Macroscopic structure of *Pinus sylvestris* L. wood during introduction to the Central forest-steppe

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Abstract. The macroscopic structure of *Pinus sylvestris* L. wood growing in the geographical cultures of the Central forest-steppe (Bryansk, Voronezh, and Volgograd climatypes), natural forests of the broad-leaved forest zone of the Bryansk region, the zone of the southern forest-steppe of the Voronezh region and the dry steppe of the Volgograd region was studied. The dependence of the annual ring width on the degree of humidification was found. When *Pinus sylvestris* L. moving in arid conditions of the dry steppe, changes in the annual ring width were noted, this is an adaptive feature of plants to environmental conditions. The early wood is more susceptible to changes in width depending on the growing conditions than late wood. In geographical cultures of *Pinus sylvestris* L. created in the Central Forest-steppe of the Voronezh Region climatypes from the Bryansk region have a decrease in the annual ring width and climatypes from the Volgograd region have an increase in the annual ring width, which is related to a change in the degree of humidification. Macrostructural features of wood can be an indicator of the climate in certain natural conditions.

1. Introduction

The introduction of *Pinus sylvestris* L. is of great scientific and practical interest, since this species is forest-forming. The main success of the growth of *Pinus sylvestris* L., introduced beyond the range into geographical cultures, depends on the hereditary properties of ecotypes and environmental factors at the test points. The study of the natural gene pool of the species on specific ecotypes and the creation of its introduced gene pool allows us to identify bioecological features that ensure the active adaptation of plants.

The key issue in the introduction of plants is the adaptive reaction of species to new growing conditions. Special attention should also be paid to the study of physiological features of the main forest-forming species in their natural habitats – ecological range, since the adaptive response to natural climatic conditions was formed during the evolution of the species [1].

The analysis of the radial growth of *Pinus sylvestris* L. allows us to identify the adaptation features to various conditions of existence, to determine promising ecotypes for further reforestation, which will help to solve global forestry problems.
The structure of coniferous plants wood, the annual tree ring width and its variability depending on forest growing conditions and, in general, the adaptability of *Pinus sylvestris* L. is considered by various authors [2,3]. Quantitative indicators of the anatomical structure of wood reflect the adaptation of plants to environmental changes. Early wood is modified by the influence of climate, and late wood depends on season of the year [4].

The features of annual growth are directly related to seasonal fluctuations. On automorphic soils when drought in the second half of the growing season, the plants of *Pinus sylvestris* L. have a “loss of the annual ring” during the late wood formation. In the first half of the growing season, the soil moisture deficit at elevated temperatures affects the reduction in the early wood width [5].

In the stands of *Pinus sylvestris* L. of the Leningrad region, there is a large dependence of the formation of radial growth elements on average temperatures. In mixed forests of *Pinus sylvestris* L., the dependence on temperature indicators is especially pronounced in July-September. When decreasing of other tree species percentage, the connection between late wood and average temperatures increases, and the width of the early wood zone and the radial growth indicators decrease [6].

Climate fluctuations have a significant impact on the wood structure. The time of the climate influence is reflected in the structure of the annual rings [7]. The plant is stressed by drought due to increased temperatures and lack of water. The study of two coexisting pine species in a seasonally arid region showed a decrease in the maximum wood density due to an increase in temperature and, as a result, an increase in the in air and soil dryness [8]. Dendrochronological studies of various pine species under contrast conditions showed the influence of climate on carbon storage, which is associated with the volume of accumulated biomass [9].

It is believed that the climate warming will increase the duration of the growing season for plants of northern and temperate latitudes, but observations have shown a direct dependence of the wood growth on the air and soil humidity. The process of forming *Pinus ponderosa* wood has a high phenological plasticity especially under the influence of moisture; it is a problem in arid conditions [10].

In Latvia [11], a study of the annual tree rings width in three geographical climatypes of *Pinus sylvestris* L. showed that plants from warm places have less growth sensitivity to weather conditions and are more resistant to adverse changes due to the ability to use a longer growing season and absorb more nutrients. Studies of the reaction of trees to temperature depending on the duration of the growing season showed that trees from areas with a short growing season react faster to rising temperature and stop growth earlier than trees in areas with a longer growing period. The mismatch between the growth phenology and the environment can lead to reduced adaptation and poor plant growth.

