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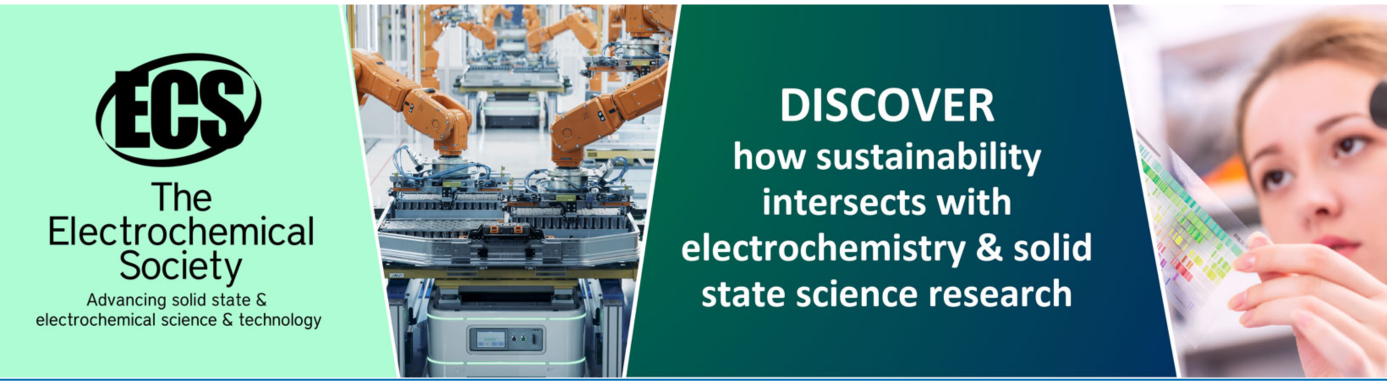

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Dendroclimatic investigations of *Pinus sylvestris* L. in the sub-Arctic boreal forests

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Abstract. The aim of the study was to assess the influence of climatic factors on the growth of pine trees in the boreal forests of the sub-Arctic zone, and to identify environmental conditions for which it is possible to obtain tree chronologies containing a climate signal. Most suitable for dendrochronological analysis are the composite data series on pine stands sparsely growing in over-moistured conditions, as these have the highest sensitivity coefficient. In bilberry pine forests, stress index is low despite the proximity to the pulp and paper mill, recreational load, and improvement felling. The pine stands on wetlands show the average stress index. In conditions of anthropogenically caused air pollution, the tree-ring chronologies for pine growing on wetlands are characterized by increased levels of autocorrelation of the first order, which requires such pine stands be excluded from standardization process. Moderate correlation of growth indices, with precipitation in May and June, was revealed in the bilberry pine forests which underwent thinning. In the remaining sample plots, the relationship between the growth indices and the temperatures and precipitation of individual months may be weak or absent.

1. Introduction

The analysis of the wooden structures of the Arctic Islands and, ultimately, of the Arctic exploration in general and the Arctic drifting wood in particular, should rely on the supporting chronology of boreal forests [1]. The existing banks of reference chronologies are not enough due to the fact that the trees growing in optimal and extreme conditions defy time referencing. The dendroclimatic studies allow reconstructing and forecasting of natural and climatic changes [2]. The most important stage in carrying out dendroclimatic work is the selection of such areas and habitats for which it is possible to obtain tree chronologies containing a climate signal [3]. In tree-ring chronology, the climate signal is manifested in the trees growing in pessimal habitats (boundary of tree plant habitats, northern areas) [2]. This is due to the fact that in the North, the reaction of trees to changes in the environment manifests itself earlier and in a more pronounced manner [4].

The land territories of the Arctic zone are unique ecosystems, the close attention to which is connected with their global ecological significance and active involvement in a wide industrial development [5]. At present, it is believed that the ecological functions of the Arctic forests are much more important than their resource potential. The sub-Arctic forest vegetation plays a climate-protective role [6]. Boreal forests tend to deposit more carbon than any other terrestrial ecosystem, and almost twice as much as tropical forests. This makes boreal forests a key factor for climate change in the future [7]. The boreal and tundra forests play an important role as stabilizers of the natural hydrological regime of the Arctic Basin rivers, influencing the regional climate change and the Arctic ice edge [8].

