The effect of meteorological factors on the annual increment of spruce (Picea abies (L.) Karst.) growing on double layer soils

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Abstract. The present work analyzes the effect of temperature and precipitation in the growing season on annual increment and structural elements of spruce xylem. The objects of study were stands aged 100-120 years with different spruce proportion, restricted to soils of binary genesis that allowed levelling out the conditions of growth and determining the main meteorological parameters influencing the increment of spruce wood. The study revealed that, depending on the stand composition, the average temperatures during the growing season have change the effect on the annual increment of spruce wood. In the given soil conditions, the highest meteorological sensitivity in spruce was recorded when its share in the stands was less than 60%. With a decrease in the spruce share in the stand composition, the influence of meteorological factors on macrostructural elements also decreases, but if broad-leaf species are present in the stand, there is an increasing in the influence of weather factors on the increment of wood and its structural elements.

1. Introduction
Among the external factors that affect the increment rate of the stand, climatic and soil conditions, plant community relationships, various kinds of disasters, and human economic activity should be mentioned. Several works covering in detail the influence of external factors on the variability of annual ring widths have been published [1-5]. The widespread use of tree-ring dating in the study of various environmental issues and the history of forest ecosystems contributed to the development of the theoretical foundations of general dendrochronology and dendroecology [6-9].

Under the same conditions or under the influence of various factors of biotic, abiotic, and anthropogenic origin, the annual increment of coniferous stands in the boreal zone can differently respond to the changes in meteorological parameters. This is caused by the different resistance of the species composing these stands to external influences. Wood increment characterizes the state of biota and landscapes in the most complete and adequate way, since it reflects the direct impact of a whole complex of factors and their interactions on the basis of the ecological pyramid. Complex multi-level forest ecosystems have rather large ranges of tolerance, which to some extent makes it difficult to obtain reliable information on their response to changes in meteorological factors [10]. Depending on
the physiological state of a plant, the same climatic factors may generate different responses in the radial increment of trees [2].

In different parts of the boreal zone, spruce-dominated stands (*Picea abies* (L.) Karst.) respond differently to climate change, therefore it appears relevant to analyze the specifics of meteorological factors influence on the radial increment of spruce depending on the composition of the plant community. Forest-forming species have different hereditary ecological properties. In the process of intraspecific competition in spruce stands, fluctuations in radial increment are expected to occur in a different manner, depending on what species is the main competitor of spruce in the plant community [11]. Practice shows that mixed spruce stands should adapt better to the environment [12, 13]. The choice of the planting composition for the future stand should take into account many factors: a growth rate, a demand for soil fertility, shade tolerance, a tolerance of drought. It is important to determine the parameter in the study that would be a reliable indicator of changes in the trees condition under the influence of certain climatic factors. The radial increment of trees can serve as an indicator of the plantation condition as a whole [14]. Stand composition optimization according to the reaction on the climatic factors is of particular interest in silviculture. Currently, there are relatively few attempts to study radial increment in relation to the analysis of the stands' structure and the assessment of factors determining their resistance to stressful weather conditions [12, 15].

2. Methods and Materials

2.1. Objects of the study

The objects of the study are stands with a predominance of spruce, aged 100-120 years, on double layer sediments that cover up to 36% of the entire territory in the Oredezh-Luga landscape of the Leningrad Region, Russia. The analysis of the long-term dynamics of the radial increment of trees on the experimental sites was based on the principles and methods of modern dendroclimatology. These methods are quite well described in works dedicated to this subject [6, 16-18]. Were selected stationary objects with a stable or slightly changing composition of the stand and share of spruce in the green-moss forest group. Permanent experimental objects were founded in different years over the last century by employees of the Leningrad (now St. Petersburg) Forestry Research Institute for the observation of the natural course of stands growth, free of forestry impact.

The objects belong to a subgroup of forest land on the double layer sediments of drained plains and slopes of various steepness with *Myrtillosum* and *Oxalidosum-Hylocomiosa* spruce forests. The types of land under consideration are widespread in the boreal zone in the Valdai glaciation area: within the moraine plain and in the north – along the tops and slopes of moraine hills. Binary sediments are sandy loam or sandy rocks of low thickness (30–70 cm), bedding on loams, which serve as the first from the surface water-resistant horizon. The main distinguishing feature of the hydrological regime of drained lands on binary sediments is the presence of a surface soil- and groundwater horizon in April – May and September – November, which screens the loam located below [19]. On these lands, on coarse-humus podzolic sandy and sandy loam soils, bilberry and green-moss spruce and pine forests are identical in the composition of the lower stratum vegetation to bilberry forests on drained sands and sandy loam. This, apparently, is associated with the screening of soil- and groundwater of the underlying loam. At the same time, on moder-humus soils, here are mentioned spruce, birch, and aspen wood sorrel forests that are floristically close to the drained sandy loam forests described above [10, 19]. The productivity of the stands of these types of forests is higher than on sand and sandy loams: on coarse humus soils, pine trees at the age of 80 years have a height of 22 m, whereas spruce forests – 21 m, like on moder-humus soils of sandy loam lands. At this age, pine forests and spruce forests on moder-humus soils reach 25 m in height, whereas on less common moder-mull soils, wood sorrel spruce forests are up to 28 m high. Thus, near loam bedding affects the forest productivity to a greater extent than the composition of the vegetation of the lower stratum [19]. The effect of fires is not significant here: post-fire lingonberry-green-moss pine forests on soils with thin coarse humus are quite rare [10].
2.2. Methods

