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Dendroclimatic Assessment of a 200-Year-Old Scots Pine Stand in the Voronezh Biosphere Reserve

S. M. Matveev[a, b, *] **and D. A. Timashchuk**[a, b]

[a] *Voronezh State University of Forestry and Technologies, Voronezh, 394087 Russia*
[b] *Belgorod National Research University, Belgorod, 308015 Russia*
**e-mail: lisovod@bk.ru*

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Abstract—This paper addresses the effects of climatic limiting factors (precipitation and air temperature) on the radial increment variability of Scots pine (*Pinus silvestris L.*) growing in the Voronezh State Biosphere Reserve under the conservation regime conditions. A natural 200-year-old pine stand belonging to the grassy pine forest with oak type was studied. The following analyses have been performed: a mathematical analysis of the strength and frequency of the relationship between the monthly precipitation amounts and average monthly air temperatures (based on the data of Voronezh and Voronezh Nature Reserve meteorological stations), as well as radial increments of the Scots pine throughout the period of 80 years. It was established that the sums of precipitation in April and especially in May have the maximum effect on the radial increment of Scots pine (spring wood). The precipitation in July–August significantly affects the late wood growth. A strong correlation between the radial increment and September and especially October temperatures of the current year ($r = 0.43$) and the previous year ($r = 0.40$) was identified. In addition, a negative correlation between the radial increment and summer temperatures was established. The correlation ratio of the relationship between the meteorological factors and radial increment was considerably higher than the correlation index, which confirms the nonlinear nature of this relationship. Based on the cyclical dynamics of the radial increment of Scots pine (11- and 34-year cycles), models have been built using two forecasting methods (Caterpillar Singular Spectrum Analysis (SSA) and an additive increment model described by a sinusoid function with a given period), and an increment forecast for the 10-year period was produced. According to the models, the radial increment is going to decrease in 2018–2019, increase in 2021 ± 1, and decrease again in 2024 ± 2.

Keywords: Scots pine, radial increment, weather factors, cycles, forecast

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INTRODUCTION

The studies into the cyclicity of the trees' radial increment dynamics and its dependence on climatic factors commenced in the beginning of the previous century; American scientists carried out such researches most intensely (Schulman, 1941; etc.). The findings published by A.E Douglass back in 1936 showed that all the studied tree groups feature an 11-year cycle, which is also typical for the solar activity dynamics.

Many studies published in the 21st century are also dedicated to the influence of climatic factors on the radial increment of pine stands in regions with various climatic conditions (Magda and Zelenova, 2002; Safonov and Gurskii, 2005; Agafonov and Kukarskikh, 2008; Vakhnina, 2011; Malysheva and Bykov, 2011; Matveev et al., 2012, 2017; Matskovskii, 2013, Matskovsky et al., 2016; etc.). The predominant influence of both the temperature regime (Vaganov et al., 1996; Manov, 2014; etc.) and atmospheric moistening regime (Matveev, 2003; Glyzin et al., 2005; Matveev et al., 2012, Vakhnina, 2013, etc.) on the radial increment dynamics was established. It was also noted that the joint effect of the temperature regime and precipitation causes an unstable climatic response under arid mountainous conditions (Magda and Vaganov, 2006; Magda et al., 2011).

In areas with a predomination of a single climatic factor limiting the growth of arboreal plants, the local growth conditions (relief, soil layer depth and composition, slope grade and orientation, etc.) do not affect significantly the radial increment variability (Babushkina, 2011; Os'kin and Bolbotunov, 2015).

The radial increment dynamics of forest–steppe tree stands features polycyclicity determined by the natural solar activity and variability of climatic factors.

The tree-ring chronologies constitute time series or random functions of a discrete (natural) argument containing information on various environmental factors, including climatic ones. The implementations of these time series may consist of values of various parameters of an arboreal plant's annual ring; each of

Table 1. Statistical parameters of the dendrohronological series

Research subject	Period	Age	Standard deviation	*CV* mean value	Synchronism coefficient	Mean value, mm	Probable error mean value (*Psr*)	EPS	SNR
Chronology 487/6	1817–2015	199	0.409	30.9	82	2.564	8.2	0.99	73

(487/6) planning quarter number/plot number; variation coefficient (*CV*), population signal (EPS), signal-to-noise ratio (SNR).

such parameters contains certain information about the tree growth specificity and environmental factors affecting the radial increment (Shishov et al., 2015).

