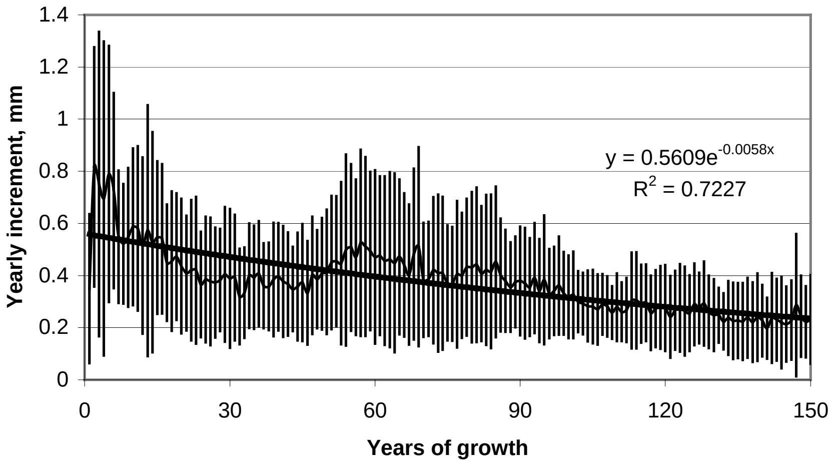


Fig. 2. Yearly radial increment depending on age of *Pinus sylvestris* trees: average, standard deviation and exponential fit. Graph is based on 18 trees older than 200 years in reference year 2001.

Correlation coefficient between exact yearly increment and its exponential fit is 0.85. Consequently, this approximation is applicable as a guess of undisturbed growth curve of growth.

The 200-year series fit based on only two oldest trees gives almost the same curve:

$$r = 0.55e^{-0.0061a} \tag{2}$$

(correlation coefficient 0.78). Thus, the average growth deceleration is rather stable despite (possibly climate-induced) fluctuations.

To compare the growth rates of trees of different age, yearly increments of all trees from samples listed in Table 1 were divided to *r*, formula (1). The result, further referred to as normalised increment, is fluctuating around the value 1, if growth conditions are similar to the 19th and early 20th century.

Atmospheric transparency

The atmospheric transparency was used to assess aerosol pollution of the atmosphere in the past. Transparency is one of the primary measures indicating the state of the atmosphere. Long-term time series of transparency allow us to assess quantitatively the variability of turbidity of the air and to make climatological conclusions with respect to aerosol content of the atmosphere.

In Estonia, multi-annual time series of atmospheric transparency were derived from routine measurements of the broadband direct solar beam at three locations: Tartu, Tõravere and Tiirikoja.

Before the World War II, 1932–1940, measurements of direct solar beam were started at Meteorological Observatory of the University of Tartu (Liivi Str 4, 58.38°N, 26.72°E). After the war, since 1950 the measurements were continued at the Tartu Actinometric Station, located at the outskirts of the town (58.35°N, 26.68°E). In 1965 the station was removed to its present location, Tõravere (58.27°N, 26.47°E, 20 km from Tartu). Since 1999 the Tõravere actinometric station (officially the Tartu-Tõravere Meteorological Station) has been included into the Baseline Surface Radiation Network. The BSRN is a project of the World Climate Research Programme (WCRP) and the Global Energy and Water Experiment (GEWEX), and as such, is aimed to detect important changes in the radiation field at the Earth's surface which may be related to climate change.

Due to closeness of Tartu and Tõravere, the same radiation sensor (Yanishevsky actinometer AT-50) and unchanged measurement methods used, the data of both stations can be combined in one time series, covering the years 1950–2006. With some reservations, the earlier measurements in Tartu (1932–1940) can be also considered as a prolongation of the length of this time series.

From the end of 1955, the measurements of broadband solar beam were started at the Tiirikoja Lake Station (58.87°N, 26.95°E) located on the western shore of Lake Peipsi, 70 km NE from Tõravere and about the same distance SW from the Narva Power Plants. Summarizing, there are two multiannual time series of broadband direct solar radiation available for Estonia: a longer but interrupted series for Tartu-Tõravere, 1932–1940, 1950–2006, and an entire but shorter series for Tiirikoja, 1956–2006. They both allow calculation of coefficients of atmospheric (column) transparency.

According to the well-known Bouguer-Lambert law, the ratio of the intensity of the broadband direct solar beam S_m, which reaches the Earth's surface after attenuation in the air (direct solar radiation) to that at the top of the atmosphere, S_0, serves as the basic quantity for calculation of various characteristics of atmospheric transparency and turbidity. The basic parameter, the Bouguer atmospheric integral transparency coefficient, p_m, is given by formula:

$$p_m = \left(S_m / S_0\right)^{1/m}, \tag{3}$$

where m is the relative (optical) air mass and S_0 is the actual extraterrestrial broadband solar irradiance. Its average value, the Solar constant, is 1.367 kW/m^2.

