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Seasonal radial growth dynamics of Scots pine (Pinus silvestris L.) in Voronezh region (Russia)

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Abstract. One of the insufficiently studied areas in dendroclimatology is the seasonal dynamics of the radial growth of trees in regions with different climatic conditions. The urgency of this problem has increased due to the observed climate changes. This paper presents the results of a three-year experimental study (2016-2018) on the seasonal growth dynamics of Scots pine in the Voronezh region, as well as the weather conditions during these growing seasons. It has been established that the Scots pine ecotype under the conditions of the forest-steppe zone demonstrates a multi-peaked cyclical dynamics of cell growth rate within the growing season. At the same time, the culmination of growth differs significantly in different calendar years. Annual averages for the following growth traits were registered for the Voronezh region: the duration of the formation of the annual ring (4 months), the onset (25.04-03.05) and the end (29.08) of annual-ring formation, the end of earlywood formation and the onset of the formation of the transition zone from earlywood to latewood (01.07) and the onset of latewood formation (01.08).

1. Introduction

The duration of wood formation of various tree species, the timing of growth onset and end in different climatic zones and forest growing conditions, the distribution of wood growth over the growing season, the end of earlywood formation and the onset of formation are insufficiently studied issues in forestry and dendroclimatology. One of the reasons for the increased attention of researchers in different countries of the world to these issues in recent years is the observed change in climate and conditions for tree growth.

Separate studies of the stages of formation of wood of various tree species in Europe were carried out as early as 1950 - 1960 by Schober (1949), Ladefoged (1952) [1], Larson (1964), and others. In Russia, fairly detailed studies of the xylogenesis of conifers were carried out in Siberia, in the laboratories of dendrochronology at Yekaterinburg and in Krasnoyarsk [2-4].

In the last decade, interesting results of studies on the xylogenesis of various tree species and the relationship of this process with climate in various forest conditions were obtained [5-9].

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In the process of a 9-year monitoring of climate and timing of wood formation in black spruce (*Picea mariana*) (Canada) was found that all plots showed an increase in both annual temperatures and temperatures from May to September, and a significant increase in the duration of xylogenesis from 1950 to 2010. The authors of this study believe that the development of cambial activity can change the short time window for the growth of boreal species and significantly affect the dynamics and productivity of trees in temperature-limited ecosystems [6].

At the Great Basin Mountain Observatory (USA), studies of shifts in the timing of the formation of wood of limber pine (*Pinus flexili*) were carried out. To simulate climate change, the authors of the study used an altitudinal transect. The measurements were carried out by automated dendrometers and through repeated histological microcores in 2013–2014. To account for the natural variability in ring width among samples collected at different points around the circumference of the stem and to reduce data noise, the cell count was standardized to the total cell count in the previous three rings. Then the standardized number of cells was averaged over the tree and over the sites [7].

To better understand the response of coniferous growth to predicted climate change, it is necessary to study the process of their wood formation [8]. Study of temporal variations of various phenological stages of cambial activity in *Abies pindrow* during 2014-2015 along the gradient of altitudes of about 2300-3000 m above sea level in the northwestern Himalayas showed that the onset of cambial activity occurred more than a week earlier at the lowest level than at the highest level. Tracheid formation ceased about three weeks earlier in trees at the highest altitude [8].

The purpose of our research was to establish the duration, timing of the onset and end of the stages of wood growth formation in Scots pine: the formation of the annual ring, the end of the formation of early wood and the onset of the formation of latewood, as well as the distribution of growth extremes by months of the growing season in the climatic conditions of Central forest-steppe of the Russian Plain for three growing periods - 2016, 2017, 2018. In the Central forest-steppe of the Russian Plain, such studies have not previously been carried out.