The qualitative analysis normally precedes a research aimed at the identification of a possible trend, cyclical components, or a random component in the studied time series. A linear–aggregated model reflecting the annual ring width formation (*Rt*) is accepted in dendrochronology:

$$Rt = At + Ct + D1t + D2t + Et, \quad (1)$$

where *A* is the growth trend caused by the normal ageing process;*C* is the effect of climatic factors; *D1* reflects endogenous impacts, e.g., fruiting; *D2* reflects exogenous impacts, e.g., pests, pollution; and *E* is the random component.

The analysis of the above formula makes it possible to define the primary goal of environmental studies: identify the 'trace' left by the factor we are interested in (Tishin and Chizhikova, 2011).

The purpose of this study was to identify and assess the climatic signal (i.e., factors limiting the growth of tree stands in the Central forest–steppe: precipitation and air temperatures) in the radial increment of a 200-year-old pine stand in Usmanskii Bor, as well as model and forecast the radial increment (i.e., productivity) of the pine stand for subsequent use of this information in the course of the planning of forestry practices and assessment of the forest stand condition.

MATERIALS AND METHODS

The study was performed in the Voronezh State Nature Biosphere Reserve designated in 1923, under conservation regime conditions. The climatic parameters are based on the data collected by Voronezh (Weather and climate, 2016) and Voronezh Nature Reserve (Bazil'skaya and Bulkina, 1979; Bazil'skaya, 1997, 2007) meteorological stations located 40 km from each other.

The Voronezh Biosphere Reserve is located at the border between Voronezh and Lipetsk oblasts; it occupies the northern half of Usmanskii Bor insular forest tract. The geographical coordinates of the study area are as follows: 51°52′–52°02′ N and 39°21′–39°47′ E. From the climatic perspective, the biosphere reserve area is a forest–steppe, although it is close to the forest zone by some parameters (snow cover duration, etc.). Forest stands of the biosphere reserve are of great value due to their diversity (including the landscape, typological, species, and genetic diversity) and constitute a unique information base. Scots pine is the primary forest forming species in Usmanskii Bor, which occupies 48% of forested lands in the protected area.

The sample areas were established in a pure pine stand (planning quarter 487, plot 6). By the forest growth conditions, this is a fresh subor (pine forest on moderately moist sandy loamy soils; B_2 symbol on the Pogrebnyak's scale); by the forest type, it is a grassy pine forest with oak.

The dendroclimatic studies have been carried out on the basis of 22 bore specimens (two specimens from each tree) collected in 2015 using an increment borer at heights of 0.5–1.0 m. A LINTAB-6 linear tree-ring measuring tool and TSAP-Win software platform for tree-ring analysis (Rinn, 1996) were used for the dating and measurement of annual rings. The reliability of the tree-ring measurement data was verified using the Student's criterion (*t*): factual values (*tf*) exceeding the standard value (*tst* = 2.18) for the probability level of 0.95 were received for each calendar year (i.e., the average increment value was determined reliably).

The data standardization included the indexing of the annual ring measurement data using a commonly-accepted formula:

$$I = if/is \times 100\%, \quad (2)$$

where *I* is the relative index (%); *if* is the factual width of an annual ring; and *is* is the smoothed value of the standard radial increment calculated using TREND software with the application of sliding and polynomial data smoothing depending on the age. The main statistical parameters of the dendrohronological series (mean values, variation coefficient, standard deviation, probable error, etc.) (Table 1) were calculated using STADIA 6.0 and STATISTICA 6.0 software.

The calculated statistical parameters of the dendrohronological series include, among other things, a clearly manifested Expressed Population Signal (EPS) reflecting the chronology's reliability and the signal-to-noise ratio (SNR) reflecting the mutual correlation of individual chronologies used to produce the generalized chronology.

$$SNR = Nr/1 - r, \quad (3)$$

where *N* is the sample volume and *r* is the average between-run CV.

The calculated EPS value was 0.99; therefore, taking that the commonly accepted threshold value is 0.85, the chronology is representative enough (i.e., the annual ring width for each year adequately reflects the increment of the entire population). The calculated SNR was 73; i.e., the generalized chronology contains a high variability caused by the influence of climatic factors (the studied trees are sensitive to changes in climatic conditions).

The coefficients of similarity between the width of annual rings of each sample and the average value of the studied stand were calculated using TSAP-Win software platform (where GLK was the synchronism coefficient; CC, the correlation coefficient) (Shiyatov et al., 2000).

The correlation coefficient (GLK = 82%) corresponds to the middle level on the Shiyatov's scale (Shiyatov, 1986) with fluctuations from 65–68 to 83–86%. It should be noted that the lowest (less than 70%) values of the similarity (either correlation or synchronism) coefficients of each sample in comparison to the average value for each sample area were noted only for one, out of the two, radiuses of the tree and never noted for both radiuses; and the latter one was always higher.