Because of the Forbes effect, caused by the selective spectral attenuation (especially scattering) of direct solar radiation in the atmosphere, p_m depends on solar elevation angle h even in the case of stationary and azimuthally homogeneous atmosphere. In order to eliminate the Forbes effect, it is generally accepted to reduce the p_m from the actual air mass m to p_2 which corresponds to air mass $m = 2$ (solar elevation $h = 30°$).

This transformation (elimination of diurnal trends of broadband optical characteristics) comprises a complicated problem of atmospheric optics. In this work we used an engineer formula, elaborated in the University of Tartu [9]:

$$p_2 = p_m \left(\frac{2}{m} \right)^{\frac{\log p_m + 0.009}{\log m - 1.848}}, \quad (4)$$

which enables transition from any optical mass m to a standard one, $m = 2$.

The annual average atmospheric broadband transparency coefficients, according to Formula (4), are given in Fig. 3. During the years 1980–1984 and 1991–1994 there were sharp minimums due to volcanic eruptions. As volcanic gases like SO_2 affect the atmospheric transparency at large distances and long time scale through the processes in the stratosphere, these minimums have no effect on growth conditions. Therefore, these years were excluded from the intercomparison of atmospheric transparency and yearly radial increment of trees.

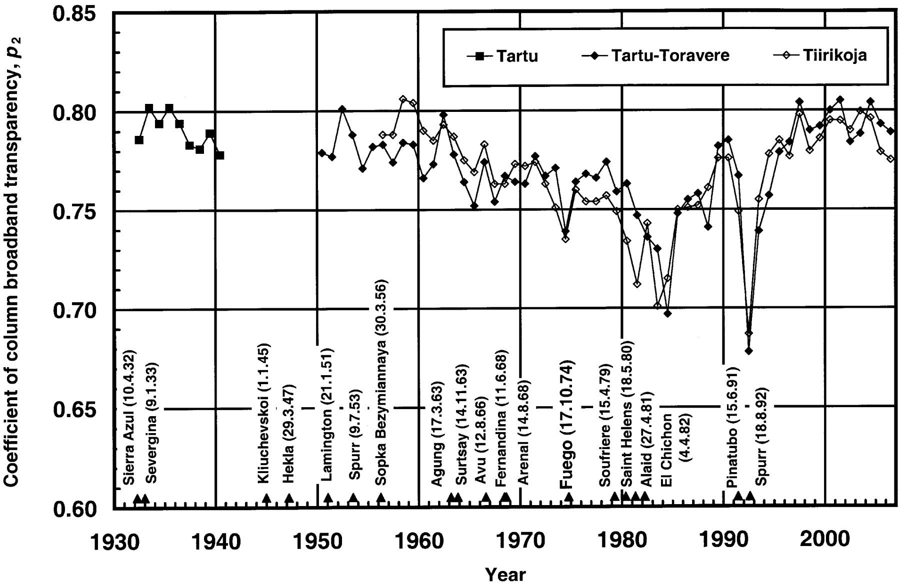


Fig. 3. Variations of atmospheric column broadband transparency, yearly average values in monitoring stations Tartu, Tartu-Tõravere and Tiirikoja. Times of volcanic eruptions are given with labelled triangles.

Results

The time series of average normalised yearly increment are given in Fig. 4. The same general pattern, expressed more or less clearly, is present in all four areas: (1) nearly stationary growth, approximately during 1930–1959; (2) growth acceleration, (1960–1989); (3) deceleration, (1990–2001). Thus, for further analysis, increments from all 4 areas were grouped into these three time intervals, thus producing 12 groups of data, containing from 876 to 10560 single results of measurements (normalised yearly increments) each.

According to one-sample Kolmogorov-Smirnov test, the normal distribution hypothesis is rejected for all 12 groups. One of reasons of non-normality is obvious: infinite range of data is an assumption for normal distribution, but yearly increment is limited from below: it cannot be less than zero. That condition for normality is not fulfilled even approximately, because variability of data is in the same range with mean (see standard deviations in Table 2).

Table 2. **Basic statistics of normalised yearly increments, grouped by areas and time intervals**

Area	Years	Valid N	Mean	Median	Lower quartile	Upper quartile	Std. dev.
North-East Estonia	1990–2001	3970	1.80	1.56	0.97	2.33	1.15
	1960–1989	10045	1.98	1.70	1.09	2.58	1.24
	1930–1959	10118	0.93	0.81	0.52	1.20	0.57
Estonia, background	1990–2001	4152	1.43	1.23	0.81	1.83	0.88
	1960–1989	10463	1.48	1.26	0.82	1.90	0.93
	1930–1959	10560	0.94	0.81	0.54	1.20	0.60
Finland	1990–2001	1294	1.09	0.88	0.56	1.49	0.72
	1960–1989	3297	1.11	0.97	0.62	1.44	0.69
	1930–1959	3300	1.00	0.88	0.57	1.30	0.60
Lithuania	1990–2001	876	1.11	0.99	0.56	1.58	0.69
	1960–1989	2190	1.49	1.15	0.65	1.85	1.26
	1930–1959	2190	1.05	0.82	0.43	1.42	0.86

Due to non-normality, the non-parametric sign test was applied to estimate the significance of differences between groups. The zero hypothesis (belonging of both groups in the same statistical ensemble) was rejected for all pairs of groups with one exception: between Finland, 1930–1959, and Lithuania, 1960–1980. In this case, the Lithuanian sample has long tail towards high values, making a clear difference in means, but leaving the sign test inefficient.