2. Material and methods

The examined stand of Scots -pine is located in the Central forest-steppe of the Russian Plain on the territory of the Educational Experimental Forestry Voronezh State Forestry University, district forestry of Right-bank of Voronezh river-, quarter 54 site 52 (PRP). A single species Scots pine stand (artificially created in 1966 developed, in the type of forest growth conditions described as "Pine forest on the moderately moist sandy loamy soils" [10] was studied; object coordinates: 51° 46' N, 39° 13' E. Stand age was 50 years. In 2016, three trees of this stand were selected for taking wood samples (microcores). Diameters at breast height (DBH) were 40, 34, and 24 cm (figure 1). In 2017, microcores were selected from four trees, incl. two trees used for coring in 2016 and two other matched trees (DBH = 40, 34, 26, and 29 cm). In 2018, microcores were taken from four trees, including two trees used for coring in 2017 and two other matched trees (DBH = 26, 29, 25, and 34 cm, figure 2).

To study the stages of wood formation of Scots pine, we applied the method of periodically removing small samples -of -wood from the trunk of a growing tree during the season. The periodic sampling turns the picture of the seasonal formation of the annual ring from static to dynamic, by means of which you can calculate the rate of division and the passage of cells for individual periods of differentiation and maturation can be calculated. The main disadvantage of this method is the large variability of the measured characteristics, due to the fact that each subsequent sample is taken at a different radius of the circumference of the barrel [3], but this method makes it possible the indefication of the timing of the onset and end of the stages of wood formation during the growing season.



Figure 1. The layout of the research object.

During three growing seasons (2016, 2017, 2018) microcores were taken from the selected Scots pine trees using a Haglof borer [11]. The following core sampling scheme was adopted: every 7-8 days, sequentially 3-4 cm apart, following a clockwise vertical shift along the trunk (figure 2a, 2b). In total, 60 samples (cores) of seasonal growth were taken from three trees in 2016, 96 samples were taken from four trees in 2017, and 88 samples were taken from four trees in 2018. The resulting wood cores were placed in plastic Eppendorf tubes with fixing fluid (water, alcohol, glycerin), labelled and sent to take measurements in Kazan (Volga region) Federal University.

In the department of general ecology of the Institute of Ecology and Nature Management of Kazan Federal University, anatomical studies of wood samples were carried out. The parameters of pine tree rings were measured on thin $(10-12 \ \mu\text{m})$ cross sections of wood microcores obtained using a GSL1 microtome [12]. Sections were stained with aster blue (2% solution) and safranin (1% solution) for contrast differentiation of non-lignified and lignified tissues, respectively [13-15]. The number and size of cells were measured in triplicate using an Image analysis system and the Axio Vision 4.8.3 software package [16] (figures 3a and 3b).

The meteorological characteristics (monthly sums of precipitation and average monthly air temperatures) are presented according to observations of weather station No 34123 "Voronezh" (51°40' N 39°13' E) [17], located at a distance of about 1.5 km from the studied stand. Calculation of average weather conditions for each year (table 1) and a graphical representation of the information were performed with the Microsoft Excel 2010 software.

An important characteristic about frequency of the atmospheric droughts is the hydrothermal coefficient (HTC) which was for the first time proposed by climatologist G.T. Selyaninov [18]. This index demonstrates the connection between the air temperature and precipitation during the period with active plant growth, and calculated using the following formula (1):

$$HTC = \frac{\sum P}{0.1\sum T^*} \tag{1}$$

where P is the precipitation (mm), and T^* – mean temperature for the months with daily temperature above 10°C. In the city of Voronezh and Voronezh region, the period with average monthly temperature above 10°C extends from May to September, which was used for HTC calculations here.



(a)

(b)

Figure 2. Wood sampling (microcores) by Haglof borer (a) and the scheme of core sampling (b).



Figure 3. Tree number 2, 12.05.2016 – the first xylem cells begin to appear (a) and tree number 4, 15.08.2017 – the latewood formation observed (b).

3. Results and discussion

Our analysis of weather conditions during the years of research (2016, 2017, and 2018), according to the Voronezh weather station, allowed us to give the following brief description of vegetation periods by year.

