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Dendroclimatic investigation of Caucasian spruce (*Picea orientalis* (L.) Link) in Moscow botanical gardens

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Abstract

Caucasian spruce (*Picea orientalis* (L.) Link) has a native natural area at Caucasus and Pontic Mountains around the eastern Black Sea in Russia, Georgia, Armenia and Turkey. This species forms pure stands or mixed with other conifers and hardwoods. In Moscow it is cultivated at the Arboretum of Main Botanical Garden of Russian Academy of Sciences N. V. Tsitsin and at the Arboretum of Botanical Garden of Moscow State University M. V. Lomonosov. It has been established that the following meteorological parameters have the main adverse effect on the growth of this spruce species: temperature in February, precipitation in February, March, April, May and July, temperatures of April and July. In the conditions of global climate change, this species may become important for forest crops and urban landscaping.

Key words: dendrochronology, dendroclimatology, dendroecology, tree-ring analysis.

Introduction

Caucasian spruce (*Picea orientalis* (L.) Link) has a native natural area at Caucasus and Pontic Mountains around the eastern Black Sea in Russia, Georgia, Armenia and Turkey. This species forms pure stands or mixed with other conifers and hardwoods, often as a dominant on moist, shaded slopes or in ravines, at altitude 1000–2000 m a.s.l. (Eckenwalder 2009).

In Moscow this species is cultivated and introduced at the arboretums of Main Botanical Garden of Russian Academy of Sciences N. V. Tsitsin and Botanical Garden of Moscow State University M. V. Lomonosov. According to the results of long-term observations in the Botanical Garden of the Russian Academy of Sciences, this species is characterized by low winter hardiness (Demidov 2005). Caucasian spruce has stable growth only in the southern and western regions of Russia and is damaged by frosts already at the latitude of Kiev (Kolesnikov 1974).

The high sensitivity of Caucasian spruce to moisture regime is well-known in the Russian forest science. But at the same time, it is relatively frost-resistant species, which has been formed the tree line high in the mountains. Also, this species is characterized by great shade tolerance and its undergrowth does not tolerate direct exposure to sunlight (Tkachenko 1955).

Despite the fact that the species sometimes demonstrates high frost resistance in its natural range, it is impossible to predict its winter hardiness when introduced in other geographical conditions. Winter hardiness is a complex indicator that depends not only on specific temperature values in certain periods of winter, but also on the combination and order of alternation of such values, as well as on the combination of temperature values with the values of other meteorological parameters. These provisions can be illustrated by the example of Siberian fir (*Abies sibirica* Ledeb.). In its natural range, this species is able to tolerate severe winter frosts up to -50 ^{o}C and below, but when cultivated in Western Europe, it is damaged by frost at relatively small low temperatures below zero (Bulygin 1991). This makes it necessary to conduct experimental studies of the growth of the success of the species in the conditions of introduction in each individual region. Dendroclimatic method provides such an opportunity, as it allows to retrospectively analyze a series of experiments set by nature, the results of which are recorded in the variability of annual rings.

The fossil remains of the Caucasian spruce indicate that its range has repeatedly changed due to the impact of climate change (Kapper 1954). Taking into account the scenario of climate warming in the European part of Russia, the Eastern spruce may become important as a valuable forest-forming breed: in native area it forms stands with wood volume 800–1000–1500 $m^3 \cdot ha^{-1}$ cubic meters per hectare (Tkachenko 1955). It may have perspective for urban tree planting too.

Dendroclimatic analysis makes it possible to better understand the factors critical to the good condition of this species and to predict its response to climate change (Fritts 1976). Some numbers of works are devoted to the dendroclimatic analysis of the growth of the eastern spruce in its natural range. So, the study of Özkan (1999) attempted to describe the variations in the annual growth of Caucasian spruce and to give a mean annual ring curve using annual rings.