Thus, we have demonstrated that growth conditions affecting the increment were different at different areas and also, between the three time intervals, therefore the further comparison of all 12 groups is meaningful.

Mean normalised increments during the “local pre-industrial era” (1930–1959) fit within a narrow diapason of ±8% around one (incl. Lithuania), but differences increase dramatically during the next time interval, 1960–1989. The increments increased at all areas, but in North-Eastern Estonia their mean values were doubled, at the same time the growth acceleration in Finland was only 10%. At Estonian background sites and Lithuania the growth was accelerated nearly by a factor of one-and-a-half. In North-Eastern Estonia and Lithuania the deceleration after 1989 was significant, but mean increment remains well above the initial level in 1930–1959. All medians are lower than means, reflecting the asymmetric distribution due to zero-limit below.

Analysing the normalised yearly increments in separate sampling sites (Table 3), we found that despite a quite large variability, there exists a tendency of decrease with the distance from Narva Power Plants (exactly:

from the Estonian Power Plant, the largest one) during 1960–1989 and 1990–2001. The retrospective overview of deposition fluxes of particulate matter, based on the atmospheric dispersion modelling (AEROPOL model), basic features see [10], recent updates [11]), is given in [12], more detail time series since 1988 in [13]. The emission data for modelling (1960–1990) were estimated by Punning *et al*. [14], later data originate from annual reports by the Environmental Information Centre of the Ministry of Environment of Estonia. In Table 3 there are given the average yearly deposition fluxes in 1960–89 and 1990–2001 at exact locations of increment coring sites. The fluxes in all sites before 1960 were nearly equal to zero except Ratva, where the main pollution source, the Kohtla-Järve Power Plant, started to operate from 1950. Comparing the yearly radial increments with model-estimated deposition fluxes near the Narva Power Plants, it is evident that the increment tends to increase with deposition flux.

Table 3. **Average normalised yearly increments compared to the deposition fluxes of oil-shale fly ash**

Name of bog	Distance from Estonian Power Plant, km	Normalised increment			Fly ash flux, g/m^3 per year	
		1990–2001	1950–1989	1930–1959	1990–2001	1960–1989
Kõrgesoo	10	1.72	2.23	0.77	26.1	53.2
Puhatu, North	14	2.22	2.18	1.01	5.4	11.5
Puhatu, Central	18	1.59	1.79	0.74	4.2	9.0
Agusalu	28	1.78	2.00	0.93	2.3	6.6
Ratva	39	1.81	2.08	0.99	1.4	5.9
Sirtsi	64	1.31	1.40	1.08	1.1	2.8
Endla	105	1.55	1.57	1.00	–	–
Laeva	126	1.54	1.86	0.99	–	–
Meenikunno	152	1.17	1.07	0.75	–	–
Keava	172	1.60	1.73	0.96	–	–
Kellamäe	189	1.16	1.44	1.03	–	–
Orkjärve	215	1.19	1.12	0.94	–	–
Suursoo	230	1.72	1.60	0.88	–	–
Finland	349	1.09	1.11	1.00	–	–
Lithuania	620	1.11	1.49	1.05	–	–

Yearly average normalised radial increments *versus* atmospheric broad-band transparency coefficient are plotted in Fig. 5. Keeping in mind the time series of both quantities (Figures 3 and 4), it is obvious that high increments occur with low transparencies and *vice versa*. Naturally, the dependence is much clearer for Estonian sites than for the foreign (more remote) ones. Correlation between the increments in North-Eastern Estonia and transparencies at Tiirikoja (just at the edge of this area) is as good as –0.81. It is interesting that

