RESEARCH PAPER

CLIMATIC FACTOR IMPACT ON THE HEIGHT GROWTH OF LAPLAND PINE IN THE NORTHWESTERN RUSSIA

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ABSTRACT. Lapland pine (*Pinus sylvestris* var. *lapponica Hartm.*) is a geographical and climatic ecotype and subspecies of *Pinus sylvestris* L. It is widespread in the north of Eurasia. Its height growth is interconnected with both climatic parameters and the state of the habitat of pine trees. Long-term data on height growth indices of Lapland pine from various humid biogeocenoses of three specially protected natural territories of Northwestern Russia were studied. Also, sixteen basic climatic parameters averaged over the growth period of the examined trees were calculated for these regions. The comparison of different climatic parameters and pine stand height growth in various biogeocenoses was made using cluster analysis. It was established that the mean daily average temperature in January (-9.4°C, -10.4°C, -16.1°C in the Kivach, Polar Circle and Pechora-Ilych Reserves respectively) and the amount of precipitation in spring and early summer periods have a primary influence on the cluster similarity of the Lapland pine height growth in Northwestern Russia. The similarity of soil and biocenotic conditions also influenced the similarity of Lapland pine height growth indices, but had a lower rank within the two main clusters distinguished by climatic values. Our studies showed that it is possible to identify the rank influence of the most significant climatic factors and biogeocenotic conditions on the pine height growth using cluster analysis.

KEYWORDS: Lapland pine, height growth, climatic factors, soils, cluster analysis

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INTRODUCTION

Forest ecosystems play an important role in the life of our planet. They "provide ecological, economic, social and aesthetic services to natural systems and humanity" (Bonan 2008). Tree species are closely related both to macroecological conditions, including the climate of the regions in which they grow, and to microecological conditions, such as the soil, which nourishes and saturates them through the root system. The annual growth rate of pine depends on weather conditions (temperature and humidity), both current and over several previous years. This dependence is especially evident in extreme conditions of pine growth, including areas on the northern border of the range (Elagin, 1976; Rysin and Savelyeva, 2008).

The species *Pinus sylvestris* L. is characterised by a high degree of polymorphism, i.e. the presence of a wide variety of intraspecific forms (Pravdin 1964). The largest taxonomic ranks within this species are distinguished based on the geographical area of the individual population. The main forest-forming species of the Russian North European taiga territory is Lapland pine (*Pinus sylvestris* subsp. *lapponica Holmb*. or *Pinus sylvestris* var. *lapponica Hartm.*), one of the geographic subspecies of *Pinus sylvestris* L. (Plant List 2022; Gymnosperm DB 2022). This subspecies is widespread in Eurasia north of 61-62° N. This is a low plant with a maximum height of 20 m. There is also a wide variety of morphogenesis determined by the soil ecological conditions in the area of growth, which results in lower taxonomic ranks that stand out at the species level of *Pinus sylvestris* L. within the main subspecies. In particular, the swamp edaphic ecotype var. nana Pall., which grows in moist and waterlogged ecotopes (Pravdin 1964, Plant List 2022).

One of the main types of pine response to various environmental conditions is its linear growth (=height growth). Its variability is closely related to climatic factors and ecological conditions (Koukhta 2003; Chernogaeva and Kuhta 2018; Jansons et al. 2013a, b; Pozdnyakova et al. 2019; Zhou et al. 2019). The height growth of *Pinus sylvestris* L. in cold and moist regions is limited by the temperature in the previous summer and the length of the growing period (McCarroll et al. 2003; Pensa et al. 2005; Salminen and Jalkanen 2005). On the other hand, height growth of pine in southern regions is restricted by the amount of precipitation and available water, showing a positive correlation with summer precipitation and a negative correlation with summer temperature (Dobbertin et al. 2010; Mutke et al. 2003; Thabeet et al. 2009). Despite the importance of the linear growth indicators in studying various stands and their changes, the attention to it among research communities is much lower than to the radial growth of trees (Jansons et al. 2013a; Sánchez-Salguero et al. 2015; van der Maaten et al. 2017; Misi et al. 2019). Identifying the effects of each of these factors is a difficult but important task for understanding the relationships in the "climate-soil-plant" system in various biogeocenoses. Most often, correlation and regression analyzes are used to identify the relationship between environmental factors and linear growth. Cluster analysis stands out in multivariate statistical analysis, but it is rarely used for assessing the influence of ecological factors on plant trait changes. However, the advantage of the method is that it allows to compare qualitative and quantitative features and to build their classification systems (Gitis 2003).