The purpose of this work is to study the variability of the annual tree ring width of the *Pinus sylvestris* L. wood (divided into early and late wood zones) in the geographical cultures of the Central forest-steppe, depending on the different conditions of origin of climatypes, and to identify the growth limiting factors.

2. Materials and methods

The object of research was *Pinus sylvestris* L., which grows in the geographical cultures of the Voronezh forestry (Bryansk, Voronezh, Volgograd origin) and in the natural forests of Bryansk (Karachevsky forestry), Voronezh (Khotenskovsky forestry), Volgograd (Archedinsky forestry) regions. The growing conditions of the research objects are characterized by various natural and climatic indicators (table 1).

The material for the study was collected in the summer period of 2008 and 2014. According to the materials of the taxation description, the areas with old-age plantations of *Pinus sylvestris* L. were selected in natural forests. Test areas of 50x80 m, i.e. 0.40 ha, were laid at each site. It is necessary that there are at least 200 trees of the main breed (pine) on the trial area. Geographical cultures of *Pinus sylvestris* L. are 45-60 years old. The area of the registered plots for these plantings is 0.05 ha.
In all the selected plots, a continuous list of trees was carried out with a distribution by thickness stages. When measuring diameters of the trunk at the height of the chest, a measuring fork was used, and a manual altimeter RM-5/1520 Suunto (Russia) was used to measure the heights.

**Table 1.** Characteristics of natural and climatic conditions of objects research growth.

| Indicator                             | Bryansk region (Karachevsky) | Voronezh region (Khrenovskoy) | Volgograd region (Archedinsky) |
|---------------------------------------|------------------------------|------------------------------|-------------------------------|
| Natural-climatic zone                 | Broad-leaved forest zone     | Southern forest-steppe zone   | Dry steppe zone               |
| Average annual temperature, °С        | +4.5                         | +6.9                         | +6.9                          |
| Rainfall per year, mm                 | 750                          | 486                          | 200                           |
| Hydrothermal coefficient (HTC)        | 1.6 (sufficient humidification) | 0.9 (moderate humidification) | 0.5 (weak humidification)     |
| Temperature above +10° C, number of days | 185                         | 200                          | 206                           |

To compare the macrostructural features of wood in geographical cultures, 16 trees of each climatype were examined. Samples were taken from trees in the middle rows of the stand. The height and diameter of the selected trees did not significantly differ from the average values for the climatype. Wood samples were taken with an incremental borer. Wood cores for each tree were taken in 2 opposite radii and the results of the annual tree rings width, the width of early and late wood on the tree were averaged. Model trees of *Pinus sylvestris* L. in the amount of 16 from each site were cut down in the natural conditions.

The annual tree rings width and the size of early and late wood were determined using the LINTAB 6 (RINNTech, Germany) measuring device for annual rings with a resolution of 10 µm (1/100 mm). The results were calculated using the Excel computer program.

When processing the results of the annual tree rings width, the width of early and late wood, the characteristics were calculated: sample arithmetic mean, sample mean quadratic deviation, average error S of the sample arithmetic mean, the sample coefficient of variation V in percent, relative accuracy of the sample arithmetic mean.

The indexed characteristic values are obtained by the ratio of the real values to the approximated ones. The approximation of the annual tree rings width was made using a fourth-degree polynomial and a second-degree polynomial was used for late wood fraction.

During statistical processing, a two-way check of the correlation coefficients for statistical significance was applied. The work uses the programs “Statistica 8.0” (Statsoft) and Microsoft Office Excel 2007.

3. Results and discussion

The average taxation indicators of geographical groups are shown in table 2. The results of measurements of the macrostructure of *Pinus sylvestris* L. in geographical cultures of the Central forest-steppe are presented in table 3.