Consequently, boreal forests are an important element in conservation and study of the Arctic. Therefore, it is important to study both ecological and indicator functions of sub-Arctic boreal forests.

The aim of this study is to assess the influence of climatic factors on the growth of pine trees in the sub-Arctic boreal forests, and to identify environmental conditions for which one can obtain tree chronologies containing the climate signal.

2. Results

The study covered the pine plantations enjoying different growing conditions in the one of Arkhangelsk forestry units (64°20′N - 64°40′N). The forests growing in the northern part of Arkhangelsk Region fall within the southern border of the Arctic. According to the commonly accepted definitions of the Arctic borders, the 60th parallel constituted the southern boundary of the Arctic [9, 10, 11, 12].

The sample plots (SP) were laid by conventional methods [13, 14] in bilberry pine forests exposed to various anthropogenic factors – recreational load (SP4), proximity to pulp and paper mill (PPM) (SP 1,2), improvement felling (SP6); as well as to extreme conditions of wetlands (SP8) (table1). The stage of digression was determined according to the method developed by H.S. Kazanskaya [15]. 15 to 20 model trees were selected by random sampling on the sample areas. Preference was given to healthy trees with no visible signs of damage. The samples of pine wood for dendroclimatic analysis were taken from growing trees in the form of cores at a height of 1.3 m on one radius on the northern side using Pressler increment bore. The width of tree rings was measured on semiautomatic measuring system LINTAB with software package TSAP with 0.01 mm precision. From the obtained individual series of increment in each forest type, 10 of the most old-age trees were chosen. Generalized tree-ring chronologies were obtained from them. To identify the influence of climatic factors, the relative increment indexes were calculated using the method of 11-year sliding smoothing. To assess the quality of dendrochronological series, the following parameters were calculated: correlation coefficients, synchronization coefficient [16], sensitivity coefficient [17], stress index [18], expressed population signal (EPS) [19].

To compare the generalized chronology with weather conditions, we used the archive of instrumental meteorological data of the All-Russian Research Institute of Hydrometeorological Information; the world data center was used (www.meteo.ru/data) with a monthly course of air temperature and precipitation according to weather station "Arkhangelsk".

Statistical processing of the results was performed using MS Excel 2000, Statistica 10.

Table 1: Description of sample plots

SP	Type of forest*	Structure**	Average height, m	Average diameter, cm	Relative density	Age years	Stage of digression	Distance from PPM, km
1	BPFW	9P1B unitS	16.8	16.7	0.58	65	I	3 south
2	BPFF	9P1B unitS	18.0	19.8	0.62	68	I	3 northwest
3	BPFF	9P1BunitS	18.9	20.1	0.56	63	I	6 southwest
4	BPFF	9P1S+B	22.0	24.0	0.57	110	III	7 northeast
5	BPFW	9P1S+B	16.8	20.6	0.60	73	I	7 northeast
6	BPFF	9P1S+B	22.0	23.0	0.70	110	I	12 southwest
7	BPFF	9P1B+S	21.6	20.7	0.75	78	I	100 southwest
8	PB	10P	10.0	15.0	0.30	230	I	8 northeast

*BPFF – bilberry pine forest fresh; BPFW - bilberry pine forest wet; PB - pine bog;
** P – pine; B – birch; S – spruce

As a result of standardization of increments in model trees, seven composite tree-ring chronologies were obtained (Figure 1). These composite chronologies contain an external signal caused by homogeneous soil, phytocenotic and microclimatic habitat conditions [20]. The statistical analysis of the series of radial growth of pine has confirmed the good quality of the material and the possibility of its use in dendroclimatic studies (Table 2).

The synchronization coefficient is calculated to establish the relationships between the chronologies. The synchronization coefficient in different sample plots, regardless of the influence of abiotic and anthropogenic factors is at the same level of 0.63-0.70. According to P.A. Feklistov [16], at a synchronization coefficient of more than 0.5, the chronologies are synchronous and can be used for compiling composite tree-ring chronologies.