The aim of this work was to assess the soil biocenosis and climatic characteristics of three different areas of Lapland pine growth, as well as to identify the relationships between individual soil and climatic parameters and the linear growth of this subspecies in the North European Russia using cluster analysis.

MATERIALS AND METHODS

Study area

Studies were carried out in three specially protected natural territories (SPNTs) located in Northern Russia: the Kivach state nature reserve (SNR) (KNR 2020), the Polar Circle state nature complex reserve (SNCR) of regional significance (BCNKC 2020), and the Pechora-Ilych state nature biosphere reserve (SNBR) (PISNBR 2020) (Fig. 1). According to the climatic classification of B.P. Alisov (1956), Polar Circle and Kivach Reserves are part of the northwestern subregion of the Atlantic-Arctic forest region of the temperate zone, and the Pechora-Ilych Reserve is located in the northeastern subregion of the same region, which has a more continental climate compared to the northwestern one (Fig. 1). The climate of investigated regions is characterized as cold and quite humid.

According to the geographical zoning of soils, all studied SPNTs are located in the European-West Siberian taiga forest region of podzolic and sod-podzolic soils of the Boreal belt (Dobrovol'skii and Urusevskaya 2004). In terms of vegetation zoning, all the studied protected areas belong to the Holarctic Boreal subkingdom, Circumboreal region (Voronov et al. 2002).

The Kivach SNR is located on the northwestern coast of Onega Lake in the southeastern region of the Baltic (Fennoscandinavian) crystalline shield. The territory of the reserve is characterized by a complex topography, formed as a result of tectonic and glacial processes. Ridge and hilly landforms here are interspersed by glacial lacustrine plains and swampy depressions (Fedorets et al. 2006). The variety of landforms determines the complexity of the soil cover. The territory corresponds to the Karelia province of alpha-humus podzols and bog soils of the middle taiga podzolic soils subzone (Dobrovol'skii and Urusevskaya 2004). The most biocenoses of the Kivach reserve are represented by