2018).				
Year	Spring	Summer		
	(after a warm, snowy winter)			
2016	warm, humid, April – 442% more	hot, July – dry,		
	precipitation compared to the	August – with occasional rains		
	norm			
2017	dry (especially May),	June, July – warm, with heavy rains;		
	not hot	August – dry, hot		
2018	wet, hot May	hot, July - wet, August - dry (hereinafter		
		- the record warm September)		

Table 1. Brief description of the features of vegetation periods by years of research (2016, 2017, and

The amount of precipitation during the growing season was significantly higher in 2016 than in 2017 and 2018, and mean air temperature was maximum in 2018 (table 2). We also calculated, in accordance with the methodology of G.T. Selyaninov [18], hydrothermal coefficient for 2016-2018, characterizing the dryness of the growing season (May-September). The calculation results show (table 1) that weather conditions in the Voronezh region became dried from 2016 to 2018. Xylem structure and cambial phenology (i.e. onset and cessation of cambial cell division) of conifers growing under severe water-limitations can change dramatically [19].

Table 2. Weather conditions of tree growth seasons in 2016-2018^a.

Year of research	Precipitation May- September, (mm)	Average temperature May-September (°C)	Yearly precipitation (mm)	Yearly average temperature (°C)	Hydrothermal coefficient May- September
2016	256	18.5	784	8.1	0.91
2017	229	17.6	621	8.1	0.85
2018	230	19.6	612	7.6	0.77

^aAverage precipitation May – September (norm): 295 mm. Average temperature May – September (norm): 17.3°C.

As shown by the results of measurements of the dynamics of wood radial growth during the vegetation periods 2016-2018, the growth rate of Scots pine cells has a multi-vertex cyclic dynamics, which differs in calendar years both in absolute values of growth and in terms of calendar dates of seasonal wood radial growth culmination (figure 4). Figure 4 shows the range of growth rates of Scots pine wood during growing seasons 2016, 2017 and 2018; interquartile range (IQR) of growth rate, including the central 50% values of the range rate of radial growth of pine wood; median; average value of the range of growth rate.

The distribution of growth culminations corresponds to the weather conditions of each calendar year; moisture regime is a primary, factor limiting the growth of trees in the forest-steppe (figure 5). The earliest growth climax recorded for 2016 (June 30) was, in our opinion, the result of a warm, abnormally high-water April and a relatively dry hot summer. In 2017, growth peaked in mid-July (July 13). In 2017, as we noted above, after a dry spring, heavy rainfalls were registered in June and July. In 2018 there was a small culmination of growth around June 30, but the most abundant rainfall in July and the record warm weather in August led to a shift in the main culmination of radial growth of pine towards mid-August (10 August and a smaller peak in 24 August) (figure 4).

The culmination of Scots pine growth from 2016 to 2018 shifted towards the end of the growing season (figure 4), just as the values of the hydrothermal coefficient increased from 2016 to 2018, i.e. dryness of the growing season (table 1).



Figure 4. Dynamics of radial growth in Scots pine during the growth seasons 2016, 2017 and 2018.



Figure 5. Precipitation sum (P, mm): a) and average air temperatures (t, °C) b) for the months of the growing season in 2016 - 2018 according to the "Voronezh" weather station.

Conifers (including Scots pine) show a pronounced maximum growth rate in the first half of the growing season. However, an analysis of the seasonal growth dynamics of Weymouth pine (*Pinus strobus*) and resinous pine (*Pinus resinosa*) in the forests of the southern and northern regions of the United States showed that northern ecotypes have their seasonal growth rates concentrated within a short period, and southern species have a more uniform distribution of seasonal growth rates. The explanation for the observed phenomenon is that the northern ecotypes have preformed shoots (limited growth) and only one period of shoot formation per year, while the southern shoots show periodic growth of shoots [3].

As our studies have shown, the Voronezh ecotype of Scots pine, being a representative of the southern limit of the distribution of island pine forests, shows a relatively uniform (multi-vertex) seasonal distribution of cell growth rate. Moreover, the wood radial growth culmination varies significantly between calendar years characterized by different weather conditions (precipitation and temperature) during the growing season (figure 4).

As many researchers have noted [3, 5, 20] the leading factor in the start of vital activity (reactivation, division) of cambium in spring is the thermal regime of air. As a result of four-year (2007-2010) studies of the influence of environmental factors (air and soil temperature, precipitation, photoperiod) on the beginning of wood formation in Scots pine at an altitude of 750 m above sea level, carried out in Tyrol (Austria), it was found that the sum of air temperatures, and not precipitation or soil temperature, trigger the onset of wood formation in Scots pine. The start of timber formation varied from mid-April (2007) to early May (2008). This study used the method of multiple sampling of wood samples from the trunks of growing trees [5].