The criterion for assessing the reliability of chronology is the expressed population signal (EPS), which shows the extent to which the real chronology reflects the hypothetical represented by an infinite number of trees [19]. The obtained chronologies are found to be reliable, for EPS≥0.85 [21]. The greatest factor of reliability of chronologies is noted in the bilberry pine forest that underwent improvement cutting. Therefore, the obtained composite chronologies can be used for dendroclimatic analysis.
The correlation coefficients were calculated to assess consistency of individual chronologies. The relationship between radial increments is positive, the correlation from moderate to significant being statistically significant. The greatest correlation of individual chronologies is noted in pine forests when underwent improvement cutting.

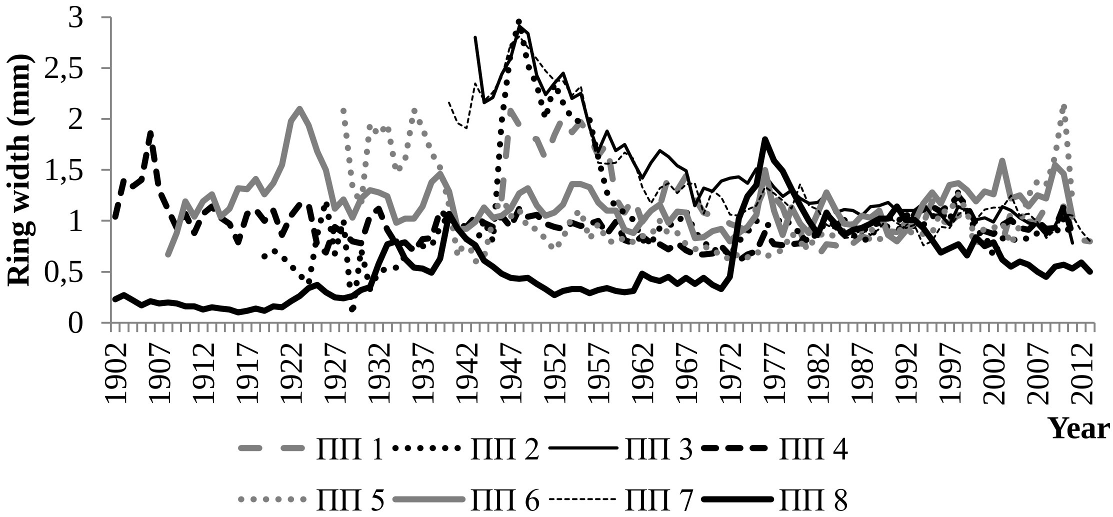

Figure 1. Composite tree-ring chronologies for scotch pine.

Table 2: General chronology statistics for composite scotch pine chronologies obtained from different environmental conditions.

	Sample plot							
	1	2	3	4	5	6	7	8
Number or trees	11	13	13	10	10	10	15	10
Series length (year)	66	93	69	110	84	106	74	228
Time span	1946-2011	1919-2011	1943-12011	1902-2011	1928-2011	1908-2013	1940-2013	1786-2013
Standart deviation	0.365	0.497	0.525	0.177	0.377	0.238	0.561	0.201
Mean sensitivity coefficient	0.228	0.223	0.182	0.210	0.259	0.195	0.187	0.275
Stress index	0.100	0.134	0.084	0.100	0.127	0.100	0.080	0.200
Synchronization coefficient	0.64	0.70	0.63	0.66	0.64	0.65	0.65	0.64
Expressed population signal	0.910	0.929	0.907	0.855	0.855	0.864	0.970	0.907
Correlation between trees	0.48	0.500	0.430	0.370	0.370	0.390	0.680	0.494

One of the most important indicators is the sensitivity coefficient. With this factor, one can select the trees and habitats most suitable for dendrochronological analysis. The higher the coefficient, the stronger the climate signal contained in the tree-ring chronologies [22]. The highest average sensitivity coefficient in found in individual series of pine bog (0.275), as well as in wet bilberry pine forests (0.259). The average sensitivity coefficient of the composite series depends on the density of stand (r =

- 0.71). The greater the density of the stand, the lower the sensitivity of the series to environmental factors. Consequently, the composite pine series of sparse stands of over-wetted growing conditions are most suitable for dendrochronological analysis.