The probable error of the average radial increment (i.e., the width of annual rings) does not exceed 10%.

The strength of influence exercised by the meteorological factors on the radial increment was calculated as the ratio between the factorial sum of squares (*Df*) and the total sum of squares (*Dc*) of the dispersion complex according to the formula below (STATISTICA 6.0):

$$\eta^2 = \frac{Df}{Dc}, \tag{4}$$

The relative increment index values were used as the resultant parameter, while meteorological factors, as independent variables. If the factual value of *F*-criterion is higher than the reference value ($Ff > Fst$), then the entire equation is recognized statistically significant.

An autocorrelation function making it possible to determine the carrier frequency (lag) of the signal, which is concealed by interfering noises and oscillations on other frequencies, (i.e., eliminating the statistical dependence of the increment dynamics on random processes) was used to assess the signal characteristics (Vessart, 1978; Grippa and Potakhin, 2016).

A cross-spectral analysis (involving the data smoothing method proposed by Richard W. Hamming) was performed using STATISTICA v. 6.0 to identify combined extrema of the cyclical dynamics of relative increment indexes and meteorological factors (precipitation in the warm period and average air temperature) limiting the growth of the Scots pine.

The radial increment modeling and forecast were performed using two different methods: (1) SSA involving the transformation of a one-dimensional time series into a multidimensional one with subsequent application of the principal component method to the resultant multidimensional time series (D'yakonov, 2001; Golyandina, 2004) and (2) construction of an additive model with the application of a polynomial trend enabling to considerably reduce the model's error.

The production of a forecast on the basis of a time series involves its preliminary analysis: formulation of fundamental principles of the time series structure, assessment of the random component, etc.

RESULTS AND DISCUSSION

The annual radial increment of arboreal plants depends on a number of factors, including internal (genetically determined species and individual features, origin, and age) and external ones (forest growth conditions, climatic factors, interspecies and intraspecies relations, and effects caused by pests and diseases). Draughts are the most significant limiting factor in the Central forest–steppe (Tarankov, 1991; Matveev, 2003).

An objective and broadly used parameter reflecting the moistening and atmospheric drought recurrence is the hydrothermal coefficient (HTC) proposed by G.T. Selyaninov (Gustokashina and Maksyutova, 2006; Strashnaya et al., 2011). If HTC is less than 1.0, slight draughts are observed; if it is less than 0.8, moderate draughts occur; and if it is less than 0.6, severe draughts are registered (Tarankov, 1991; Strashnaya et al., 2011). The average HTC value in the period of 1932–2014 was 1.19. HTC was less than 0.6 in 1938 and 1971; it was less than 0.8 in 1939, 1946, 1954, 1966, 1972, 1981, 1992, 1996, 2010, and 2014. The lowest HTC value (0.51) was registered in 1971.

The analysis of the annual ring width dynamics made it possible to identify reliable reference years with the minimum radial increments: 1936, 1939, 1946, 1972, 1984, 1992, 2002, 2010, and 2011; it also revealed the significant influence of draughts on the annual ring width in the studied stand, even though it is not always proportional to the draught intensity.

The radial increment CV varies in certain years from 12.8 to 52.3% in all studied samples. High CVs are most frequently observed in the 200-year-old Scots pine stand in years of severe draughts and especially in the subsequent years (1936, 1938–1939, 1946, 1972–1973, 1992–1993, and 2010–2011).

To identify the quantitative input of climatic parameters in the variability of the Scots pine radial increment, a correlation analysis of paired associations of the annual ring indexes and climatic parameters (precipitation sums and average monthly air temperatures based on the data of Voronezh and Voronezh Nature Reserve meteorological stations) was performed (Fig. 1).