Soil temperature, moisture regime and photoperiodism also have a great influence on the onset and end of the stages of coniferous wood formation [1-3, 21]. As a result of studying the external and internal regulation of the transition from earlywood to latewood and the properties of latewood of Siberian spruce (*Picea obovata*) (Russia, Eastern Siberia), the interaction of internal and external factors in the regulation of tracheid differentiation was revealed along an altitudinal transect. Timing of climatic response highlighted the role of photoperiod as a trigger in the earlywood-to-latewood transition, and the crucial role of the growth season ending for latewood development [21]. In the Czech Republic, the interaction between the development of xylem and needles of mature Scotch pine trees was studied for three consecutive years (2014-2016), differing in spring temperatures, onset and duration of summer drought. It was found that summer drought did not affect the development of needles, but changed the rate of production and morphology of late wood tracheids. The improvement in the water status of trees in July led to the formation of intra-annual fluctuations in the density of pine wood [22].

In the study of seasonal coniferous growth carried out in the Urals (Visimsky Reserve, Russia) [2] the dates of the beginning and end of cambium activity, and latewood formation, and the period of

maximum growth were set for spruce, fir and Siberian cedar under different forest conditions. In spruce and fir, the beginning of growth (on average over 4 years) took place from June 3 to 8, the beginning of the formation of late wood – in July 18-20, and the end of cambium activity – in August 12-17. Also, a relationship has been established between the stages of formation of wood growth and phenophases of development of woody plants. The author of the study found that the differences in the time of onset -of phenological phases in different trees in the stand reached 7-12 days.

The study of spatio-temporal trends in the characteristics of tree rings of Scotch pine in the foreststeppe zone in southern Siberia (Russia), as well as their response to climate, revealed the sensitivity of annual-ring parameters to drought [9].

We have established the following dates for the beginning, end and duration of the wood radial growth of Scots pine in the Voronezh region in 2016-2018 (table 3).

2010-2018.						
Year	Growth onset	Onset of transitional wood formation	Onset of late wood formation	Stop of Growth	Duration of the growth period (months)	
	28.04-05.05			25.08-01.09		
2016	(average –	01.07	01.08	(average –	4	
	01.05)			29.08)		
	22.04-28.04			24.08-02.09		
2017	(average –	01.07	01.08	(average –	4	
	25.04)			29.08)		
	,			26.08-01.09		
2018	03.05	01.07^{a}	01.08	(average –	4	
				29.08)		
Average	01.05	01.07	01.08	29.08	4	
0~~ 1						

 Table 3. Dates of onset of the stages of wood formation of Scots pine in the Voronezh region in 2016-2018

^aGrowth stopped in July 2018, then continued.

On average, for three years (2016-2018), the radial growth of pine began around May 1. From July 1, the formation of the transition zone (between earlywood and late-wood) of the annual ring began, however, in July 2018, growth was suspended, apparently due to the dry June and high air and soil temperatures in July. From August 1, the formation of late wood begins. Radial growth ends about August 29, but in some trees it continues until early September. Differences in the times of onset of the stages of wood growth formation in different surveyed trees reached 7-10 days.

The total duration of seasonal radial growth of Scots pine is about 4 months (May - August) in the study region.

Summary

The purpose of our research was achieved: averages values over three years were obtained for: duration of the formation of the annual ring (4 months), onset (25.04-03.05) and end (29.08) of the formation of the annual ring, end of earlywood formation, onset of the formation of the earlywood to latewood transition zone (01.07), the onset of latewood formation (01.08) and distribution of monthly growth extremes of vegetation period for Scots pine under in the study region. Variability in the calendar dates of the stages of wood formation in Scots pine between years of observation was related to, different weather conditions. Variability among trees of the same stand in the dates of onset and end of annual ring formation was also established. Fluctuations in these terms were rather small (7-10 days).

This contribution represents the most exhaustive report to date of the stages of wood growth formation in Scots pine trees in the Central forest-steppe of the Russian Plain, which can be used in future dendrochronological and dendroclimatic studies.

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