At the sample plots with different shares of spruce were collected wood cores from 1.3m height. Were collected at least 20-30 pieces per plot, depending on the distribution of trees by the diameter classes (the area of the plots was 0.25-0.5 hectares each). After preparing the wood core samples for measurements, the rings are preliminarily dated and labelled. Knowing the exact calendar time of sampling and the formation of a ring under the bark in the sample, the calendar dates of formation of all rings of the measured core are determined by a reverse counting. To make the measurements of the generalized series of each experimental plot comparable and to level the so-called “large growth curve” inherent in all biological systems, the measurements were averaged over forest stands depending on the proportion of spruce [16]. The summary sets for each forest stand were used as the basis for constructing a generalized set of tree rings. We used long-term data from the “Belogorka” weather station located at a 1-5 km distance from the objects of study [20]. To determine the influence of meteorological conditions on the radial increment of spruce, we calculated the relations [21, 22] between the annual radial increment and the average temperature and the amount of precipitation during the growing season in the region of study from May to September.

3. Results and Discussion

On objects with different share of spruce at homogeneous soil and hydrological conditions, the relationship between the radial increment of the annual layer of stands and the average temperature during the growing season was assessed. In previous studies, it was noted that the effect of precipitation on spruce growth is insignificant and deviations from these characteristics can be found depending the specific conditions of the habitats [12]. This is associated with the fact that spruce being in optimal growth conditions in the boreal zone, is most sensitive to positive temperature changes during the growing season [17].

The construction of generalized dendrograms allowed excluding individual features of spruce growth in each local habitat and served as the basis for determining the dates of abnormal deviations from the long-term norm. The analysis of the absolute value curves of the radial increment indicates certain patterns in the fluctuation of these values depending on meteorological parameters and the stand composition. The graph of average temperature fluctuations over the growing season and increment in relatively pure spruce stands shows that the increment fluctuations are well traced over the entire observation period, and in relatively pure spruce stands a pronounced reaction to temperature increase is seen (figure 1).

For stands with a smaller spruce share, the indicators of radial increment changes repeat well the temperature maximums in the stands with 80% of spruce and 20% of pine and 70% of spruce and 30% of broad-leaf species (shown in figure 2; here and further: “S” – spruce, *Picea abies*; “P” – pine, *Pinus sylvestris*; “B” – birch, *Betula pendula*; “A” – aspen, *Populus tremula*). However, in a stand with a larger share of broad-leaf species, the radial increment decreases with age, and in general, its reaction to average temperature fluctuations over the growing season is more uniform.
Figure 1. Average air temperature and annual increment in spruce stands with the share of spruce 90-100% at experimental objects.

In spruce stands mixed with broad-leaf species, various trends are observed in wood increment fluctuations resulting from the temperature changes. Initially, in the stands with a smaller broad-leaf species share, the radial increment was less and the reaction to temperature changes was not clearly expressed. In subsequent years, the spruce increment increased and began to coincide with temperature fluctuations.

For stands with a spruce share of 40-60%, various increment fluctuations are observed depending on the stand composition (figure 3).
Figure 3. Average air temperature and annual increment in spruce stands with the share of spruce 40-60% at experimental objects.

In the stands with a greater spruce share of 60%, a pronounced reaction to temperature peak changes is actually observed only now. The greatest reaction to changes in average temperature during the growing season is observed in the stands with a spruce share of 50%. In the stands with a smaller share of spruce, there is a trend for a delayed reaction to temperature maxima.

In general, the obtained dendrograms of the average air temperature influence adequately show differences in radial increment depending on the composition of the stand.

The proportion of the influence of meteorological factors on the formation of the spruce wood structure indicators was calculated. The linear regression analysis was carried out with two influencing meteorological factors – the sum of positive temperatures and precipitation during the growing season; table 1 shows the results of the analysis.

Table 1. The level of joint influence of average positive temperatures and the amount of precipitation during the growing season on the formation of the spruce wood structure indicators in stands with spruce predominance.