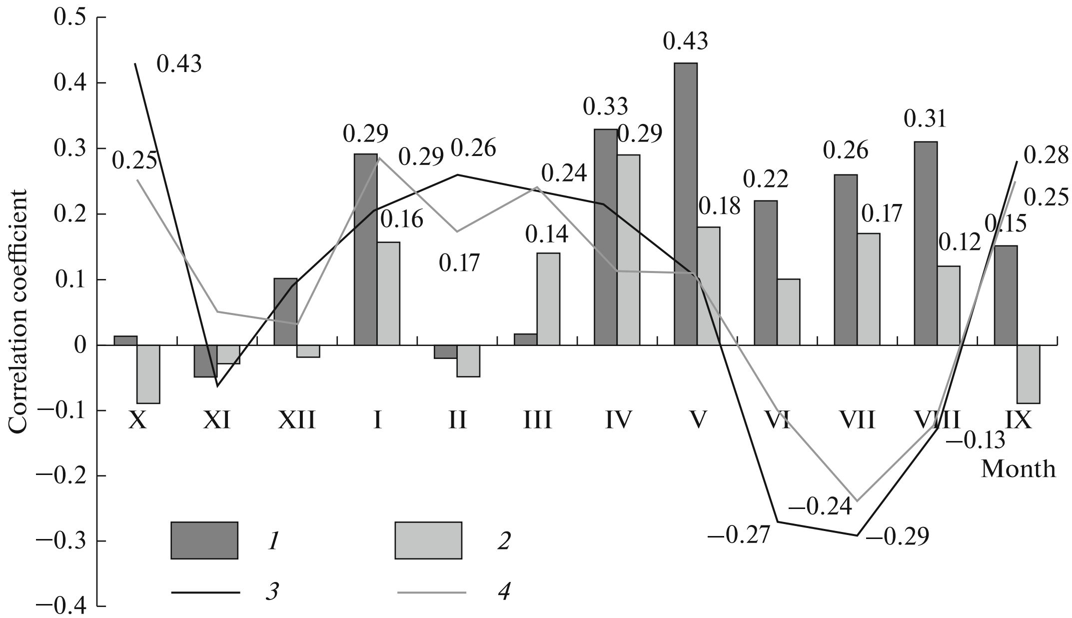

Fig. 1. Significant correlation coefficients between radial increment indexes of Scots pine, precipitation amounts, and average air temperatures by months of the year: (*1*) precipitation registered by the Voronezh Nature Reserve meteorological station, (*2*) precipitation registered by the Voronezh meteorological station, (*3*) temperatures registered by the Voronezh Nature Reserve meteorological station, (*4*) temperatures registered by the Voronezh meteorological station.

The analysis of the climatic response of the pine's radial increment to the meteorological factors (precipitation sums and average air temperatures) was performed for two meteorological stations; it covers the continuous observation period from 1932 to 2014. The correlation coefficient (r) between the precipitation sums registered by the two meteorological stations is 0.68; the correlation coefficient between the average air temperatures recorded by the same stations is 0.7.

As can be seen on Fig. 1, high positive correlation coefficients (by calendar months) between the precipitation sums and radial increment indexes are observed from April to August (from 0.22 in June to 0.43 in May). The peak values are registered in April–May (pine trees form spring wood in May and June) and in August (the late wood is largely formed in August and early September). The January precipitation also significantly affects the pine radial increment (r = 0.29), which indicates the limiting effect of the moisture reserve. A positive correlation between the pine increment formation and temperatures of April–May is observed as well, although it is not as strong as the correlation with precipitation: the temperature regime of these months is not a limiting factor for the pine growth in the Central forest–steppe. The correlation between the radial increment and temperatures of March (i.e., beginning of the spring snowmelt) is strong enough (r = 0.24). There is a moderate negative correlation between the radial increment and summer temperatures (from 0.13 in August to 0.29 in July). The strongest correlation is observed between the radial increment and September temperatures of the current year (the late wood formation in Voronezh oblast ends in September, and lignification of the cells begins) and especially October temperatures (r = 0.43 for October temperatures of the current year, and r = 0.40 for October temperatures of the previous year). The October temperatures mark the beginning of the dormant period for Scots pine and, apparently, are important for the lignification of the tree cells and preparation to the dormant period; the high correlation coefficient value (r = 0.43) for October temperatures of the current year confirms this. In addition, the October temperatures may be important for the dormant period beginning (i.e., for the future cell fission next spring); the almost equally high correlation coefficient value (r = 0.40) for October temperatures of the previous year confirms this. The positive effect of October temperatures on the growth of arboreal plants was noted in northern part of Eurasia as well (Shishov et al., 2015).

Results of the analysis of the relationships between the radial increment indexes on the one hand and precipitation amounts and average air temperatures throughout the hydrological year (based on the data of Voronezh and Voronezh Nature Reserve meteorological stations) on the other hand are provided in Table 2.

