The effect of meteorological factors on wood macrostructure in mixed pine stands (*Pinus sylvestris* L.) on different soils

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Abstract. The present work analyzes the relationship between meteorological factors and soil conditions and the annual radial increment of naturally formed pine stands of the boreal zone. It has been noted that on dual sandy loam and drained illuvial sandy loam soils, the annual increment of pine trees has greater response to the sum of temperatures than on loamy soils. Under different soil and hydrological conditions, when the pine share in the composition changes, the structural elements of xylem demonstrate an increasing dependence of annual increment on the share of the species in the composition of the plantation. This dependence is stronger for early wood than for late wood. At coarser soils and decreasing pine share in the stand composition, the growth of pine's macrostructural xylem elements becomes less influenced by meteorological factors.

1. Introduction

The formation of the annual increment of coniferous wood in the boreal zone depends on a complex of factors. When studying the process of wood formation, the leading factors in various soil and hydrological conditions shall be identified. Especially relevant is the study of ecosystems that occupy excessively humid or dry ecotopes, where even slight changes in temperature and precipitation can cause serious alterations in the annual increment. Studies of climatic parameters using dendrochronology are usually confined to territories where tree growth is limited by external factors [1-5]; in the ideal case, there should be only on such a factor. Therefore, for areas with optimal tree growth conditions, only a few dendroclimatic studies are available. The complexity of the analysis of dendrochronological series obtained in the areas with optimal growth conditions for wood is associated with poor consistency of these series, both among the series themselves and with the measured environmental parameters [6-9]. In the boreal zone of the middle taiga, the temperature factor does not limit the growth of trees so severely as at the thermal boundaries. The growth of the forest stand more often depends on the relief characteristics and the associated redistribution of soil moisture in the places of growth. Under such conditions, most often as the object of study serves the *Pinus sylvestris* that forms the longest ecological line depending on the soil moisture factor. On the example of this species, the cyclical nature of radial increment index fluctuations in trees of dry land and swampy habitats is described in detail. As well as the influence of weather factors on the xylem
ring width depending on the nature of soil hydration [10-13]. However, the results are contradictory, which is caused by a pronounced dependence of radial increment on local soil hydrological features of specific habitats. The mechanism of the conjugate action of weather and soil factors limiting the growth of pine stands depending on the composition of the plantation has also been studied insufficiently [14].

Considering the relevance of this issue, we have carried out a study of the influence of meteorological factors on wood increment in pine-and-spruce stands in bilberry forests under various soil and hydrological conditions.

2. Methods and Materials

2.1. Objects of study

The objects of study are mature stands with a predominance of pine with a different share of the main species in different soil conditions in the boreal zone of the North-West of the European Russia. The studies were carried out in the accounting areas with a long observation period not affected by the economic activity, on the stands with a predominance of 85–95 years old pine trees in the in Gatchina Forestry of Leningrad Oblast. The mensuration indices of stands at experimental sites on loamy soils had an average stock of 350–407 m$^3$/ha, an average diameter of 22–24 cm, and an average height of 24–26 m. For pine-spruce plantations on dual sandy loam and loam soils on moraine loams, the average stock was 350-460 m$^3$/ha, the average diameter 24-26 cm, and the average height 26–28 m. On drained illuvial ferruginous sandy loams, the average stock of mixed pine and spruce stands was 326–407 m$^3$/ha, an average diameter 22–24 cm, and an average height 24–26 m.

2.2. Experimental part

Measurement of stand indicators was carried out using conventional mensuration methods that have already been used before [15]. A continuous counting of trees was carried out on the plots; soil patches were taken on each sample area to determine the soil conditions. The samples for macrostructural analysis were taken from the experimental plots, taking into account the quantitative representation of the diameter class in the stand (not least 25-30 core samples were taken on each plot). The core samples in the radial direction were extracted at the height of 1.3 m from the root collar using Pressler's increment borer. The macrostructure of wood was characterized by the annual early wood and late wood increment width over the period of study.