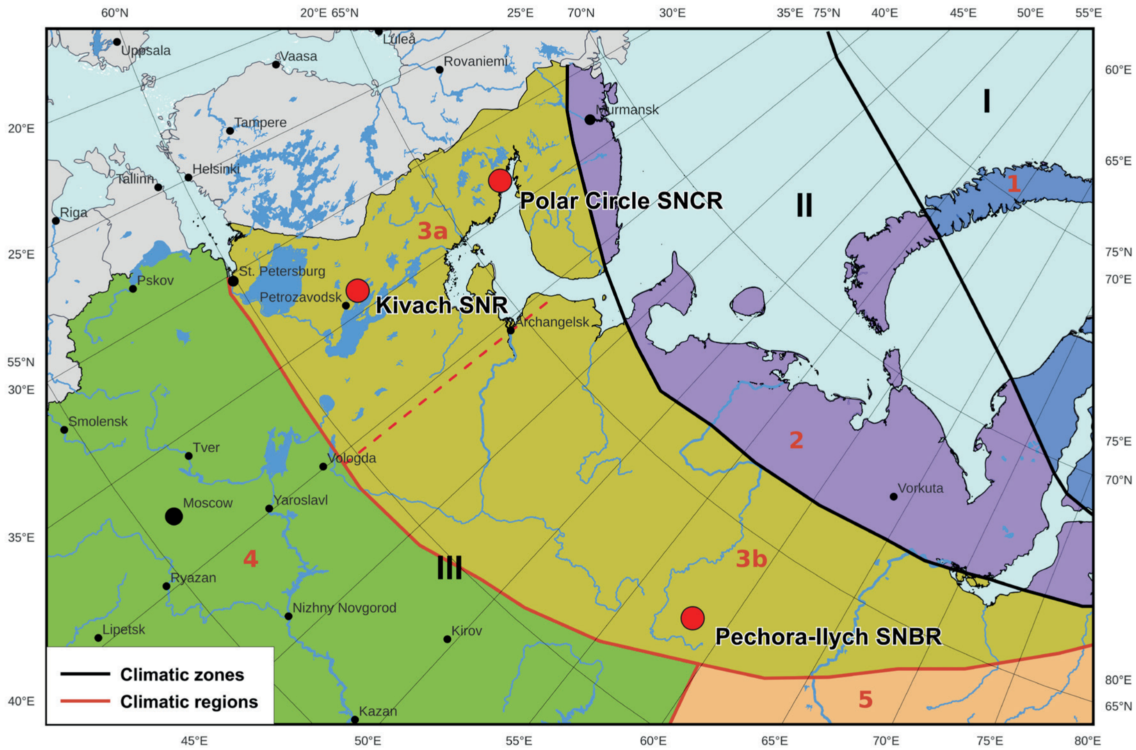


Fig. 1. Geographical location of studied territories: Climate zones: I – Arctic, II – Subarctic, III - Temperate. Climate regions: 1 – Atlantic arctic, 2 – Atlantic subarctic, 3 – Atlantic-Arctic forest (a - northwestern subregion, b - northeastern subregion), 4 – Atlantic-Continental forest, 5 - Continental forest West-Siberian. Borders of climate zones and regions are given according to the classification of B.P. Alisov (1956)

different pine forests (Fedorets et al. 2006). The territory is located on the border of the ranges of *Pinus sylvestris* L. subspecies *P. sylvestris* var. *sylvestris L.* and *Pinus sylvestris* var. *lapponica Hartm*.

The Polar Circle SNCR is located in the Loukhsky municipal district in the northern part of the Karelian Republic, on the northwest coast of the White Sea in the Kandalaksha Bay coastal zone. The region belongs to the Kola-Karelia province of alpha-humus podzols and bog soils of the northern taiga gley-podzolic and podzol soils subzones (Dobrovol'skii and Urusevskaya 2004). There are three main types of landscapes in the Polar Circle SNCR. The major part is occupied by the North-taiga East European lowland (57.6%). Other types of landscapes are represented by various swamps (6.2%) and marine areas (36.2%) (SPTsR 2020).

The Pechora-Ilych SNBR is located in the Komi Republic on the western slope of the Ural Mountains. Currently, it consists of two isolated sections located in the southwestern and eastern parts of the Upper Pechora and Ilych interfluve. The studies were carried out in the Yakshinsky (southwestern) site, which is bounded by a segment of the Pechora River between the mouths of its right and left bank tributaries of Polovinnaya and Krutaya. The reserve is part of the Onego-Vychegda province of podzolic and bog-podzolic soils of the middle taiga podzolic soils subzone (Dobrovol'skii and Urusevskaya 2004). Most of the reserve is occupied by coniferous forests. In depressions, there are raised and transitional sphagnum bogs (Degteva and Lapteva 2013). The dominant tree is Pinus sylvestris L. Similarly to the Kivach reserve, the Pechora-Ilych SNBR is located on the southern border of the Lapland pine and the northern border of Scots pine ranges (Pravdin 1964).

Stand data

We investigated the annual variability of the indexed linear growth of Lapland pine in humid ecotopes, which were distinguished according to the V.N. Sukachev classical typology (Sukachev 1972). The classification of soil for each examined area was carried out based on the following studies (Egorov et al. 1977; Degteva and Lapteva 2013; Fedorets et al. 2006). The object of our study was the swamp edaphic ecotype of Lapland pine, which is represented in fig. 2.

The studies spanned multiple years, lasting from 2000 to 2013. Measurements were conducted for undergrowth, young stand and maturing trees of Lapland pine. For unification, trees with similar morphological and age characteristics were selected. The height of measured trees was above 1 m and below 2.5 m. The age of registered undergrowth and maturing trees was 7-25 years. Stem internodes were measured on each tree, starting from the top (current year growth) and to the last clearly distinguishable one near the ground. The variability of the series of growths was estimated using standard deviation. The series of growths were indexed using the standard method adopted in dendrochronology by dividing the absolute values of each year's growth by a moving average over 5 years. A similar procedure was used to remove the age trend and obtain annual deviations from the course of growth. Then, the obtained values were averaged over the trial plots. The calculation technique is described in (Koukhta and Titkina 2005).