The effect of climate change for Caucasian spruce forest was investigated by group of Turkish scientists according to regional climate model (RegCM3) (Tüfekçioğlu et al. 2008). Climate change could significantly influence distribution, diversity, structure and stability of the oriental spruce ecosystems. According to RegCM3 regional climate model, the temperatures will increase 2–4 °C in the region in the next century. Future climate scenarios predict 200–300 mm increase in precipitation in the eastern part of the region, while the western part won't have any increase in precipitation in the next century. Temperature increases in the western part of the region can cause more stress on spruce trees and would probably increase bark beetle attacks. Also, fire could become an important threat in the western part of the region. It is possible to observe 400–800 m upward shift in the spruce belt in the western part. Tree line of spruce stands would probably move upwards both in western and eastern part of the North-eastern Black Sea Region.

Also, Caucasian spruce was investigated by bioclimatic modelling methods (Örücü 2021). This study seeks to identify the change that will occur in future in the current habitat of *Picea orientalis* L.

under climate change scenarios. To this end, a model was developed in the MaxEnt 3.4.1 software programme using 19 bioclimatic variables obtained from the Worldclim database. The study made use of the Community Climate System Model (CSSM) version 4 and the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios for 2050–2070 developed in accordance with the fifth report of the Intergovernmental Panel on Climate Change (IPCC). The results of the Jackknife test, which was used to identify the bioclimatic variables that affect the geographical distribution of the species, mostly showed that isothermality was the variable that generated the greatest gain. In conclusion, the total extent of the 'suitable' and 'highly suitable' areas within the study area, constituting the current distribution area of the oriental spruce, is found to be 45,323 km^2 by 2070, according to the model, this figure rises to 65,042 km^2 in the RCP 4.5 scenario and 90,861 km^2 in the RCP 8.5 scenario. In view of the results of the study, it is anticipated that the oriental spruce will start to occur in those areas that will come in future to display climatic characteristics, similar to those in its natural distribution area.

The works of Dutch scientists are of particular interest in the context of our research, too (Song et al. 2021). Conifers are key components of many temperate and boreal forests and are important for forestry, but species differences in stem growth responses to climate are still poorly understood and may hinder effective management of these forests in a warmer and drier future. They studied 19 Northern Hemisphere conifer species planted in a 50-year-old common garden experiment in the Netherlands to (1) assess the effect of temporal dynamics in climate on stem growth, (2) test for a possible positive relationship between the growth potential and climatic growth sensitivity across species, and (3) evaluate the extent, to which stem growth is controlled by phylogeny. Eighty-nine percent of the species showed a significant reduction in stem growth to summer drought, 37 % responded negatively to spring frost and 32 % responded positively to higher winter temperatures. Species differed largely in their growth sensitivity to climatic variation and showed, for example, a four-fold difference in growth reduction to summer drought. Both growth sensitivity to climate and growth potential were partly phylogenetically controlled. Conclusions: A warmer and drier future climate is likely to reduce the productivity of most conifer species. Scientists did not find a correlation between growth potential and growth sensitivity to climate; instead, some species combined high growth potential with low sensitivity to summer drought. The results of this investigation may help to select productive species that are able to cope with a warmer and drier future.

Dendroclimatic studies of Caucasian spruce in the conditions of introduction on the European territory of the Russian Plain have not been carried out until now. Such kind of research allows us to identify specific climatic factors limiting the success of the growth of the species in the conditions of introduction. Knowledge about them makes it possible to predict the success of the growth of the species in the region under different scenarios of global climate changes. The most goal of the investigation was to establish climatic factors affecting tree ring width forming, where ring width considered as an indicator of good or bad health condition of trees.

Materials and Methods

The coring of wood samples in the eastern spruce plantings on the territory of Main Botanical Garden of Russian Academy of Sciences N. V. Tsitsin and Botanical Garden of Moscow State University M. V. Lomonosov was carried out during the period 2009–2010. The coring was made by a Pressler drill. The characteristics of sample trees are given in tables 1 and 2. A comparative characteristic of tress can be seen from photos on figures 1 and 2. The number of samples could not be larger, as the number of collection of specimen in arboreta was limited.

Table 1. Characteristics of the sample trees of the Caucasian spruce in November 2009 in Botanical Garden of Russian Academy Sciences.