To study the elements of wood macrostructure in samples in the form of cores, the method of processing samples with a high resolution scanner was used, which, according to modern research, gives results with a measurement accuracy interval of ± 0.01 mm. The prepared wood sample, ground smooth and glued to the holder, was placed on a high resolution scanner, and the sample surface was scanned with an accuracy of 1200 dpi in full color mode (16.7 million colors). The digitized scanned image was adjusted subsequently in terms of brightness and contrast indicators to better distinguish early and late core wood. To measure the indicators of the wood macrostructure in the obtained image, the application “Geo-information system Panorama 10” was used. The image was converted to a geographic information system with a resolution similar to the scanning resolution (conventionally, 1 m on an electronic map was taken as 1 mm). GIS tools were used to draw a line along the longitudinal axis of the core. For each annual increment, the boundaries of the zone of the late and early zones of wood were established and points were set on the line at the appropriate places. Thus, as indicators characterizing the macrostructure of wood, we measured the average width of the annual layers and the content of the late and early xylem in the annual layer during the life of the tree. These indicators were determined for all wood samples taken from model trees in study plots. Later, the Microsoft Excel spreadsheet processor was used to systematize the obtained quantitative and qualitative data on the macrostructure of pine and spruce wood.
The collected field materials were processed by variation statistics methods, the processing of the obtained qualitative and quantitative data was carried out using the following software: “Statistica 10”, “STATGRAPHICS Centurion XVI”, and “Microsoft Excel” [16].

3. Result and Discussion

In the studied stands, the relationship between the average temperature as the most significant meteorological factor and the annual radial increment of stands was analyzed. A preliminary analysis showed that there are qualitatively distinct growth and development stages of pine trees and stands. Each stage is characterized by specific growth parameters and relationships between trees in the community, depending on soil conditions and plantation composition.

In order to exclude the qualitative difference of the material due to the factor of time, the time series of local chronologies were limited to only one stage of tree growth. Therefore, this study analysed annual increments of trees and meteorological data over the period from 1960 to 2015, which gave fairly uniform material both from the point of view of increment and relationships of trees in the community, and the dynamics of temperatures and precipitation.

Figure 1 shows average temperature fluctuations and radial increment during the growing season in objects on double layer soils with different composition of pine stands (here and further “P” – pine, Pinus sylvestris; “S” – spruce, Picea abies; “B” – birch, Betula pendula; “A” – aspen, Populus tremula).

Figure 1. Average air temperature and increment in pine stands at experimental sites on double layer soils.

During the observation period, there was a reduction of the average annual radial growth of pine wood up to present days. It should be noted that the best response of average annual increment to precipitation and average temperature fluctuations over periods is observed in stands with the largest, 80-90%, and the lowest, 20%, share of pine in the stand at the given soil conditions.

Under these conditions, the growing stock reacted to the carried out drainage melioration after its carrying out in 1970 with less variability of annual growth on the fluctuations of meteorological factors (figure 2).
Figure 2. Average air temperature and increment in pine stands at experimental sites on drained ferruginous illuvial sandy loam soil.

It can be seen that on drained ferruginous illuvial sandy loam soil, the observed growth rates of pine wood in terms of temperature and precipitation varied for the first decades of the observation period and were almost equal in the subsequent period.

For plantations with different shares of pine growing on loamy soils, are also observed different increment fluctuations depending on meteorological factors during the period of study (figure 3).

Figure 3. Average air temperature and increment in pine stands at experimental sites on loamy soils.

However, while during the first decades, a joint fluctuation of increment following the changes in meteorological factors was observed, then in the subsequent period, the increment changes became
smoother in response to weather condition changes. In these soil conditions, mixed pine stands are less responsive to meteorological fluctuations than on other soils. Apparently, these soil and hydrological conditions are optimal for the growth of pine-and-spruce plantations.

When the direction of meteorological influence on the annual wood increment is considered, it is observed that a significant linear relationship, estimated using the regression analysis, is observed only when there is a combined action of the sum of positive temperatures and precipitation during the growing season. When used separately, these parameters showed statistically insignificant influence. Therefore, the regression analysis is carried out for both parameters and the results of the analysis are shown in Table 1.