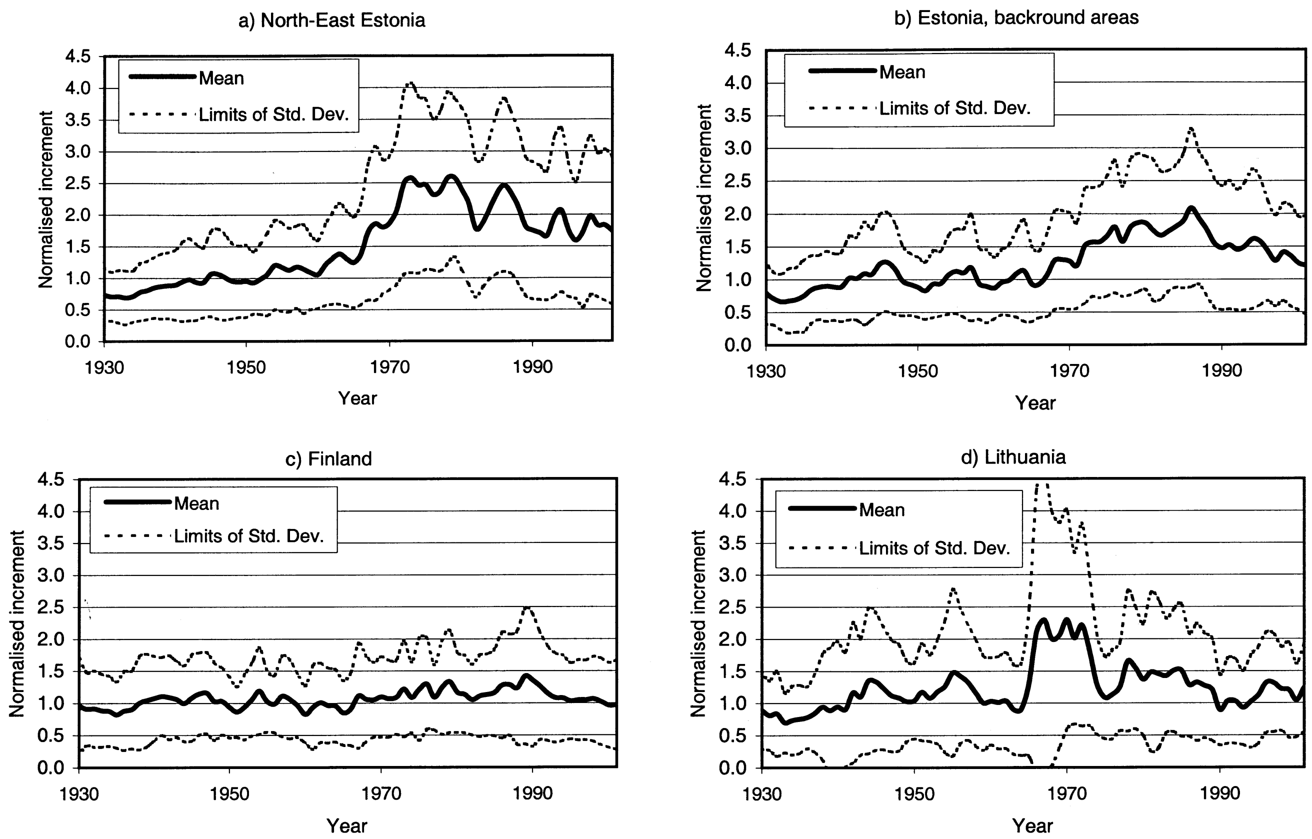


Fig. 4. Time series of normalised yearly increment (annual mean and standard deviation: a) North-Eastern Estonia, b) Estonia, other parts (background), c) Finland, d) Lithuania.