Climate data

For all three areas, we also calculated 16 climatic parameters that could affect the Lapland pine linear growth. The calculations were carried out based on daily resolution meteorological data, which included ground-based measurements of air temperature and precipitation on a network of Roshydromet international exchange hydrometeorological stations located in the areas of research (RSRIHI-WDC 2014). The values were averaged over the period 1991-2010, which coincides with the research period and the previous growing time of the examined trees. The calculated climatic parameters are:

Total annual precipitation (TAP): sum of precipitation for the year, mm;

Precipitation in spring (PSp): sum of precipitation for the period from March to May, mm;

Precipitation in April-June (PAJn): sum of precipitation for the period from April to June, mm;

Precipitation in July-September (PJlS): sum of precipitation for the period from July to September, mm;

Precipitation in the cold season (PCS): sum of precipitation from October to April, mm;

Precipitation in the growing season (PGS): sum of precipitation from May to September, mm;

Mean annual air temperature (MAAT): mean annual daily average air temperature, °C;

Fig. 2. The swamp edaphic ecotype of Lapland pine in a typical humid ecotope, the Polar Circle SNCR (Foto by A.E. Koukhta, unpublished)

Mean temperature in May (MTM): average daily temperature in May, °C;

Mean temperature in the warmest month (MTWM): average daily temperature in July, °C;

Mean temperature in the coldest month (MTCM): average daily temperature in January, °C;

Sum of active temperatures above 5°C (SAT>5°C) and above 10°C (SAT>10°C), °C×days (Equation 1):

$$T_a = \sum_{n=1}^{d} T_{n,>T_0} \tag{1}$$

where T_a is the annual sum of active temperatures (SAT), T_n is the average daily air temperature above the temperature threshold T_0 which in this work is 10°C for a time period d corresponding to the number of days in a year (Popova et al. 2017);

The number of days in a year with the daily average temperature above 5°C (NDY>5°C) and above 10°C (NDY>10°C), days;

The hydrothermal coefficient (HTC) of Selyaninov was calculated according to Equation 2:

$$HTC = \frac{r_n}{0.1\sum T_n} \tag{2}$$

where r_n is the sum of daily precipitation in the growing season (PGS) of the calendar year n; ΣT_n is the sum of the daily average active air temperatures with a threshold of 10ºC for the same period of the year (May-September) (Selyaninov 1928);

The simplified aridity index (SAI) of Budyko was calculated according to Equation 3 (Sirotenko and Pavlova 2012):

$$SAI = \frac{0.18\sum T_{>10^0}}{r_{1-XII}} \tag{3}$$

where $\Sigma T_{>10°}$ is the annual sum of active air temperatures above 10°C (SAT>10°C); r_{I-XII} is the annual amount of precipitation (TAP).

Statistical analyses

Generalized data for the entire observation period in individual sites of the three studied regions were compared using hierarchical cluster analysis with R function hclust (method "complete") using the OpenOffice.org Calc table processor.

The similarity of climatic conditions in different protected areas was also studied for individual climatic parameters using hierarchical cluster analysis and dendrograms, constructed using the SciPy package for the Python 3 programming language (Raschka, Mirjalili, 2017). The Euclidean distance (d) was used as a metric both in the case of linear growth of pine trees and for climatic parameters (equation 4):

$$d(p,q) = \sqrt{\sum_{i=1}^{n}(p_i - q_i)^2} \tag{4}$$

where p and q are the measured variables (i.e. values of a climatic parameter of two compared plots) and i indicates an individual measured value of the variable from a total number of n measurements.

RESULTS

Cluster analysis of the annual average values of the swamp ecotype of Lapland pine linear growth index variability in the three examined SPNTs for the entire observation period revealed a division of these indicators into two main clusters (Fig. 3). One of them includes values obtained from various test sites of the Polar Circle SNCR and the Kivach SNR, which belong to the northwestern subregion of the Atlantic-Arctic forest region of the Temperate zone, and the other includes values obtained from various test sites of Pechora-Ilych SNBR, which is part of the northeastern subregion of the same region. Thus, we see that climatic conditions, in general, have a more significant effect on the clustering of the selected indicators of linear growth.