Number	DBH, cm	Height, m	Height of coring, m
1	10	10	1
2	10	9	0.70
3	12	11	1
4	12	11	1
Average	11	10	0.9

Table 2. Characteristics of the sample trees of the Caucasian spruce in September 2014 in Botanical Garden of Moscow State University.

Number	DBH, cm	Height, m	Height of coring, m
1	5	3.0	0.8
2	4	3.2	0.8
3	4	2.8	0.8
4	4	4.0	0.8
5	5	2.5	0.8
Average	4.4	3.1	0.8

Despite the comparable age, the trees are differed in biometric characteristics. It relates with condition of growth in plantings. In the Arboretum of Main Botanical

Fig. 1. Caucasian spruce curtain in the Arboretum of the Russian Academy of Sciences (photo July 2010).

Fig. 2. Caucasian spruce in the Arboretum of Moscow State University (photo September 2014).

Garden they grew in an open landscape, in sparse planting. In the Arboretum of Moscow State University, they grew under the canopy of a multi-species stand. That is why the sizes of trees differ more than two times.

Caucasian spruce has annual rings with a clearly distinguishable structure, a clear boundary between early and late wood. This enables reliable measuring of the width of annual ring even with its small size. The general view of the annual rings of the Caucasian spruce is shown on Figure 3.

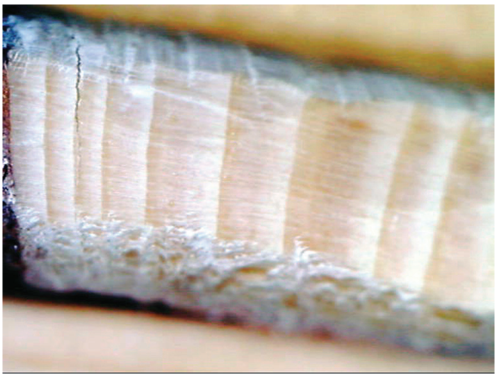

Fig. 3. Structure of annual rings at the accounting tree of the Caucasian spruce.

Measurements of the width of the annual rings were carried out using a binocular microscope MBS-10 with accuracy 0.05 mm or more. Before measuring the core, surface was cut with a scalpel and after that rubbed with chalk powder. Cross-dating was carried out by visual analysis of graphs in Microsoft Excel. All the chronologies were cross-dated before they were averaged in chronologies for plots.

For dendroclimatic analysis the climagramm method was used (Lovelius 1997, Rumyantsev 2010). The essence of this method is to compare the average values of meteorological parameters for different groups of years. Such meteorological parameters as the average monthly air temperature and the monthly precipitation amount were compared.

Correlation method was used for correlation analysis, too. Correlation method uses as simple and reliable instrument for estimation connections between annual rings width and meteoparameters fluctuations. Traditionally raw ring data series expose to indexation procedure in order to remove the trend line before correlation analysis (Fritts 1976, Cook et al. 1992). But in our case, we observe untypical trend of ring width time variability expressed in a stable increase in the width of the annual ring, which may relate with the trend of meteoparameters, especially important that it may relate with positive trends of winter temperature dynamics, which are clearly observed for Moscow climatic data. That is the reason for work with absolutely ring width data during correlation coefficients calculation. In our case, for the 27-year-long time series, there are 25 degrees of freedom for a confidence level of 0.95 (0.05) and the significant are correlation coefficients with values 0.38 or more.

Results of correlation analysis sometimes give possibilities for radial growth modelling according meteoparameters dynamic. For investigating chronology, such kind modelling has been completed by linear regression equation with using of standard Microsoft Excel functions.

Results and Discussion

Individual chronologies by the ring width for accounting trees were averaged and the results for two objects are shown at Figure 4.