The correlation analysis of paired associations of annual ring indexes of Scots pine and meteorological factors has identified higher correlation values with the data of the Voronezh Nature Reserve meteorological station. A moderate correlation with the precipitation is observed: the correlation coefficient is 0.33; the

Table 2. Correlation coefficients between radial increment indexes of Scots pine, precipitation sums, and average air temperatures for the period of 1932–2014*

Climatic parameters	Correlation coefficient, $r \pm m$	Correlation ratio, $\eta \pm m$
Voronezh meteorological station		
Precipitation sum	0.21 ± 0.054	0.35 ± 0.048
Average air temperature	0.11 ± 0.088	0.24 ± 0.075
Voronezh Nature Reserve meteorological station		
Precipitation sum	0.33 ± 0.082	0.51 ± 0.056
Average air temperature	0.18 ± 0.077	0.31 ± 0.089

* The data were examined throughout the hydrological year.

Table 3. Correlation coefficients between radial increment indexes of spring and late wood of Scots pine and precipitation sums (Voronezh Nature Reserve meteorological station)

Climatic parameter	Spring wood		Late wood	
	correlation coefficient, $r \pm m$	correlation ratio, $\eta \pm m$	correlation coefficient, $r \pm m$	correlation ratio, $\eta \pm m$
Precipitation amount in April–May (P4–5)	0.52 ± 0.041	0.80 ± 0.062	–	–
Precipitation amount in July–August (P7–8)	–	–	0.35 ± 0.078	0.66 ± 0.089

"–" indicates that no calculations were performed because spring wood is formed in April–May, while late wood, in July–August.

Table 4. Dispersion analysis of the influence exercised by meteorological factors on the radial increment of Scots pine

Factor affecting the increment	Strength of influence parameter $\eta^2 \pm m$	Actual Fisher's criterion (Ff)	Standard Fisher's criterion (Fst)
Sum of precipitation for April–September	0.59 ± 0.013	8.3	3.9
Average annual air temperature	0.18 ± 0.036	6.3	3.9

data of Voronezh meteorological station demonstrate a weak correlation ($r = 0.21$). The correlation between the increment indexes and average air temperature is relatively low. The correlation ratio of the relationship between the studied parameters is considerably higher than the correlation coefficient; it varies in the range from 0.24 to 0.51, which confirms the nonlinear nature of the relationship between the radial increment and meteorological factors.

In order to identify relationships between the spring and late wood taken separately and precipitation sums in April–May and July–August respectively, their mutual correlation analysis was performed (Table 3).

According to Table 3, the precipitation amount in April–May strongly affects the spring wood growth; the correlation coefficient is 0.52. The precipitation amount in July–August significantly affects the late wood growth ($r = 0.35$).

The dispersion analysis confirmed the significant influence of the precipitation amount in April–September on the radial increment of Scots pine. The strength of influence exercised by average annual temperatures was low (Table 4).

The actual Fisher's criterion values ($Ff = 8.3$ and 6.3) are higher than the standard (threshold) value ($Fst = 3.9$) for all studied factors. It is safe to say that the influence of the precipitation amount in the period of April–September on the resultant parameter (radial increment) is significant. The stationarity of relative increment indexes (a 200-year-old stand) was assessed using an autocorrelation function. The significant period for this tree-ring chronology is 15 years. Each consecutive increment value correlates with the previous one; the first-order autocorrelation is 0.59, i.e., the growth has a clearly manifested seasonal nature. The autocorrelation function reveals a significant relationship between the radial increment of Scots pine in the current year and its increments in the two preced-