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 pine wood structure in stands with the prevalence of pine.

| Stand composition | Late wood | Early wood | Annual increment |
|-------------------|-----------|------------|------------------|
|                   | R², %     | P-Value F-| R², % P-Value F-| R², % P-Value F- |
|                   |          | Ratio     |          | Ratio     |          |
| Double layer soils|           |            |            |           |            |
| 90P10S            | 9.33      | 0.08       | 2.68*     | 11.39     | 0.04      | 3.52      | 11.79     | 0.04      | 3.47      |
| 80P20S            | 6.41      | 0.18       | 1.78      | 9.93      | 0.07      | 2.87      | 9.17      | 0.08      | 2.62      |
| 80P10S10B         | 8.85      | 0.09       | 2.53      | 10.15     | 0.06      | 2.94      | 10.17     | 0.06      | 2.94      |
| 40P40S20B10A      | 11.85     | 0.04       | 3.49      | 11.34     | 0.04      | 3.33      | 11.72     | 0.04      | 3.45      |
| 20P10S60B10A      | 2.96      | 0.44       | 0.82      | 6.23      | 0.18      | 1.79      | 5.13      | 0.24      | 1.46      |
| Drained ferruginous illuvial sandy loam soils | | | | | | | |
| 100P              | 2.93      | 0.47       | 0.76      | 16.37     | 0.01      | 4.89      | 12.34     | 0.04      | 3.52      |
| 60P30S10B         | 10.85     | 0.05       | 3.16      | 13.90     | 0.02      | 4.20      | 13.51     | 0.02      | 4.06      |
| Loamy soils       |           |            |            |           |            |           |            |           |            |
| 90P10S            | 17.25     | 0.01       | 5.63      | 19.26     | 0.00      | 6.44      | 19.08     | 0.00      | 6.37      |
| 70P(10-20S) drained | 2.23      | 0.56       | 0.59      | 6.09      | 0.20      | 1.69      | 5.18      | 0.25      | 1.42      |
| 70P30S moistened  | 4.87      | 0.27       | 1.33      | 12.22     | 0.03      | 3.62      | 9.58      | 0.07      | 2.76      |
| 60P(30-40S) waterlogged | 5.43      | 0.23       | 1.52      | 9.68      | 0.07      | 2.84      | 7.48      | 0.13      | 2.14      |
| 50P40S10B moderately moist | 5.93      | 0.20       | 1.64      | 9.03      | 0.09      | 2.58      | 8.33      | 0.10      | 2.36      |
| 50P20S10B10A waterlogged | 0.61      | 0.85       | 0.17      | 1.53      | 0.66      | 0.42      | 1.15      | 0.73      | 0.31      |

* Here and further F<sub>cal=2.42</sub> (for 55 cases with 2 degrees of freedom and with p=0.1)

The analysis of the stands with a decreasing pine share on dual soils reveals a decreasing dependence of annual increment on the meteorological factors (\( t + W \)). A similar trend is observed for the amount of early wood. When the pine share is decreased to 80% in stand composition, the dependence of late wood zone on meteorological factors was also decreasing. However, with a greater share of other species in the stand, a significant effect of these two meteorological factors on both the annual increment and the late wood proportion was not confirmed.

With a change in the moistening conditions on drained sandy ferruginous soils, a decrease of the pine share in the stands causes an increased dependence of the annual radial increment from meteorological factors. Also, a relationship between the proportion of early wood and meteorological
factors observed in pure pine stands is more significant than in the stands with a lesser proportion of pine. For the share of latewood, an inverse relationship is observed – with a decrease in the share of pine, the relationship between the late wood increment and meteorological factors increases.

A change in the granulometric composition of soils, weighting and moistening of loamy soils, is clearly accompanied with a decrease in the dependence of annual increment on meteorological factors as a share of the pine in the stand decreases. In the case of drainage of the stand with a 70% pine (10-20% spruce) share, a clearly decreased influence of meteorological factors on annual increment is observed, which is explained by improved growing conditions. With a decrease of the share of pine in the stand, a similar pattern is observed in reducing the influence of meteorological factors on the formation of the zone of early- and late wood. In some cases, the influence of meteorological factors on macrostructural elements of wood is significant at a 70% confidence level (significant in 2/3 of cases).

Under different soil and hydrological conditions, when the pine share in the composition changes, the structural elements of xylem demonstrate an increasing dependence of annual increment on the share of the species in the composition of the plantation. This dependence is stronger for early wood than for late wood. Overall, as the soil texture becomes coarser, the smaller the share of pine in the stand, the less the formation of macrostructural xylem elements depends on meteorological factors.

Linear regression analysis revealed that, apparently, the influence of meteorological factors on the formation of macrostructural elements of the wood is of non-linear nature, since the calculated coefficient of determination varies from 6% to 19% of the sum of all factors that affect a given variable. A nonparametric analysis was used to confirm the hypothesis of a more complex relationship between the influencing factors and dependent variables of wood macrostructure.