The data of the macrostructure of *Pinus sylvestris* L. wood in geographical cultures (60 years) were compared with the indicators of the macroscopic structure of pine wood in natural forests (60 years) growing in Bryansk (broad-leaved forest zone), Voronezh (southern forest-steppe), and Volgograd (dry steppe) regions. Table 4 shows the average parameters of the annual tree rings of *Pinus sylvestris* L. wood in these forest-growing zones.

Analyzing the annual ring width of *Pinus sylvestris* L. from various origins, it should be noted that there is a close connection between forest growing conditions and the radial wood growth. In Central forest-steppe the annual ring width of Bryansk climatype (from the forest zone) for 60 year period ranges from 0.76 mm to 4.72 mm, the average is 1.98 mm.
Table 2. Average taxation indicators of geographical groups of *Pinus sylvestris* L. of Central forest-steppe.

| Geographical origin | Forest area                     | Coordinates of seed collection | Average height, m | Average diameter, cm | Average stock per 1 ha, m³ |
|---------------------|---------------------------------|--------------------------------|-------------------|----------------------|---------------------------|
| Bryansk             | Broad-leaved forest zone        | I.L. 54° 07′ N.L. 34° 59′      | 19.6              | 20.7                 | 157.0                     |
| Voronezh            | Forest-steppe zone              |                                | 16.3              | 13.3                 | 260.0                     |
| Volgograd           | Steppe zone                     |                                | 17.2              | 16.5                 | 219.0                     |

Table 3. Parameters of the annual ring width of *Pinus sylvestris* L. wood (60 years) in geographical cultures of Central forest-steppe, mm.

| Geographic ecotypes                      | Average characteristic value |         |         |         |
|-----------------------------------------|------------------------------|---------|---------|---------|
|                                        | Annual ring width, mm        | Early wood width, mm | Late wood width, mm |
| Bryansk ecotype (Klintsovsky forestry)  | 2.0±0.89                     | 1.3±0.08 | 0.7±0.59 |
| Voronezh ecotype (Khrenovskoy forestry) | 2.3±1.06                     | 1.6±0.07 | 0.8±0.18 |
| Volgograd ecotype (Archedinsky forestry)| 2.6±1.11                     | 1.7±0.07 | 0.9±0.11 |

The average value of the annual tree ring width in trees of the Voronezh climatype (from the southern forest-steppe) is slightly higher – 2.25 mm, with a variation from 0.71 to 6.60 mm. In the Volgograd climatype (from the dry steppe), the annual tree ring width varies from 1.26 to 6.31 mm. The average value increases to 2.60 mm.

The study of the dynamics of the annual tree ring width in trees of the Bryansk, Voronezh, and Volgograd climatypes in Central forest-steppe shows that there are no differences in the age of achieving maximum radial increase between climatypes. In Bryansk, Voronezh and Volgograd climatypes, the maximum of the annual tree ring width is observed at the age of 9. Significant differences between the average values of the annual ring width in climatypes begin to appear from the age of 22. The correlation coefficient for the annual tree ring width between climatypes is 0.97 (p < 0.001).

Table 4. Parameters of the annual tree rings of *Pinus sylvestris* L. wood (60 years) in natural forests, mm.

| Forest area                              | Average characteristic value |         |         |         |
|------------------------------------------|------------------------------|---------|---------|---------|
|                                        | Tree ring width, mm          | Early wood width, mm | Late wood, mm |
| Broad-leaved forest zone of Bryansk region | 2.5±0.07                     | 1.7±0.07 | 0.8±0.02 |
| Southern forest-steppe zone of Voronezh region | 1.7±0.05                     | 1.2±0.04 | 0.5±0.02 |
| Dry steppe zone of Volgograd region      | 1.3±0.06                     | 0.9±0.03 | 0.4±0.02 |