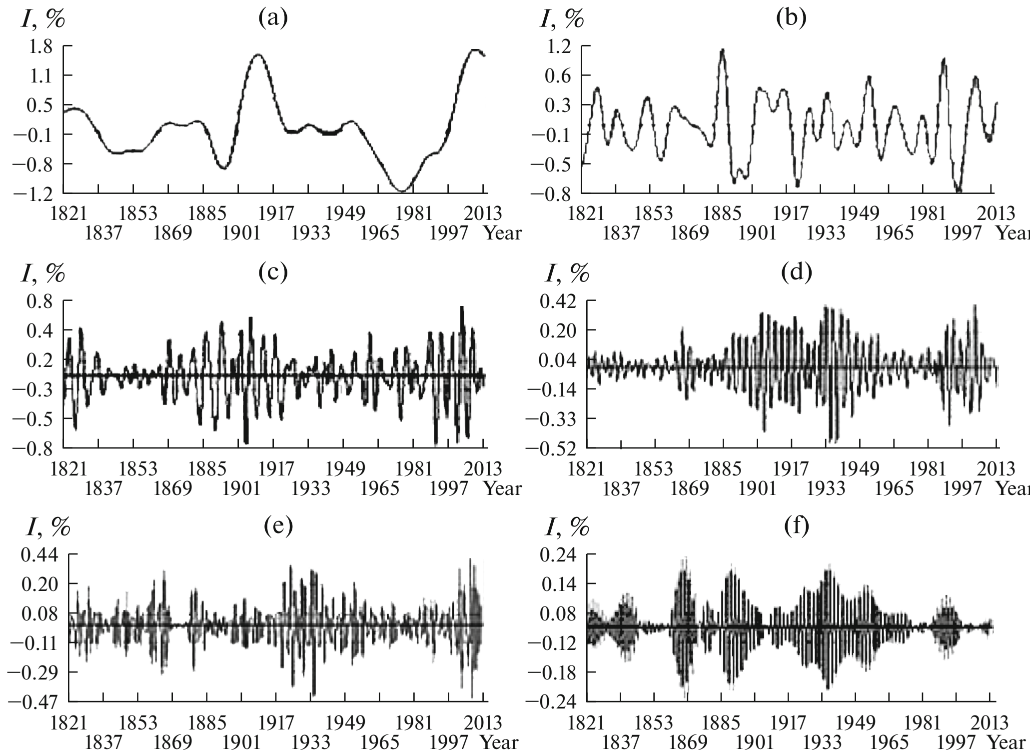

Fig. 2. Results of decomposition of the time series of relative radial increment indexes of Scots pine (one-dimensional diagrams): (a) rising trend, (b) 11-year cyclical component, (c, d, e, and f) high-frequency modulated harmonics with different amplitudes.

ing years. Persistent fluctuations are manifested clearly in the autocorrelation function; this indicates a quasi-periodic nature of the studies oscillations (Vessart, 1978).

The application of the correlation, autocorrelation, spectral, and cross-spectral analyses to the indexed dendrochronological series shows that the climate variability affects the radial increment of trees at various cyclicity levels.

The similarity of long-term changes in the radial increment on the one hand and air temperature and precipitation in the warm period on the other hand in the study area has been revealed in the course of the analysis of cross-spectral density that shows significant cyclical changes in the radial increment with the following duration: 2–3, 5–6, 7–8, 11, 20–26, and 41 years. The highest peak in the cross-spectral density of the series of relative increment indexes of Scots pine and precipitation sums for April–September is an 11-year cycle (i.e., Schwabe–Wolf solar cycle). An 11-year window was chosen for SSA. This section of the series contains basic information on the recurring oscillation cycles. Results of the composite component computation are shown on Fig. 2.

To select components representing the deterministic component of the time series, a criterion based on the input value of eigenvalues corresponding to these components was used. This value is 95%.

The mean square deviation of the source series (1821–2014) was 8.94; after the elimination of noises, it reduced to 7.13. The difference of 1.81 represents the mean square deviation of the extracted noise. In accordance with the SSA method, the decomposition, reconstruction, approximation, and forecasting of the radial increment (using the recursive method) for a 10-year period have been performed. The forecast results are presented on Fig. 3.

The forecast of radial increments of Scots pine performed for a 10-year period using the SSA method has shown the presence of cyclical oscillations with increment peaks in 2016 and 2021, a decrease in the radial increment in 2018–2019, and the minimum increment in 2023.

To forecast the annual radial increment ($y(x)$), a model described by a sinusoid function and based on a polynomial algorithm is proposed. The model has shown a higher efficiency in comparison with a linear one; it reflects 38% of the increment oscillation variability. The modeling period is 34 years. A 34-year cycle (Brückner cycle) was taken as the modeling period on the basis of researches into the cyclical dynamics of draughts, solar activity, and radial incre-