The effect of the sum of temperatures and precipitation during the growing season on the macrostructure of wood was analyzed using Spearman's rank correlation; table 2 shows the results of the analysis.

On fine-textured soils, the annual increment has the greatest correlation with the sum of temperatures. A similar relationship was observed also for the early wood width. For the late wood, a statistically significant correlation is observed at objects with the presence of broad-leaf species in the composition.

Table 2. Spearman's rank correlation coefficients $R$, for wood macrostructure indicators and weather conditions in pine-dominated stands.

| Stand composition | Latex wood | Early wood | Annual increment |
|-------------------|-----------|------------|-----------------|
|                   | Temperature | Precipitation | Temperature | Precipitation | Temperature | Precipitation |
| Double layer soils|           |            |           |            |           |            |
| 90P10S            | -0.25      | -0.21      | -0.31      | -0.05      | -0.30      | -0.08      |
| 80P20S            | -0.23      | -0.14      | -0.31      | -0.14      | -0.30      | -0.13      |
| 80P10S10B         | -0.32a     | -0.06      | -0.35      | -0.09      | -0.33      | -0.07      |
| 40P40S20B10A      | -0.34      | -0.04      | -0.37      | -0.08      | -0.35      | -0.07      |
| 20P10S60B10A      | -0.13      | -0.10      | -0.19      | -0.13      | -0.17      | -0.12      |
| Drained feruginous illuvial sandy loam soils |           |            |           |            |           |            |
| 100P              | -0.18      | -0.07      | -0.33      | -0.19      | -0.31      | -0.16      |
| 60P30S10B         | -0.36      | -0.11      | -0.32      | -0.16      | -0.34      | -0.18      |
| Loamy soils       |           |            |           |            |           |            |
| 90P10S            | -0.44      | -0.10      | -0.46      | -0.10      | -0.45      | -0.11      |
| 70P(10-20S)       | -0.09      | -0.11      | -0.17      | -0.17      | -0.15      | -0.17      |
| drained           |           |            |           |            |           |            |
| 70P30S moistened  | -0.23      | 0.12       | -0.34      | 0.05       | -0.30      | 0.08       |
| 60P30S(30-40S)    | -0.22      | -0.07      | -0.19      | -0.19      | -0.20      | -0.16      |
waterlogged
50P40S10B
moderately moist
-0.25 -0.16 -0.30 -0.17 -0.28 -0.18
waterlogged
50P20S1B10A
-0.08 0.06 -0.09 0.01 -0.09 0.04

Here and further marked bold coefficients are statistically significant at $p=0.05$

On ferruginous illuvial sandy loam soil, both annual radial increment and the share of early wood are statistically significantly dependent on the sum of temperatures. For the late wood, a statistically significant influence was observed only in the mixed stands with the presence of broad-leaf species.

On moist loamy soils, a significant influence of meteorological factors on the macrostructure of wood was not observed. On fresh loamy soils, however, both radial increment and the early wood width were statistically significantly affected by these factors. The composition of the stand and meteorological factors significantly affected all the macrostructural elements of wood only in the stands considered as pure. No statistically significant relationships were found for the stands where pine trees have a smaller share. Generally, on loamy soils, with the decrease of pine share in the stands, the radial increment and early wood width becomes less influenced by meteorological factors.

For finer soils, however, the opposite trend is observed - with a decrease in the pine share in the stand, its annual increment and the early wood share become more dependent on meteorological factors.

4. Conclusion
Base on the results, it can be concluded that in the stands on mineral loamy soils, the annual radial increment depends more on the individual characteristics of the biotope than on the climatic factors.

Under different soil and hydrological conditions, when the pine share in the composition changes, the structural elements of xylem demonstrate an increasing dependence of annual increment on the share of the species in the composition of the plantation.

This dependence is stronger for early wood than for late wood. At coarser soils and decreasing pine share in the stand, the growth of pine's macrostructural xylem elements becomes less influenced by meteorological factors.

In most cases, in mixed stands with a predominance of pine, the total climatic information from early- and late wood does not exceed the radial increment values for this species.

Pine tree-ring chronologies from the trees growing in mixed stands on sandy loam and dual sandy loam and loam soils, generally have an equal response to external changes associated with the climate of the region, therefore, they should be considered as first-choice species for dendrochronological analysis.

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