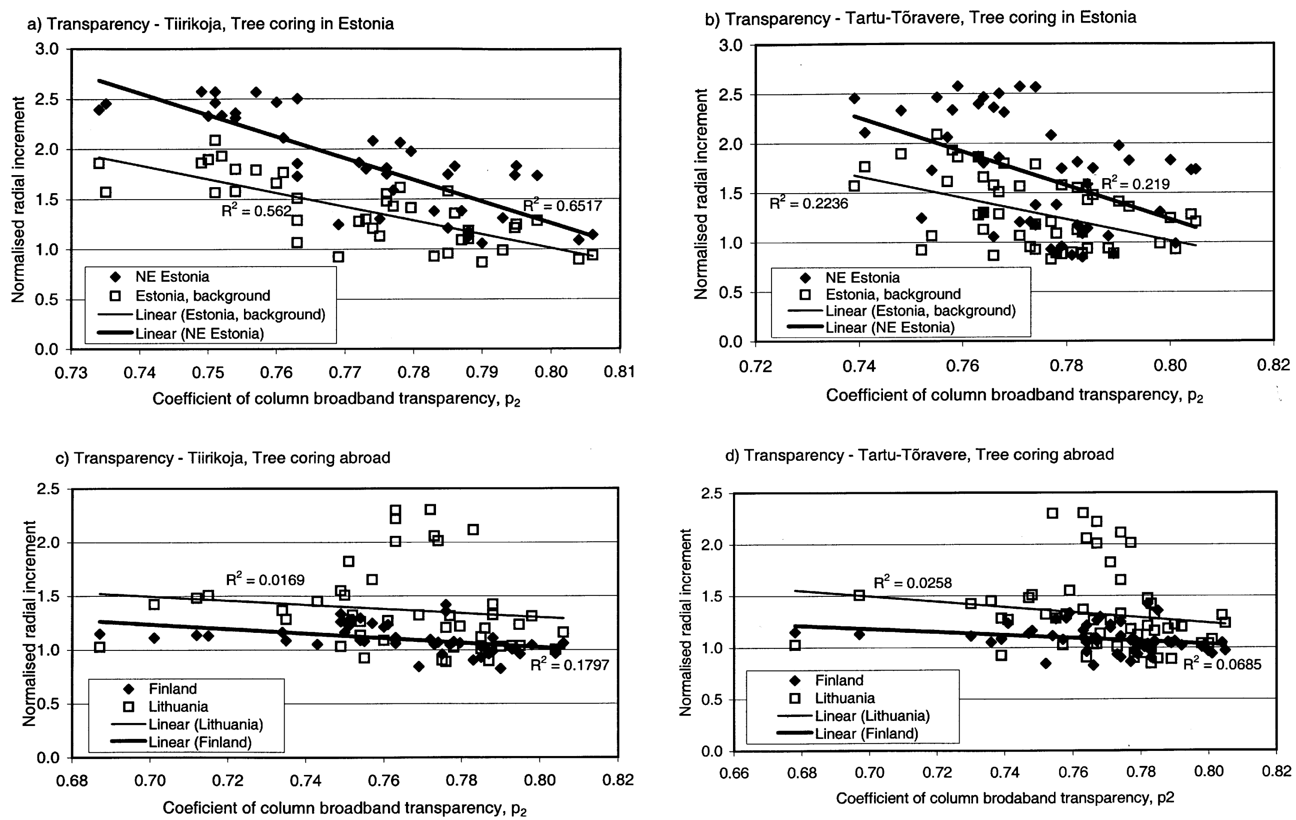


Fig. 5. Normalised yearly increment *vs.* atmospheric transparency: a) transparency at Tiirikoja, tree coring in Estonia; b) transparency at Tõravere, tree coring in Estonia; c) transparency at Tiirikoja, tree coring abroad; d) transparency at Tõravere, tree coring abroad.

even for Estonian background sites the correlation is better with Tiirikoja than with Tõravere. Selecting from Tõravere the years since 1956 only (the same as available for Tiirikoja), we get a slightly better correlation (–0.51 instead of –0.47), but still much poorer than at Tiirikoja (–0.75).

Regarding the correlation coefficients of increments at separate sites (Table 4), the sites closer to the monitoring station are in general better correlated with measured transparency, but both Tiirikoja and Tõravere have best correlation with Kõrgesoo (–0.86 and –0.60, respectively) – the site most heavily subjected to the fly ash influx. Next highest correlations occur with Keava site in central Estonia (–0.84 and –0.58). Lithuania (Čepkeliai) is the only site, which has better correlation with Tõravere than with Tiirikoja (–0.43 and –0.30, respectively). All correlations, except between Lithuanian increment and transparency at Tiirikoja, are statistically significant at confidence level of 95%.

Table 4. **Correlations between time series of normalised increments and atmospheric transparency, 1932–2001**

Name of bog	Distance from, km		Correlation with transparency	
	Tõravere	Tiirikoja	Tõravere	Tiirikoja
Kõrgesoo	148	80	–0.60	–0.86
Puhatu, North	127	57	–0.47	–0.69
Puhatu, Central	122	53	–0.56	–0.80
Agusalu	111	43	–0.53	–0.73
Ratva	115	42	–0.56	–0.80
Sirtsi	111	44	–0.67	–0.61
Endla	70	42	–0.52	–0.63
Laeva	30	56	–0.62	–0.76
Meenikunno	63	106	–0.40	–0.54
Keava	115	115	–0.58	–0.84
Kellamäe	74	135	–0.57	–0.81
Orkjärve	165	164	–0.42	–0.56
Suursoo	179	179	–0.47	–0.62
Finland	417	363	–0.42	–0.56
Lithuania	489	561	–0.43	–0.30

Discussion

The most common reason of long-term variability of tree increment is (often periodical) variability of meteorological parameters. But hardly there exists any significant climatic factor, correlated with rapid growth acceleration since 1960 and deceleration after 1990: tendencies of warming and increase of precipitation amounts have been found rather monotonous during the second half of the 20th century [15]. Increase of CO_2 concentration in the atmosphere is expected to affect directly the plant growth. Again, this is a monotonously increasing factor that cannot explain alone the curve of radial growth having a maximum in eighties. The extent of acceleration-deceleration is much higher at sites located near known air pollution sources (North-Eastern Estonia – oil shale industry; Čepkeliai, Lithuania – higher population density, closer to Central Europe) than at more remote sites (Hyytiälä-Siikaneva area, Finland). On the other hand, the radial increment is well (negatively) correlated with atmospheric transparency, which is an indicator of aerosol pollution in the atmosphere, recorded for long time enough to follow the changes in industrial emissions.