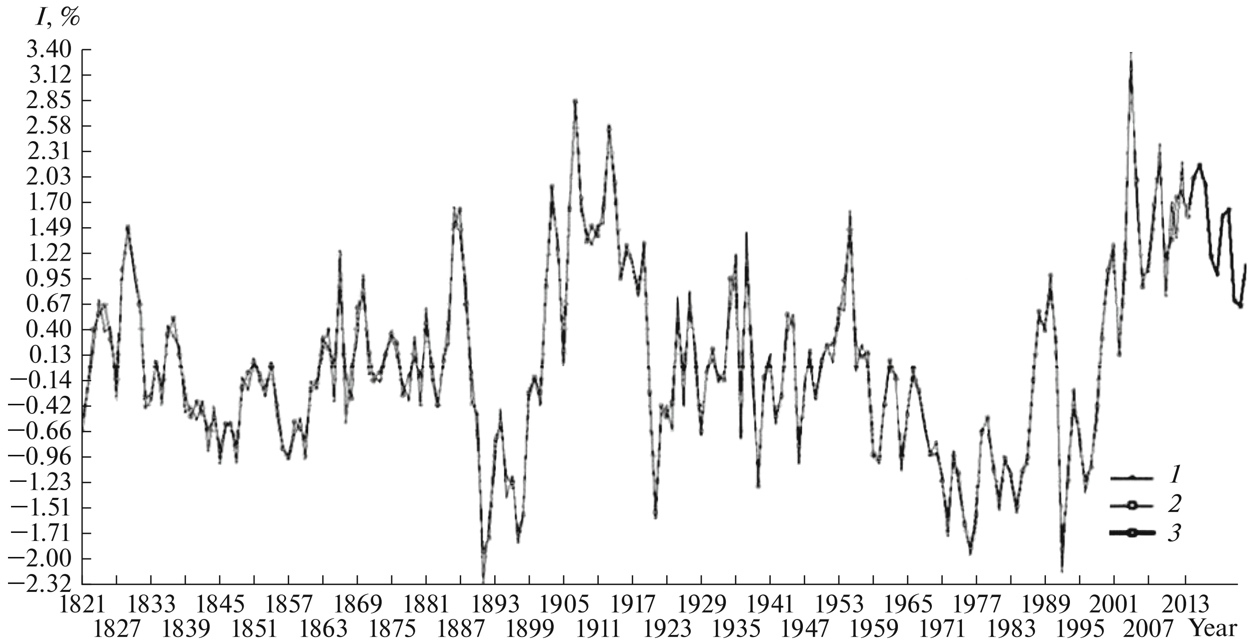

Fig. 3. Forecast of the radial increment of Scots pine for the 10 years: (*1*) index, (*2*) forecast base, (*3*) index (forecast).

ments in stands of the Central forest–steppe. The function is described by the following equation:

$$y(x) = \sum_{k=1}^{k=m_1}\left[a_k\cos\left(2\pi k\left(\frac{x-1}{T}\right)\right)+b_k\sin\left(2\pi k\left(\frac{x-1}{T}\right)\right)\right] + \sum_{k=0}^{k=m_2}c_k\left(\frac{x-1}{T}\right)^k, \quad (6)$$

where T is the period; ak, bk, and ck are regression coefficients; k is the autocorrelation coefficient of the source time series; π is a constant (3.1416); t is the point of time; $m1$ is the trigonometric series degree; and $m2$ is the polynomial (trend) degree.

Regression coefficients calculated for this increment dynamics model are provided in Table 5.

A radial increment model has been built on the basis of the given and calculated parameters of the function; its graphical representation is shown on Fig. 4. The model reliability was assessed using the Fisher's criterion (F): its empiric value (9.1) is much higher than the permissible threshold value (3.9). The reliability is recognized significant; this confirms the model validity.

The analysis of radial increment indexes makes it possible to identify cycles of various duration: from high-frequency (3–5 years) to secular (70–90 years) ones; these cycles reflect the dynamics of favorable and unfavorable periods of climatic conditions. The increment depressions in drought periods of 1891–1897, 1921, 1938–1939, 1971–1975, and 1992 are shown on the graph as deep minimums. Well-defined increment peaks were observed in 1866, 1886, 1907, 1913, 1955, 1990, and 2004. The periodicity (cyclicity) of severe draughts entailing catastrophic consequences in the Central forest–steppe correlates with the Brückner cycle (the average recurrence interval is 33–35 years) (Matveev et al., 2016). However, the 11 ± 2-year Schwabe–Wolf cycle is also clearly manifested both in the draught and radial increment dynamics.

Table 5. Regression coefficients of the time series (T = 34 years, $m1$ = 5, $m2$ = 1)

K	ak	bk	ck
0	–	–	$c0$ = 3810.02442
1	$a1$ = 2716.27446	$b1$ = 72.3713607	$c1$ = 365.602345
2	$a2$ =1203.58436	$b2$ = –797.63215	–
3	$a3$ = 554.666029	$b3$ = –111.2723	–
4	$a4$ = –52.758971	$b4$ = –584.62092	–
$m1$ = 5	$a5$ = –15.227401	$b5$ = –457.72058	–

K is the autocorrelation coefficient of the source time series; ak, bk, and ck are regression coefficients.