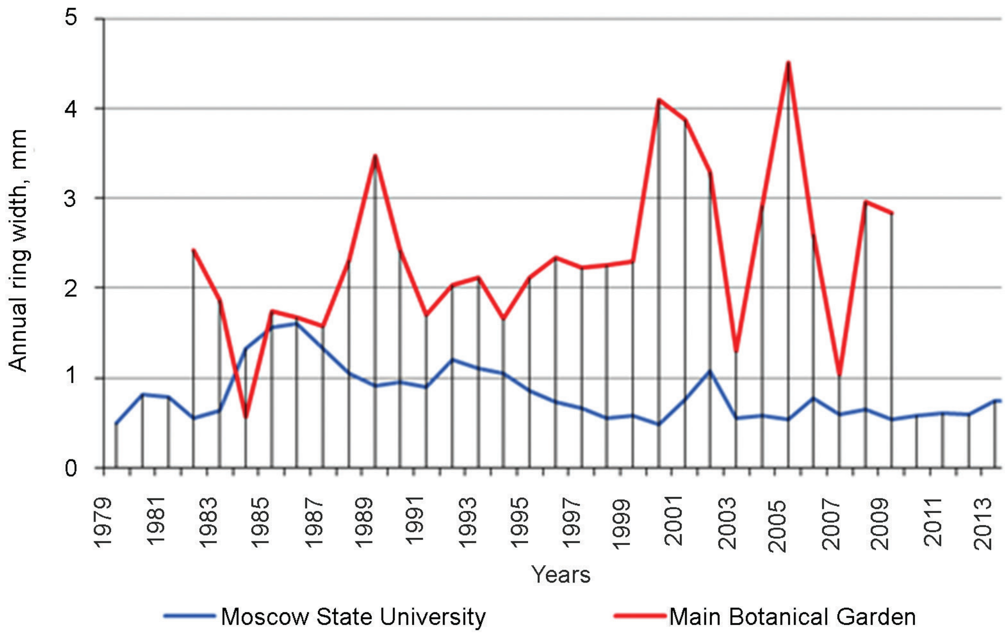

Fig. 4. Average annual ring width by the years for two arboretums.

As it can be seen from graphs at Figure 4, both plantings have a comparable age: about 45 years in 2022. The more accurate determination of the age is impossible due to core sampling at a height of more than 0 m, different growth rates in height at objects, as well as the uncertainty of age of used planting material. It is quite clear that the radial growth of spruce in conditions of Main Botanical Garden of Russian Academy of Sciences exceeds the radial growth in the conditions of Botanical Garden of Moscow State University by several times (the specific amount of excess varies for different years). This should be explained by the factor of inhibition of spruce growth under the influence of interspecific competition at the second object. Also, interannual fluctuations in radial growth are more pronounced on the first object than on the second. So, for significant dendroclimatic analysis is suitable for the chronology from main Botanical Garden only. Trees in the Main Botanical Garden of Russian Academy of Sciences have a trend of increasing radial increment. It is differed from normal age trend in radial growth time series, which is negative. It can be explained by steady decrease in the level of competition with other plants related or may be related with the trends in time series some meteoparameters.

For trees from MSU Arboretum, a high level of oppression on the part of the dominant tree canopy provides high asynchrony in the fluctuations of growth in individual chronologies and, as a result, when they averaged, gives a chronology with unexpressed weather changes. This chronology is characterized by low sensitivity and is unsuitable for dendroclimatic analysis.

Analyzing the dynamics of radial

growth, it is possible to distinguish by the years favourable and unfavourable for the growth of Caucasian spruce (years of local maximums and local minimums of the average width of the annual ring). The group of years with favourable environmental conditions for growth includes: 1982, 1989, 2000, 2005 and 2008. The group of years with unfavourable environmental conditions for growth includes: 1984, 1991, 1994, 2003 and 2007. More complete results for the years of low and high growth would be obtained if the key years in each sample were considered separately. It could then be possible to show what percentage of trees have decreased and increased growth in the given years. But due to the limitations in dendrochronological material, this technique cannot be implemented. The results of the dendroclimatic analysis by climagramm method are shown in figures 5 and 6.