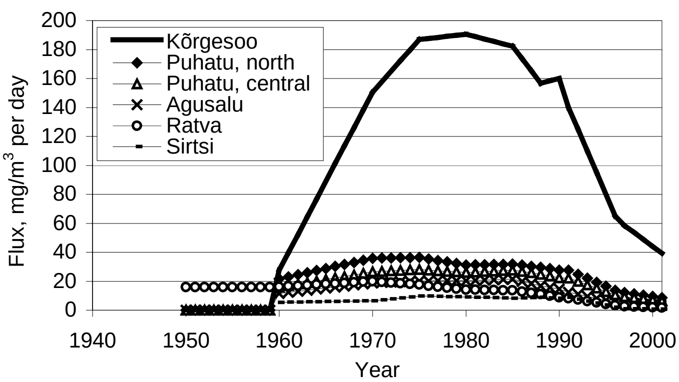
Thus, it is most natural to suppose that the main factor affecting the growth of *Pinus sylvestris* at bog (in time scale of decades) is the availability of nutrients from the air, although additional climatic effects are not excluded. Besides the general growth tendency with atmospheric load of nutrients, there exist quite large variances between sites located close to each other. These are most probably due to uncertainty choosing the sites for sampling: although visually similar bog landscapes were selected, many local factors (e.g. depth of peat layer, water level and intensity of natural drainage, fires and parasite damage in the past, microclimatic variations) may be not fully understood. Thus, fixing the site type (e.g. bog forest or ridge-hollow complex) more precisely would not help us to diminish the scatter of data: most probably the variability of increment within each site will decrease, but variability between the sites will increase, as sampling method will be more sensitive to the uncontrolled factors listed above.

It is interesting, why the Tartu-Tõravere time series of atmospheric transparency (longer and generally believed more accurate) correlates worse with yearly increments than the series from Tiirkoja station. That phenomenon is understandable for North-Eastern Estonia, as Tiirikoja is located only at 40–80 km from these sites, Tõravere at 100–150 km. However, samples from other parts of Estonia are correlated better with Tiirikoja as well. This difference cannot be fully eliminated, taking time series of equal length from both stations. Only Lithuanian (Čepkeliai) data correlate slightly better with Tõravere than with Tiirikoja. Čepkeliai is 70 km closer to Tõravere than to Tiirikoja. That a small difference in distance, however, cannot be the only reason of better correlation, as increments at Meenikunno and Kellamäe sites, much closer to Tõravere, are still better correlated with transparency at Tiirikoja. Possibly, a large part of transparency variations at Tiirikoja occurs due to fly ash particles originated from the Narva Power Plants and being relatively large, typically 5–10 mm in diameter [16] and distributed within lower 1000 m of the atmosphere. Thus, these particles are deposited mainly in Estonia, and a small part of them reaches close areas like Southern Finland [17]. Tõravere is at larger distance from Narva. Thus, the variations in transparency there may be affected mostly by long-range transport of fine aerosol that is distributed in a much thicker layer of the atmosphere and thus, giving a much smaller part of total deposition of nutrients. Then, better correlation of transparency in Tõravere with increments of trees in Lithuania may be due to a definite impact of Central European emissions or both quantities.

The question about specific transparency conditions of Tiirikoja, possibly making it more representative for entire Estonia (or more representative, indicating the airborne nutrients), remains open and needs further investigation.

Let us examine the impact of fly ash to the growth of pines at bogs in the oil shale processing area in detail (time series of deposition fluxes and normalised radial increments by sites, see Fig. 6). Pietiläinen *et al*. [6] have found that after once fertilised with potassium, the radial increment of bog pine stands start to increase and reaches maximum, as a rule, after 5–10 years that could be called the response time of stand. If fertilisation is not an instantaneous act but continuous influx during decades like in the North-Eastern Estonia, the response time can be estimated from the cross-correlation function, a common method to detect statistically the delayed impacts.

(a)



(b)

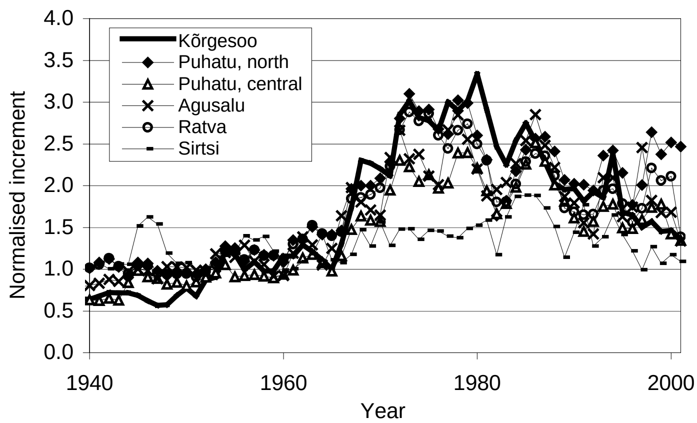


Fig. 6. Deposition fluxes of technogenic alkaline particles (fly ash and cement dust), based on atmospheric dispersion modelling (a) and normalised yearly increments (b) during 1940–2001.

For that the yearly increments are shifted by 1, 2, 3 etc. years backwards in time; then the Pearson correlation coefficient is calculated as a function of time lag. The lag of highest correlation indicates the response time. For four sites out of six the response times appear in range of 3–7 years (Fig. 7).

The far strongest impact (Kõrgesoo) seems instantaneous: correlation is maximal at zero lag; for second weakest impact (Ratva) it is delayed by 11–13 yeas. It is straightforward do think that impact of higher loads appears faster. Nevertheless, less than one year seems, perhaps, too short for that. In this connection, we have to keep in mind several activities before the oil shale combustion, e.g. construction works of the Baltic Power Plant that started in mid-fifties only a few kilometres away from Kõrgesoo site. In general, the response times seem longer for weaker impacts. Naturally, the correlations are higher for stronger impacts as a rule. All correlations presented in Fig. 7 are statistically significant.