A series of rings is considered sensitive when the average sensitivity coefficient is greater than 0.3 [23]. The dendrochronological series obtained by us have a low sensitivity coefficient (less than 0.28). Therefore, the stress index according to S.P. Arefyev [18] was additionally determined. This index shows the response to maladaptive factor that manifests itself in sharp decrease or increase in the growth increment. The stress index corresponding to the stable state of the tree is close to zero. In bilberry pine forests, the stress index, on the scale of S.P. Arefyev [18], is low, despite the proximity to the pulp and paper mill, recreational load, and improvement felling. In pine stands growing pine on bogs, the stress index average. The increased level of stress index is observed in pessimal conditions [24].

To identify the main climatic factors that determine the growth of pine within the studied areas, a correlation analysis was carried out of the increment indices and the air temperature and precipitation during the period from September of the previous year through August of the current year, as well as of the hydrothermal coefficient. The hydrothermal coefficient was calculated as the ratio between precipitation, in mm, for the period with average monthly air temperatures above 10°C and the sum of temperatures for the same period. For pine from the bog area, no statistically significant connection with climatic indicators of separate months has been revealed. In bilberry pine forests, located in the immediate vicinity of the pulp and paper mill (PP1 and PP2), there was no connection with climatic parameters. In this case, the impact of air pollution is more significant than climatic factors. A negative significant correlation between the series of pine radial growth and the mass of pollutant emissions was revealed ($r = -0.6$ $P<0.05$). Moderate correlation of increment indices with precipitation in May ($r = 0.35$) and June ($r = 0.4$) was found in the bilberry pine forest that underwent improvement felling. In the remaining sample areas, the relationship between the increment indices and the temperatures and precipitation of individual months is either weak or absent. The correlation between growth increment indexes and hydrothermal coefficient is weak on PP4, ПП5 ($r=0.28$) and significant on PP6 ($r=0.38$). The lack of correlation of growth indices and climatic factors may be a consequence of high values of autocorrelation of the first order in the individual series of pine chronologies on bog PP8 (0.68) and near the pulp and paper mill PP1 and PP2 (0.88). The first-order autocorrelation in the individual pine chronologies in the rest of sample plots varies between 0.19 and 0.30. Therefore, in stands growing on bogs in conditions of anthropogenically-caused air pollution, there is a connection between the conditions of previous year's growth and the growth in current year, which manifests itself in high values of autocorrelation of the first order in the series of chronologies.

3. Conclusions

The relatively low values of pine sensitivity coefficient indicate the response in trees to stressful conditions. The highest average sensitivity coefficient of the individual pine series is observed in stands growing on bog (0.275), and also in wet bilberry pine forest (0.259). The negative high correlation between the average sensitivity coefficient of the composite series and the stand density has been revealed. Consequently, the composite pine series of sparse stands growing in over-wetted conditions are most suitable for dendrochronological analysis. In bilberry pine forests, stress index is low, despite the proximity to the pulp and paper mill, recreational load, and improvement felling. In pine stands growing on bogs, the stress index is average.

The autocorrelation of first order in the individual chronologies of Scots pine is weak. The increased levels of first-order autocorrelation are observed in pine stands growing on bog (0.65) and those near the pulp and paper mill (0.88), leading to a lack of significant relationship between growth indices and climatic factors. In this regard, the tree-ring chronology of pine stands growing on wetlands in conditions of anthropogenically-caused air pollution defy standardization with exception of the first-order autocorrelation.

A moderate correlation between growth indices and precipitation in May and June has been revealed in the bilberry pine forests that underwent thinning. In the remaining sample plots, the relationship between the growth indices and the temperatures and precipitation of individual months may be weak or absent.

Acknowledgements
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