Thus, based on the analysis of the graphs in figures 5 and 6, it

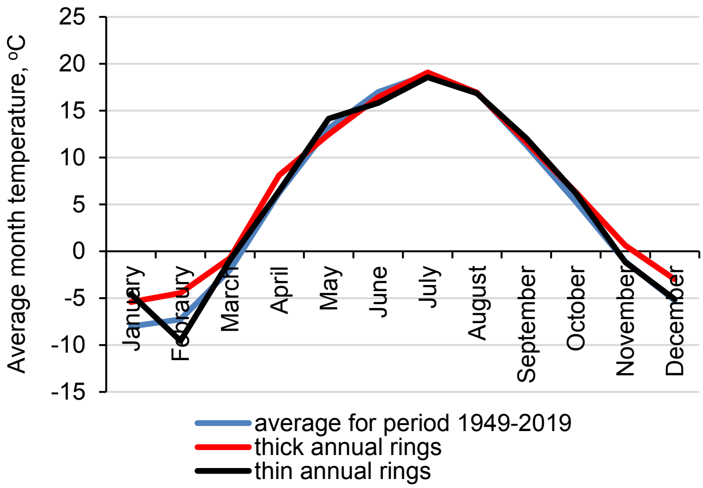

Fig. 5. The comparison of average month air temperatures in the years favourable (thick annual rings) and unfavourable (thin annual rings).

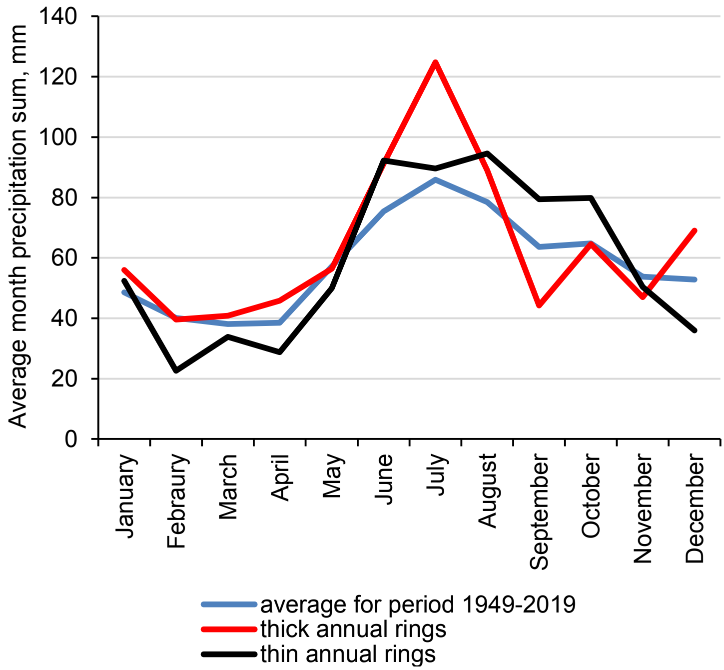

Fig. 6. The comparison of average month precipitation sums in the years favourable (thick annual rings) and unfavourable (thin annual rings).

should be concluded that high temperatures in February, as well as increased precipitation in July, are favourable for the growth of Caucasian spruce. The lack of precipitation (below average values) in February, March, April and May has negative effect on the tree ring forming and trees health. During May (and other dry periods in July) the trees may need watering. In the conditions of the onset of climate warming, Caucasian spruce may turn out to be a promising species for creating forest crops and urban landscaping, but its planting will require regular watering. Currently, it is advisable to lay test forest plantings of Caucasian spruce ecotypes in the north-west regions (as a region with great number of precipitation) of the European part of Russia, in Smolensk region for example. This species may be perspective for forest plantations in Belorussia too.

The temperature of February is a critical factor for the survival of Caucasian spruce in Moscow. Probably this is effect of winter drought. It is well-known that winter drought can be of great importance for the wintering condition of conifers (Roll-Hansen and Roll-Hansen 1998). It takes place in sunny, windy and frosty weather. In this case, the plant cannot get water from the soil and the needles can lose so much water that it will cause it to die off. But February temperature changes with a pronounced trend towards climate warming (Fig. 7).

As it can be seen from the trend of temperature dynamics in February by 2045, its average values in Moscow will reach 0 C by 2045. The conditions of existence in the Moscow region will be favourable for the Caucasian spruce.