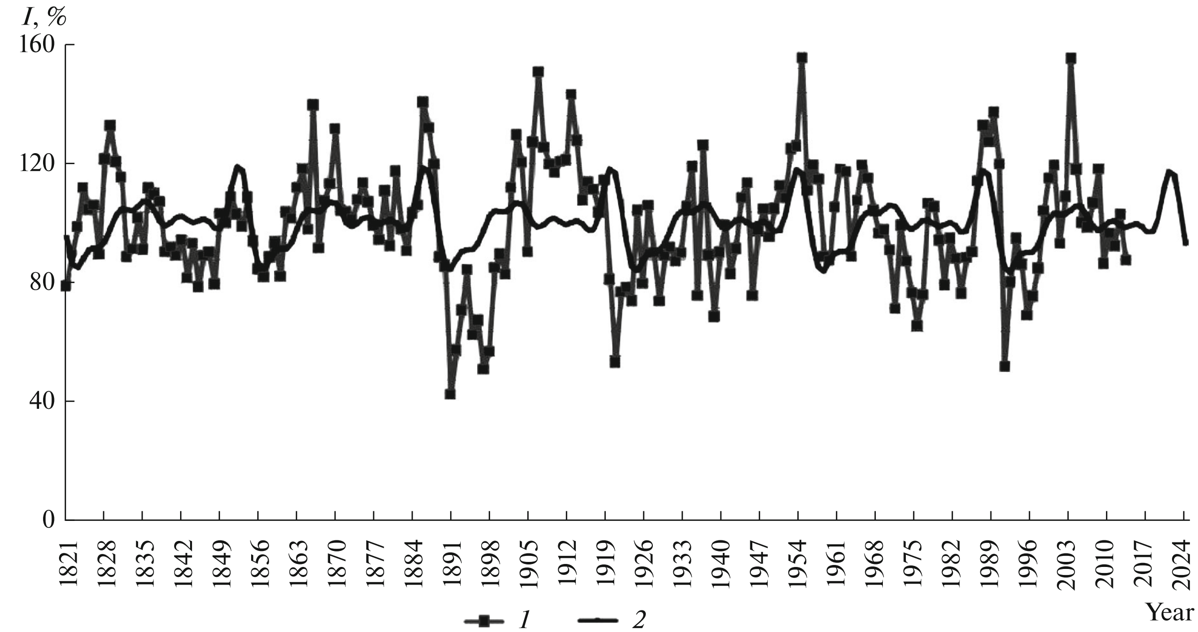

Fig. 4. Additive model and forecast of relative radial increment indexes of Scots pine: (*1*) indexes of the total annual ring width, (*2*) the model and forecast of increment indexes.

The Scots pine radial increment forecast performed using the additive model shows a slight increase in 2016, the maximum in 2021, and subsequent decrease of the increment.

The integrated forecast of Scots pine radial increment extrema in the region is based on our models that include both 11- and 34-year cyclical fluctuations. According to the models, it is possible to expect a reduction in the radial increment in 2018–2019, a larger radial increment of Scots pine in 2021 ± 1, and a smaller one in 2024 ± 2.

CONCLUSIONS

The performed studies revealed strong correlation relationships (correlation coefficient of up to 0.43; correlation ratio of up to 0.80) between the radial increment of Scots pine in the Voronezh Biosphere Reserve on the one hand and precipitation amounts in April–May of the current year and air temperatures in October of the current and previous years on the other hand. The dispersion analysis confirmed the significant influence of the meteorological factors on the radial increment of Scots pine. The precipitation in April–May of the current year strongly affects the spring wood growth; the precipitation in July–August of the current year, the late wood growth. In addition, a negative correlation between the radial increment of Scots pine and summer air temperatures was established. The climate variability affects the radial increment of trees at various cyclicity levels. The cross-spectral analysis of relative increment indexes of Scots pine and precipitation amounts in April–September has shown the prevalence of the 11-year (Schwabe–Wolf cycle) and 34-year (Brückner cycle) cyclicities. The models built on the basis of the cyclical dynamics of the radial increment of Scots pine (11- and 34-year cycles) using two forecasting methods (SSA and an additive increment model described by a sinusoid function with a given period) made it possible to forecast the increment dynamics for a 10-year period. According to the models, the radial increment is going to decrease in 2018–2019, increase in 2021 ± 1, and decrease again in 2024 ± 2.

The production of adequate models and forecast of the growth (i.e., productivity) of pine stands will make it possible to take the cyclical productivity dynamics into consideration during the planning of forestry practices (improvement cutting, development of forest plantations, and fire prevention) within the revision period, especially after the transition to the intense forest use model. The further elaboration of the modeling results and forecast of the radial increment of pine stands will be useful for the assessment of their state dynamics, including effects caused by the anthropogenic pressure.

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COMPLIANCE WITH ETHICAL STANDARDS

Conflict of interests. The authors declare that they have no conflicts of interest.

Statement on the welfare of animals. This article does not contain any studies involving animals performed by any of the authors.

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