Besides the impact time we analysed the relationship between total influx and total normalised increment during 1960–2007. Increase of total growth with influx is obvious, although not exactly for each particular site. Kõrgesoo, far the most affected site, the total growth (see Table 3) was not larger than in sites affected by 5–10 times smaller fluxes. Limited availability of some nutrients (phosphorus in first order) may be a reason, but probably even larger is the effect of obscuration of old trees by younger ones at Kõrgesoo. Dense stand of 20–40 years old pines is growing on previous open bog, sparse old trees with average age over 100 years cannot grow by the same rate in height and occurred below the younger ones.

Possible response of radial increment to the changes in climate can be studied in the same manner as to the influx – using the cross-correlations. Cross-correlations of normalised increment with time series of yearly, warm season (April–October) and cold season (November–March) average tem-

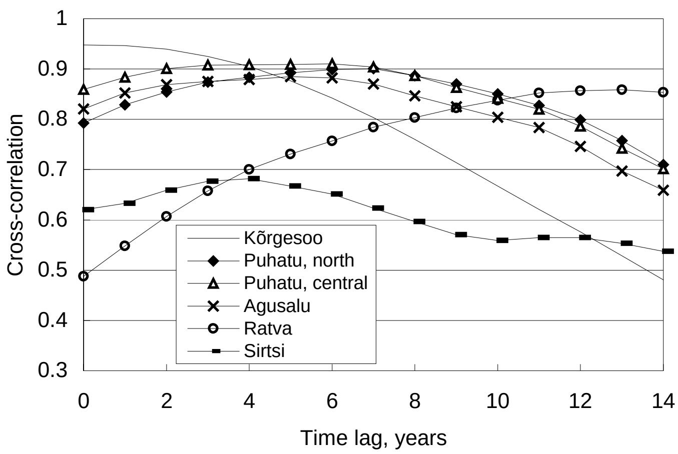


Fig. 7. Cross-correlations between the influx of technogenic particulate matter (see Fig. 6) and normalised radial increment of *Pinus sylvestris* (bog stands).

peratures (about temperature data, see e.g. [15]) appeared much lower than correlations with fly ash influx, in range of –0.35 to +0.2. The largest negative correlations (about –0.3) were found with warm season temperatures at time lags more than 10 years. Obvious reason is some cooling tendency from 1940 to 1960 and warming since 1980. Shifting the series of increments backwards in time matches the maximum of increment with a slight minimum in temperature. The cross-correlations of radial increment series from background areas of Estonia, Lithuania and Finland with temperatures are between –0.3 and +0.1. There is no reason to think that cooling summers stimulate growth of trees with delay of 10–15 years. Most probably this is just a coincidence.

A well-known reason of damages and growth deceleration of coniferous trees in northern Europe is acid rain. In the case of studied bog stands the growth changes are in opposite phase with known development of the acidification: in sixties and seventies, when the acidity of precipitations increased, the radial increments were growing; during the control and decrease of acid pollution – eighties and nineties – the increments decreased. Thus, the positive impact of increasing nutrient influx has probably overruled the negative impact of acid precipitations in observed sites. In the oil shale mining and processing area the acidification did not occur – due to excess of fly ash the precipitations were even alkaline [10, 16].

Changes in water regime can affect the growth of pine trees. Indeed, in the sixties, just in the time when radial increments increased, intense melioration was carried out everywhere in Estonia. In the nineties the activities stopped and ditches were abandoned. Nevertheless, it is doubtful that melioration could affect seriously the growth of pines in research sites – according to the research carried out by U. Tomberg, the water penetrability of bog soil is extremely low and thus, a ditch, regardless of its depth, affects the water table only at distances up to a few tens of metres [17]. None of the sampling sites was not closer than 200 m to the closest ditch, Northern Puhatu and Agusalu sites even farther than 1 km away. On the mined areas or near open-pit mines the drying of bogs from below may occur due to depression of subsoil water. That might be quite likely in Kõrgesoo and Puhatu sites, but not in Agusalu, 20 km away from the nearest mine. Nevertheless, growth acceleration in Agusalu is the second largest after Kõrgesoo.

Conclusions

1. Influx of anthropogenic nutrients from the air has caused growth acceleration of *Pinus sylvestris* at bogs in Baltic countries and Finland during about 1960–1980. Control of long-range air pollution conditioned a slight growth deceleration since 1990.
2. The growth acceleration was most dramatic (about two-fold) in the North-Eastern Estonia, due to regional impact of mineral particles from

oil shale mining, processing and energy production and smallest (about 10%) in a remote area – central part of Southern Finland.
3. Combination of tree increment drilling at bog sites and atmospheric transparency series gives valuable information about atmospheric pollution in the past – good negative correlation refers to airborne particles in the lower troposphere, containing mineral nutrients.
4. More research is needed to clarify the possible factors affecting the growth acceleration and deceleration of pines, including the changes in water regime.