The analysis of the connection between the annual tree ring width and the temperature indicators of the Central forest-steppe did not give a clear picture. Bryansk climatypes, which have hereditary adaptation to late spring and early autumn frosts, did not show the increase of the annual tree ring width with an improvement in the temperature regime. However, the analysis of the connection
between the annual tree ring width and precipitation between climatypes showed both similarities and differences. The similarity is that valid correlation coefficients for climatypes are connected with monthly precipitation in June and July. Accordingly, for the Bryansk climatype $r = 0.41$ ($p < 0.05$) and $0.48$ ($p < 0.01$), for the Volgogradsky climatype $r = 0.51$ ($p < 0.01$) and $0.39$ ($p < 0.05$). The differences are related to the influence of August precipitation. The Bryansk and Volgograd climatypes do not have a positive effect of August precipitation; the greatest correlation is connected with the total precipitation recorded from May to July ($r = 0.61$; $p < 0.001$). The Voronezh climatype has the highest correlation coefficient for the total precipitation measured from May to August ($r = 0.65$; $p < 0.001$).

Thus, in the Central forest-steppe correlation indexes of the annual ring widths of Pinus sylvestris from different origins and temperature are only negative. Under these conditions the limiting factor for tree growth is precipitation, temperature rise only has a negative effect on the duration of the xylem cells formation due to increased water deficit. The connection of the annual ring width indices with precipitation in the Central forest-steppe for the Bryansk climatype is best expressed in June, and for the Voronezh climatype is in July. When combining precipitation data for the summer months, the Bryansk and Volgograd climatypes have the highest correlation coefficient for the total precipitation from the beginning of May to the end of August.

In forest-steppe conditions up to the age of 21, the trees of Bryansk and Volgograd climatypes do not differ from the trees of the local Voronezh climatype in the annual tree ring width. In the forest-steppe the Bryansk climatype has an elongated growing season; it is confirmed by a higher correlation index of the annual ring width with August precipitation. In recent years, the Bryansk climatype is probably adapting to the early beginning of the growing season and less moisture in the spring in the forest-steppe zone. As a result, this led to a greater annual tree ring width in the Bryansk climatype at the age of 25-40 years in the forest-steppe (the average value is 2.58 mm, for the local Voronezh climatype it is 2.34 mm), mainly due to early wood.

Thus, analysis of the radial growth reaction in climatypes of Pinus sylvestris L. from various origins in the central forest-steppe on weather conditions showed the absence of a positive effect of high temperatures on the increase in the annual tree ring width in the forest-steppe zone, which is probably due to the lack of moisture at higher temperatures. In this sense, the correlations with temperature are probably negative which will suggest a temperature-induced drought, it is quite typical in the forest steppe [12,13].

In the Central forest-steppe, the trees of the Volgograd climatype differ from the Voronezh one by a greater proportion of late wood. The Volgograd climatype in the Central forest-steppe has a long growing season, which is typical for it in the steppe.

The change of late wood in the climatypes of Pinus sylvestris in the Central forest-steppe occurs under the influence of the amount of precipitation in July. Successful adaptation of Bryansk climatype trees to the conditions in the forest with a lower value hydrothermal coefficient and a longer growing season is observed from a 22-year-old age in the greater annual tree ring width in comparison with Voronezh climatype trees. Perhaps this is due to the early beginning of the growing season and the formation of a larger width of early wood zone.

The greatest annual tree ring width (2.5 mm) among the plantations of natural pine forests is observed in the conditions of the Bryansk region, since the moisture coefficient is higher there. The lowest indicator of the annual tree ring width (1.3 mm) is in the conditions of the Volgograd region, where, according to the continuous list, the height and diameter indicators for the forest are less than in conditions of sufficient moisture. Intermediate values of the annual ring width are observed in the stands of Pinus sylvestris in the Voronezh region, where the humidification conditions are moderate.

When obtaining data on the width of early wood, similar changes can be observed, that is, a decrease in indicators when moving to the dry steppe conditions (from 1.7 mm in the Bryansk region to 0.9 mm in the Volgograd region). This means that the width of early wood is an indicator that depends on changes in environmental factors. The values of late wood indicators slightly decrease from conditions of sufficient moisture (0.8 mm) to arid conditions (0.4 mm), but in general they are
stable and do not have large deviations. The late wood of *Pinus sylvestris* reacts to climatic conditions at the end of the growing season.