| Stand composition | Late wood | Early wood | Annual increment |
|-------------------|-----------|------------|------------------|
|                   | Statistical parameters | | |
|                   | $R^2$, % | $P$-Value | $F$-Ratio | $R^2$, % | $P$-Value | $F$-Ratio | $R^2$, % | $P$-Value | $F$-Ratio |
| 100% Spruce       | 13.92     | 0.02       | 4.04$^a$      | 1.35     | 0.71       | 0.34      | 2.70     | 0.50       | 0.69      |
| 90S10P+B,A        | 1.96      | 0.59       | 0.54          | 4.62     | 0.28       | 1.31      | 3.84     | 0.35       | 1.08      |
| 80S20P+B,A        | 1.87      | 0.61       | 0.50          | 5.33     | 0.24       | 1.46      | 3.31     | 0.42       | 0.89      |
| 80S10B10A+P       | 8.32      | 0.10       | 2.45          | 10.63    | 0.05       | 3.21      | 10.16    | 0.06       | 3.05      |
| 70S20P10B+A       | 6.79      | 0.17       | 1.82          | 13.13    | 0.03       | 3.78      | 13.00    | 0.03       | 3.73      |
| 60S(10P20A10B/30B10A) | 20.88   | 0.00       | 7.12          | 17.42    | 0.01       | 5.70      | 18.00    | 0.00       | 5.92      |
| 50S50P            | 4.63      | 0.28       | 1.31          | 6.46     | 0.16       | 1.87      | 6.39     | 0.17       | 1.84      |
| 40S30P20A10B      | 6.57      | 0.17       | 1.83          | 4.04     | 0.34       | 1.09      | 4.46     | 0.31       | 1.22      |

$^a$ Here and further $F_{tab} = 2.42$ (for 55 measurements at freedom degrees 2 and at $p=0.1$)
With a decrease in the spruce share in the stand, the influence of meteorological factors on macrostructural elements also decreases, but if broad-leaf species are present in the stand, there is again an increase in the influence of weather factors on the increment of wood and its structural elements. The obtained results confirm the existence of a non-linear, more complex relationship between meteorological parameters and spruce wood increment. Therefore, a non-parametric rank correlation analysis was used [21].

Spearman’s rank correlation analysis was carried out for the effect of the sum of temperatures and precipitation during the growing season on the macrostructure of wood; table 2 shows the results of the analysis. The results demonstrate that the influence of meteorological parameters on macrostructural elements is in most cases moderate or weak.

The main factor in the fluctuations of the annual increment of spruce xylem macrostructural elements is the average temperature during the growing season. For the zone of late wood there is a trend of increasing influence of average temperatures with a decrease in the spruce share in the composition of the stand. A similar relation is observed for the early wood zone of spruce.

A pronounced statistically significant dependence of the spruce wood macrostructure on temperature indicators is observed for stands with a 60% share of spruce and broad-leaf species. It should be noted that for the same stands a linear relationship was revealed between the spruce wood macrostructural elements increment and the combined influence of average positive temperatures and the amount of precipitation during the growing season. The determination of these factors was from 17% to 20% of the sum of all possible factors (Table 1), but not statistically significant.

Table 2. Spearman’s rank correlations $R_s$ for wood macrostructure indicators and weather conditions in spruce-dominated stands.

| Stand composition | Late wood | Early wood | Annual increment |
|------------------|-----------|------------|-----------------|
|                  | Temperat- | Precipita- | Temperat- | Precipita- | Temperat- | Precipita- |
|                  | ure       | tion       | ure       | tion       | ure       | tion       |
| 100% Spruce      | 0.02      | **0.37**   | 0.13      | 0.01       | 0.14      | 0.10       |
| 90S10P+B,A       | 0.20      | -0.03      | 0.24      | -0.09      | 0.26      | -0.08      |
| 80S20P+B,A       | -0.03     | 0.09       | -0.25     | 0.02       | -0.23     | 0.05       |
| 80S10B10A+P      | -0.26     | -0.07      | -0.25     | -0.13      | **-0.26** | -0.13      |
| 70S20P10B+A      | 0.23      | 0.17       | 0.20      | 0.21       | 0.19      | 0.20       |
| 60S(10P20A10B/ | **0.32**  | -0.01      | **0.35**  | -0.03      | **0.35**  | -0.03      |
| 30B10A)          |           |            |           |            |           |            |
| 50S50P           | 0.15      | -0.06      | 0.19      | -0.04      | 0.17      | -0.03      |
| 40S30P20A10B     | **-0.29** | 0.06       | -0.18     | 0.04       | **-0.22** | 0.05       |

*Marked bold correlations are statistically significant at $p=0.05$

The effect of precipitation on the spruce wood macrostructure is manifested only in pure stands for the late wood zone. This was also revealed using a linear regression method, where the combined influence with temperature contributed to 14% of the sum of all factors at a statistically significant level (figure 4). The annual increment curve repeats well the changes in precipitation, as on the graph with average temperatures (figure 1). This fact demonstrates that pure spruce forests are more sensitive to external climatic changes than mixed spruce stands.
Figure 4. Average amount of precipitation and annual increment in pure spruce stands at experimental sites on the soils of double layer sediments.

4. Conclusion
The results of the study allow concluding that:
– The annual increment of spruce wood is more affected by average temperatures over the growing season.
– The effect of precipitation on the spruce wood macrostructural elements increment is manifested only in pure stands.
– The research results show that the greatest weather sensitivity is observed in spruce when its share in the stands is less than 60% in given soil conditions.
– With a decrease in the spruce share in the stand, the influence of meteorological factors on macrostructural elements also decreases, but if broad-leaf species are present in the stand, there is again an increase in the influence of weather factors on the increment of wood and its structural elements.
– Among all the assessed stands, the stands with a share of broad-leaf species in the composition show a largest number of statistically significant correlation coefficients in the relationship between the meteorological parameters and spruce macrostructural elements.

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