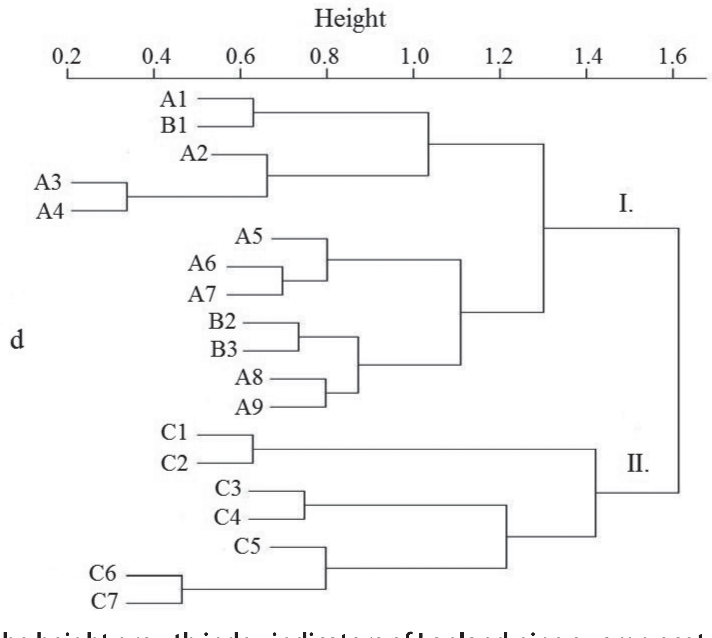


Fig. 3. Cluster analysis of the height growth index indicators of Lapland pine swamp ecotype in various environmental conditions of North European Russia, d is the Euclidean distance.
I. Northwest subregion of the Atlantic-Arctic forest region of the temperate zone. The Republic of Karelia. Kivach SNR: A1 – peat bog podzolic gleyed soil; A2, A3, A4 - transitional peat bog soil; A5, A6, A8, A9 - humus peat bog gleyed soil; A7 – peat bog gleyed soil. Polar Circle SNCR: B1 – peat bog podzolic soil; B2, B3 - humus peat bog gleyed soil. II. The northeastern subregion of the Atlantic-Arctic forest region of the temperate zone. The Komi Republic. Pechora-Ilych SNBR: C1, C2 – raised peat bog soil; C3, C4 – illuvial ferruginous gleyed podzol; C5 – transitional peat bog soil; C6, C7 – peat bog podzolic soil

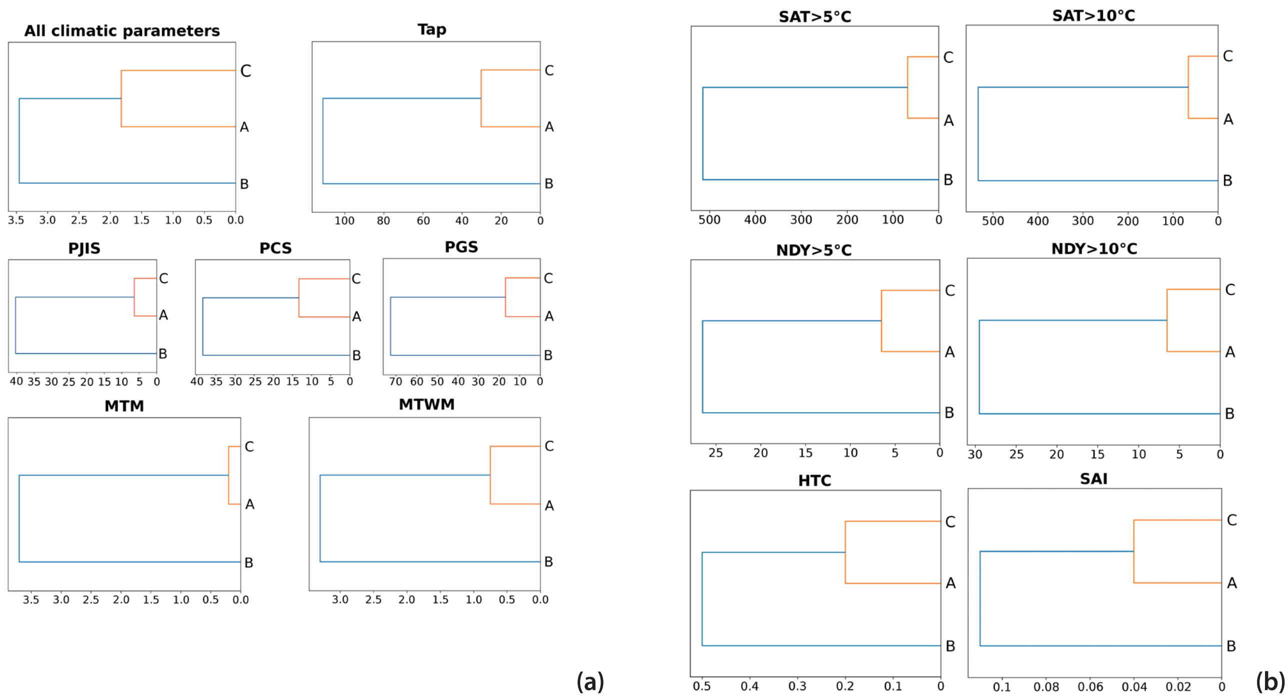
Within these two main clusters, there is a similarity between the Lapland pine linear growth indices in test plots with similar soil conditions (Fig. 3). This indicates that the influence of the ecological niche, especially its edaphic component, also affects the linear growth of pine, but has a lower rank relative to the climate effect.