In favorable conditions for growth, the wood forms wide annual rings. Data of the macroscopic structure of pine-tree wood in natural forests indicate that sufficient moisture in the broad-leaved forests of the Bryansk region contributes to the formation of the widest annual rings in comparison with plants grown in the southern forest-steppe zone of the Voronezh region and dry steppe Volgograd region. If conditions for growing deteriorate, the annual rings become narrower. The annual tree ring width of *Pinus sylvestris* L. in the dry steppe of the Volgograd region is reduced by half compared to this indicator in the zone of broad-leaved forests of the Bryansk region, it is connected with the lack of moisture for plants. When visually examining the cross-sections of wood, you can see that the boundaries of the annual layers are clearly distinguishable. In general, the lack of moisture affects the formation of forests with lower parameters in height and trunk diameter. In the southern forest-steppe of the Voronezh region, the conditions for growth are favorable; however, here plants sometimes suffer from drought. Indicators of the annual tree ring width have an average value. Thus, the movement of plants to xeromorphic conditions causes changes in the structure of plants; this is an adaptive reaction that allows the plant to survive in adverse conditions.

Comparing the average indicators of the annual ring of *Pinus sylvestris* L. in natural forests and in geographical cultures, changes in the width of the annual tree rings and the early wood of zone during introduction into the Central forest-steppe were noted. Indicators of the annual tree ring width of *Pinus sylvestris* L. When moving from broad-leaved forests to the Central forest-steppe decrease by 20%. The annual tree ring width of *Pinus sylvestris* L. when transferred from the dry steppe to the conditions of the Central Forest-steppe increases by 50%. This reaction is the result of climatic and geographical factors influence on the annual tree ring width and early wood. The limiting factor for the formation of the wood macroscopic structure of *Pinus sylvestris* L. when introduced into the Central forest-steppe is the amount of precipitation, which is characterized by the hydrothermal coefficient (GTC). The use of seed material from the Bryansk region for cultivation in the Voronezh region will lead to a decrease in the productivity of pine plantations in the Central Forest-steppe. When transferring seed material from the Volgograd region to the Voronezh region, there is a significant increase in the indicators of the annual ring and early wood, which is connected with improved moisture conditions.

4. Conclusion

Climatic and geographic factors have a huge impact on the formation of the trunk wood macrostructure of various species. We conducted a macrostructural analysis of plantings of *Pinus sylvestris* L. from natural forests and geographical cultures. According to the obtained data, plants introduced into contrasting natural and climatic conditions, adapting to changes of environmental conditions, also change.

Limiting role in the formation of the wood microstructure is played by the degree of humidification, characterized by different indicators of hydrothermal coefficient (table 1). The relatively warm and humid spring-early summer period and the warm end of the season cause the formation of the broader annual ring, but the lack of water reduces the annual tree ring width at warm temperature (annual ring width of *Pinus sylvestris* L. from Volgograd).

Knowledge of the directions of structural adaptation for species, at the level of the wood macrostructure formation, allows you to plan work on the introduction of *Pinus sylvestris* L., in particular, to clarify the current forest-seed zoning.

The obtained data of the trunk macrostructure in geographical cultures from the Central forest-steppe of the Voronezh Region also show changes in the annual tree ring width from the degree of humidification, which is characterized by a hydrothermal coefficient. *Pinus sylvestris* L. as a very flexible species reflects the following pattern on the macrostructural features – with a decrease of the humidification, the annual tree ring width also decreases. For example, the annual tree ring width of *Pinus sylvestris* L. growing in broad-leaved forests of the Bryansk region is 30% greater than that of
*Pinus sylvestris* L. growing in the forest-steppe zone of the Voronezh region. But with the introduction of *Pinus sylvestris* L. from the Bryansk region to the Central forest-steppe, the annual tree ring width decreases by 20%. The annual tree ring width of *Pinus sylvestris* L. ecotypes from the Volgograd region, where there is a lack of moisture, increases almost twice when the seeds are moved to more favorable conditions in the Central Forest-steppe of the Voronezh region.