Acknowledgements

This research was supported by the Estonian Science Foundation Grants No. 5002, No. 5857 and No. 7347.

REFERENCES

1. *Karofeld, E.* The effects of alkaline fly ash precipitation on the Sphagnum mosses in Niinsaare bog, NE Estonia // Suo. 1996. Vol. 47, No. 4. P. 105–114.
2. *Kaasik, M., Ploompuu, T., Alliksaar, T. Ivask, J.* Alkalisation and nutrient influx from the air as damaging factors for sub-boreal ecosystem // Proceedings of 8th International Conference on Environmental Science and Technology / T. D. Lekkas (Ed.). Myrina, Lemnos, Greece: University of the Aegean, 2003. P. 365–372 (available on CD).
3. *Pensa, M., Liblik, V., Jalkanen, R.* Temporal changes in the state of a pine stand in a bog affected by air pollution in Northeast Estonia // Water, Air, and Soil Pollution. 2004. Vol. 159. P. 87–99. doi:10.1023/B:WATE.0000049191.36830.a7
4. *Ots, K., Reisner, V.* Scots pine (Pinus sylvestris L.) and its habitat in Muraka bog under the influence of wastes from the Narva power plants (North-East Estonia) // Proc. Estonian Acad. Sci. Biol. Ecol. 2006. Vol. 55, No. 2. P. 137–148.
5. *Ohlson, M.* Growth and nutrient characteristics in bog and fen populations of Scots pine (Pinus sylvestris) // Journal Plant and Soil. 1995. Vol. 172, No. 2, P. 235–245.
doi:10.1007/BF00011326
6. *Pietiläinen, P., Moilanen, M., Vesala, H.* Nutrient status and growth of Scots pine (Pinus sylvestris L.) on drained peatlands after potassium fertilisation // Suo. 2005. Vol. 56, No. 3. P. 101–113.
7. *Pets, L. I., Vaganov, P. A., Knoth, I., Haldna, Ü., Schwenke, H., Schnier, C., Juga, R.* Microelements in oil shale ash of the Baltic Thermoelectric Power Plant // Oil Shale. 1985. Vol. 2, No. 4. P. 379–390 [in Russian, with English summary].
8. *Wild, M., Gilgen, H., Roesch, A., Ohmura, A., Long, Ch. N., Dutton, E. G., Forgan, B., Kallis, A., Russak, V., Tsvetkov, A.,* From dimming to brightening:

decadal changes in solar radiation at Earth's surface // Science. 2005. Vol. 308, No. 5723. P. 847–850.

9. *Ohvril, H., Okulov, O., Teral, H., Teral, K.* The atmospheric integral transparency coefficient and the Forbes effect // Solar Energy. 1999. Vol. 66, No 4. P. 305–317. doi:10.1016/S0038-092X(99)00031-6
10. *Kaasik, M.* Atmospheric dispersion and deposition of technogenic calcium: model estimation and field measurement // Proc. Estonian Acad. Sci. Ecol. 1996. Vol. 6, No. 1/2. P. 41–51.
11. *Kaasik, M., Kimmel, V.* Validation of the improved AEROPOL model against the Copenhagen data set // International Journal of Environment and Pollution. 2004. Vol. 20, No. 1–6. P. 114–120.
12. *Kaasik, M., Liblik, V., Kaasik, H.* Long-term deposition patterns of airborne wastes in the North-East of Estonia // Oil Shale. 1999. Vol. 16, No. 4. P. 315–330.
13. *Liiv, S., Kaasik, M.* Trace metals in mosses in the Estonian oil shale processing region // Journal of Atmospheric Chemistry. 2004. Vol. 49. P. 563–578. doi:10.1007/s10874-004-1266-z
14. *Punning, J.-M., Liblik, V., Alliksaar, T.* History of fly ash emission and paleo-records of atmospheric deposition in the oil shale combustion area // Oil Shale. 1997. Vol. 14, No. 3. P. 347–362.
15. *Jaagus, J.* Climatic changes in Estonia during the second half of the 20th century in relationship with changes in large-scale atmospheric circulation // Theor. Appl. Climatol. 2006. Vol. 83. P. 77–88. doi:10.1007/s00704-005-0161-0
16. *Aunela, L., Häsänen, E., Kinnunen, V., Larjava, K., Mehtonen, A., Salmikangas, T., Leskelä, J., Loosaar, J.* Emissions from Estonian oil shale power plant // Oil Shale. 1995. Vol. 12, No. 5. P. 165–177.
17. *Sofiev, M., Kaasik, M., Hongisto, M.* Distribution of alkaline particles over the Baltic Sea basin // Water, Air, Soil Pollution. 2003. Vol. 146. P. 211–223. doi:10.1023/A:1023904501653
18. *Valk, U.* (Ed.) Estonian Peatlands – Tallinn, Valgus, 1988. P. 178 [in Estonian, with English summary].

Presented by J. Soone
Received June 20, 2007