Graphs at Figure 8 show the dynamics of radial growth in the Caucasian spruce and the linear trend for this time series is demonstrated. The growth trend has a clear similarity with the trend of temperature changes in February (Fig. 7). For estimation correlations between this series, also as for estimation the influence of other meteoparameters on growth, the correlation analysis was used. Calculations were made both for the parameters in the year of the formation of the annual ring, and for the parameters of the previous year. The calculation results are shown in Table 3.

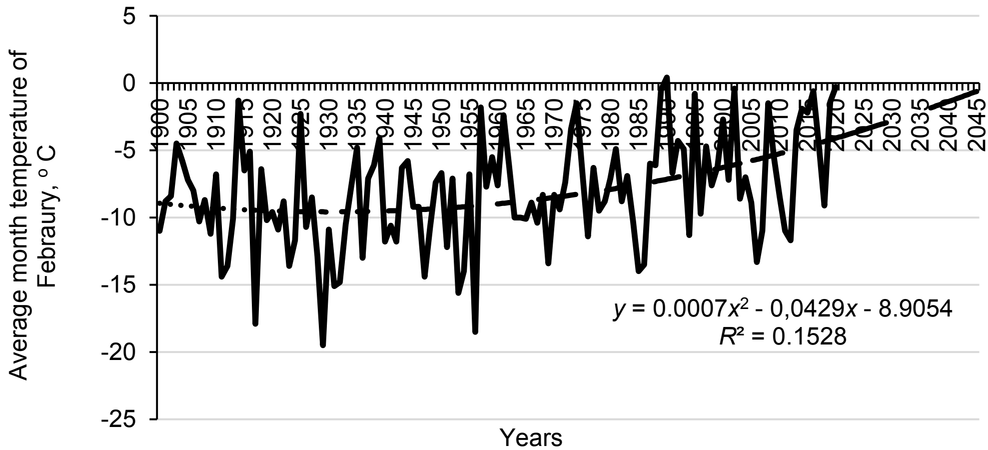

Fig. 7. Dynamics of February temperature in Moscow and forecast of its changes.

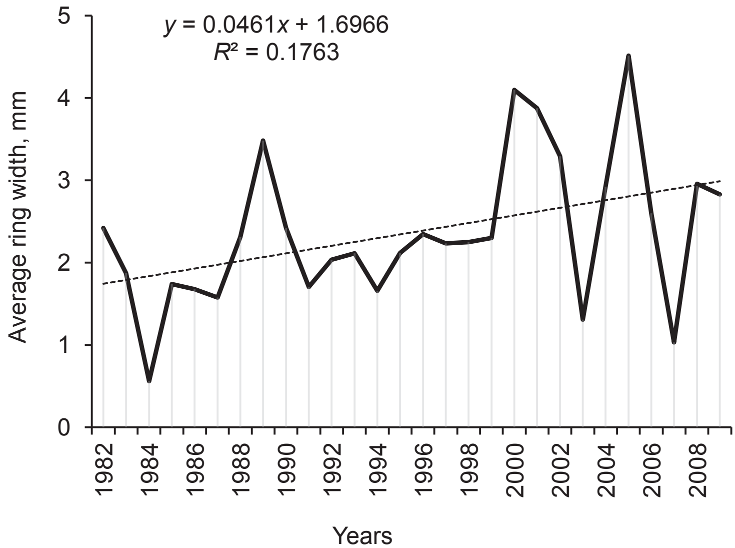

Fig. 8. Radial growth dynamics of Caucasian spruce and trend line.

Table 3. Correlation analysis results.

Month	**Month average air temperature**		**Month precipitation sum**	
	Previous year	**Current year**	**Previous year**	**Current year**
January	0.12	0.18	0.05	0.05
February	0.16	0.40*	0.34	0.54*
March	0.15	-0.02	0.18	0.35
April	0.14	0.40*	-0.27	0.00
May	-0.35	-0.34	0.25	0.24
June	0.21	0.11	-0.14	-0.02
July	0.48*	0.46*	0.26	0.11
August	0.23	0.07	0.09	-0.11
September	0.07	0.16	-0.24	-0.47*
October	0.27	0.02	-0.24	0.01
November	-0.05	0.27	-0.05	-0.05
December	0.14	0.02	0.34	0.48*

Note: * Significant value of correlation coefficient for $p = 0.05$.