An additional feature of the adaptation of *Pinus sylvestris* L. is the width of the early wood zone, which repeats the dependence of the annual tree ring width on environmental factors. That is, early wood is a variable indicator depending on environmental conditions, in particular, on the amount of precipitation. The width of late wood in *Pinus sylvestris* L., both in geographical cultures and in natural forests, is not subject to significant fluctuations when environmental factors change and is a constant sign.

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**References**

[1] Runova E, Garus I and Serkov D 2018 Growth and formation patterns of pine-larch saplings in conditions of Eastern Siberia. *J. For. Sci.* 9(64) 387 https://doi.org/10.17221/4/2018-JFS

[2] Galdina T and Khazova E 2019 Adaptability of *Pinus sylvestris* L. to various environmental conditions. *IOP Conf. Ser.: Earth Environ. Sci.* 316 012002 doi: 10.1088/1755-1315/316/1/012002

[3] Galdina T and Khazova E 2020 Histological changes in the structure of one-year sprouts of *Pinus sylvestris* L. as a reflection of the structural adaptation of the species during its introduction. *IOP Conf. Ser.: Earth Environ. Sci.* 595 012002 doi: 10.1088/1755-1315/316/1/012002

[4] Zhirnova D, Belokopytova L, Babushkina E, Crivellaro A and Vaganov E 2021 Earlywood structure of evergreen conifers near forest line is habitat driven but latewood depends on species and seasons. *Trees* 35(8) 479 doi: org/10.1007/s00468-020-02050-2

[5] Bolbotunov A and Degtjareva E 2020 Features of the seasonal annual increment of conifers wood in forest in the North of Belarus. *Vestnik of Polotsk State University Part F Construction. Applied Science* 8 29 [in Russian]

[6] Chudakov A V, Danilov D A and Zaytsev D A 2020 Influence of meteorological factors on the formation of radial growth of trees in coniferous stands of the Leningrad region. *Izvestia Sankt-Peterburgskoj Lesotehничeckoj Akademii* 232 33 doi: org/10.21266/2079-4304.2020.232.33-49 [in Russian]

[7] Belokopytova L V, Babushkina E A, Zhirnova D F, Panyushkina I P and Vaganov E A 2019 Pine and larch tracheids capture seasonal variations of climatic signal at moisture-limited sites. *Trees-Struct. Funct.* 33(1) 227 doi: 10.1007/s00468-018-1772-2

[8] Pompa-García M, Hevia A, Camarero J 2021 Minimum and maximum wood density as proxies of water availability in two Mexican pine species coexisting in a seasonally dry area. *Trees* 35(2) 597 doi: 10.1007/s00468-020-02062-y

[9] Acosta-Hernández A, Padilla Martínez J, Hernández-Diaz J, Prieto-Ruiz J, Goche-Telles R, Najera J and Pompa-García M 2020 Influence of Climate on Carbon Sequestration in Conifers Growing under Contrasting Hydro-Climatic Conditions. *Forests* 11 1134 doi: org/10.3390/f11111134

[10] Ziaco E, Truettner C, Biondi F and Bullock S 2018 Moisture-driven xylogenesis in *Pinus ponderosa* from a Mojave Desert mountain reveals high phenological plasticity. *Plant Cell Environ.* 41(4) 823 doi: org/10.1111/pce.13152
[11] Matisons R, Jansone D, Elferts D, Adamovičz A, Schneck V and Jansons Ā 2019 Plasticity of response of tree-ring width of Scots pine provenances to weather extremes in Latvia. *Dendrochronologia* **54** 1 doi: 10.1016/j.dendro.2019.01.002

[12] Arzac A, Babushkina E, Fonti P, Slobodchikova V, Sviderskaya I and Vaganov E 2018 Evidences of wider latewood in *Pinus sylvestris* from a forest-steppe of Southern Siberia. *Dendrochronologia* **49** 1 doi: org/10.1016/j.dendro.2018.02.007

[13] Tabakova M, Arzac A, Martínez E and Kirdyanov A 2020 Climatic factors controlling *Pinus sylvestris* radial growth along a transect of increasing continentality in southern Siberia. *Dendrochronologia* **62** 125709 doi: 10.1016/j.dendro.2020.125709