The next stage of our research was the identification of the climatic parameters that influenced the separation of the average annual variability values of the Lapland pine linear growth series into two different clusters. The calculated values of the selected climatic parameters averaged for the period 1991-2010 are given in Table 1. This period covers both the period of ground-based measurements of the linear growth of Lapland pine and the period of growth of this subspecies before the start of measurements, which is subsequently taken into account when conducting field observations.

Table 1. The values of climatic parameters of the studied SPNTs, averaged over the period 1991-2010

Climatic parameters (CP)	Values of CP in the studied regions		
	Polar Circle SNCR	Kivach SNR	Pechora-Ilych SNBR
TAP*, mm	523.2	604.1	634.3
PSp, mm	96.6	110.2	125.1
PAJn, mm	125.0	137.1	151.8
PJIS, mm	174.3	214.6	208.2
PGS, mm	263.6	319.4	336.3
PCS, mm	259.6	284.7	298.0
MAAT, °C	0.97	2.98	0.54
MTM,°C	4.4	7.9	8.1
MTWM, °C	14.1	16.65	17.4
MTCM, °C	-10.4	-9.4	-16.1
SAT>5°C, °C×days	1443	1958	1890
SAT>10°C, °C×days	1050	1583	1517
NDY>5°C, days	132-133	159	152-153
NDY>10°C, days	80	109-110	103
HTC	2.5	2.0	2.2
SAI	0.36	0.47	0.43

* The description of climatic parameters is given in the section "Climate data"



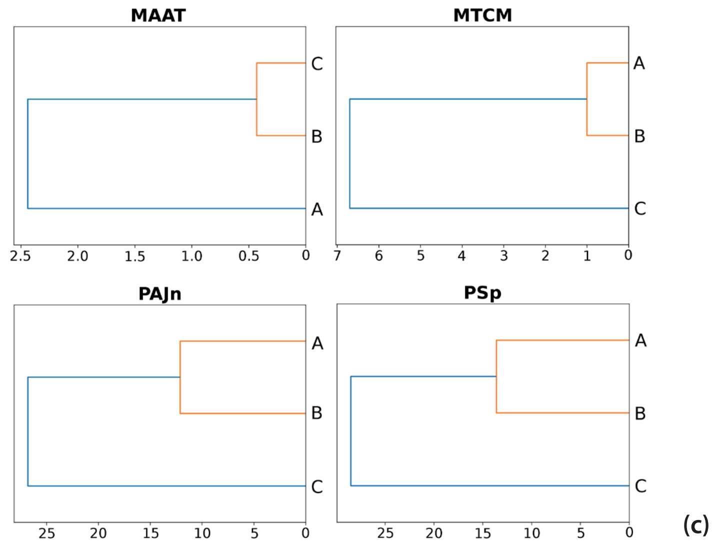


Fig. 4. Cluster analysis of the climatic parameters in the three studied SPNTs, averaged over the period 1991-2010: a) all climatic parameters, TAP, PJIS, PCS, PGS, MTM, MTWM; b) SAT>5°C, SAT>10°C, NDY>5°C, NDY>10°C, HTC, SAI; c) MAAT, MTCM, PSp, PAJn. Study sites: A - Kivach SNR, B - Polar Circle SNCR, C – Pechora-Ilych SNBR. The horizontal axis indicates Euclidean distance

After calculating the climatic parameters presented in table 1, we also performed a cluster analysis to identify similarities between the three studied SPNTs using both all climatic parameters values combined and each of them separately (Fig. 4a-c).

The results of clustering of all climatic parameters showed that the Kivach SNR and the Pechora-Ilych SNBR were the most similar across the entire set of values (Fig. 4a). The same results were obtained for most of the other climatic parameters (Fig. 4b).

However, when conducting a cluster analysis by the climatic parameter MAAT, the Polar Circle SNCR and the Pechora-Ilych SNBR turned out to be the closest (Fig. 4c). This indicator brings the more northern (Polar Circle SNCR) and more continental (Pechora-Ilych SNBR) regions closer together.