As a result, the significant and biologically explained correlations are observed for February precipitation sum of current year, for February, April and July temperatures of current year and for July temperatures of current year. Thus, the correlation analysis method confirmed the positive influence of mild, slightly frosty and snowy conditions in February on the successful growth of Caucasian spruce in the Main Botanical Garden of the Russian Academy of Sciences. Warm April and July are favourable for Caucasian spruce growth, too. The regression analysis was used for modelling the spruce growth dynamic depending of meteo parameters dynamic. As a result, the growth dynamic was described by equation (1):

$$R=-3.77337-0.01677\cdot T_2+0.042831\cdot T_4+0.026253\cdot P_2+0.27725\cdot T_{7-1}-0.03226\cdot T_7, \quad (1)$$

where:

R – the mean of average tree ring width value in the calendar year;

T_2 – the mean of average month air temperature in February in the current calendar year;

T_4 – the mean of average month air temperature in April in the current calendar year;

P_2 – the mean of precipitation sum in February in the current calendar year;

T_{7-1} – the mean of average month air temperature in July in the previous calendar year;

T_7 – the mean of average month air temperature in July in the current calendar year.

Recent model describes 53 % of real growth variability, and has correlation coefficient 0.73 and synchroneity coefficient 81 % with real growth time series (Fig. 9).

This result is expected taking into account the data of dendroclimatic analysis by the method of climagramms. The temperature of February is associated with a radial growth in a curvilinear correlation: its fluctuations within certain limits do not affect fluctuations in growth, while strong deviations from average values have a strong effect on growth.

Conclusions

Thus, the study identified the main specific climatic factors that cause poor growth of Caucasian spruce in Moscow. The lack of precipitation during the cultivation of spruce can be compensated by watering. It is important that watering is timed to the specific identified months. February frosts are an almost unavoidable factor limiting the growth of Caucasian spruce in Mos-

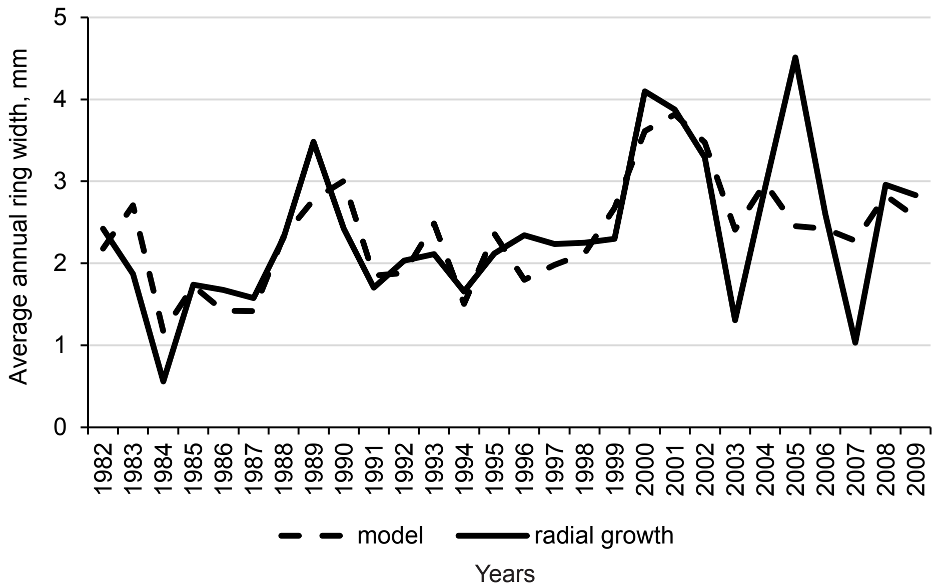

Fig. 9. Radial growth dynamics of Caucasian spruce and results of its modelling.

cow. However, the dynamics of the average monthly temperature in February is such that by 2045 the conditions for the growth of the Caucasian spruce in Moscow should become favourable. This species may become promising for plantation breeding in the Moscow region.

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