According to the climatic parameters MTCM, PSp and PAJn, the greatest similarities were found for the territories of the Kivach SNR and the Polar Circle SNCR (Fig. 4c). The cluster analysis also showed a greatest similarity in the values of the average annual variability of the Lapland pine height growth series in these surveyed SPNTs (Fig 3). Obviously, these climatic parameters have a decisive influence on the magnitude of the indexed height growth of the studied pine subspecies.

DISCUSSION

Pine height growth takes place in spring and in the first half of summer. Previously, it was shown that in Karelia, in the middle taiga region, an intensive linear growth of pine trees begins in the first half of May, reaches a maximum in mid-June and completely stops in August (Kishchenko 2019). The amount of precipitation in this period can have both a positive (in case of insufficient moisture) and a negative (in case of excessive moisture) effect on the linear growth of *Pinus sylvestris* L. (Koukhta and Titkina 2005; Pozdnyakova et al. 2019). A significant negative correlation between the precipitation in May-July and height growth indices of Scots pine were found for humid biotopes of the northern regions (Pozdnyakova et al. 2019). The same results were obtained while examining the forest pine biotopes of the Baltic region with a cool humid Atlantic-Continental European climate (Janson et al. 2013b). The reason for this phenomenon is that in waterlogged biogeocenoses, an increased amount of precipitation causes water stress in pine trees and a decrease in the internode growth rate, while also contributing to a deterioration in the quality of the established buds' renewal (Pozdnyakova et al. 2019).

MTCM is also of great importance to the vegetation of the northern regions, so its influence on the growth of Lapland pine in height is quite obvious. The negative influence of MTCM on the growth of *Pinus sylvestris* L.was also noted in the studies on the relationship between climatic factors and the height growth of pine stands in Siberia (Nikolaeva and Savchuk 2008; Shestakova et al. 2017) and the mountain regions of Spain (Sánchez-Salguero et al. 2015). However, for these regions (forest-steppe regions of Siberia and the Mediterranean climate territories of Spain), a decrease in the height growth of the examined pines was also observed with an increase in the aridity of the growing season, while the correlation with precipitation was positive.

Depending on the growing conditions, the set of climatic factors influencing the growth of *Pinus sylvestris* L.is different. In previous studies, using correlation analysis, it was found that the height growth of pine stands in Penza region decreased with increasing temperature during the growing season and increased with an increase in the amount of precipitation in the current growing season (Koukhta and Titkina 2005). When studying pine stands of the Mongolian pine (*Pinus sylvestris* L. var. *mongolica*) in three northern regions of China, it was found that the height growth of pine trees generally increased with increasing average monthly temperature in May and the amount of precipitation from October to April, and decreased with increasing precipitation in the previous growing season (Zhou et al. 2019). Also, a significant positive correlation of the height growth indices of *Pinus sylvestris* L. with May temperatures was noted by scientists conducting studies in Latvia (Janson et al. 2013b). According to our data, the May temperature did not have a significant effect on the cluster similarity of the height growth of Lapland pine in the conditions of the northern Russian protected areas. The patterns obtained are consistent with the results of previous studies, in which it was shown that the limiting factor in most habitats of boreal biogeocenoses of North European Russia is the lack or excess of precipitation, and not the temperature of the growing season (Chernogaeva and Kuhta 2018).

A relationship between the average monthly temperature of January and the growth of pine trees in the territory of northern and southern Karelia, which are located within the same climatic subregion, was found. Earlier, D.E. Rumyantsev (2004) established a significant negative correlation between pine growth and the average monthly temperature in December of the previous year (r up to -0.54), which he chose as the coldest winter period. In our study, January was taken as the coldest month of the year based on long-term meteorological data. These observations can be considered similar.

CONCLUSIONS

Our studies showed that cluster analysis can be used to identify the rank influence of climatic conditions on the Lapland pine height growth. Also, it can be used to reveal the most significant climatic factors for a given geographical subspecies. According to our results, the most significant impact on the annual variability of the Lapland pine height growth was caused by precipitation in spring and early summer, as well as the average daily mean temperature in January. A significant effect of the average January temperature on the height growth indicators of Lapland pine was revealed in our research.

The results obtained from the cluster analysis are preliminary and show directions for further more detailed observations and studies, particularly for identifying the mechanisms determining the response of height growth increments of pine stands to various climatic parameters.

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