The impact of changes in climatic conditions on the dynamics of the phenology of species of nuts of the genus Juglans in the Voronezh region (Russia)

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Abstract. Taking into account the emerging trend towards temperature increase in the region of the research in recent years, introduction and cultivation of genus Juglans in the Voronezh region is a pressing issue. The studied the dynamics of phenological phases 5 the most promising for the cultivating species of nuts (Juglans regia L., Juglans manshurica Max., Juglans nigra L., Juglans cinerea L. and Juglans cordiformis Max.), which are the most promising for the cultivating. Has been identified a significant increase in air temperature over the past 30 years. A close correlation between the temperature indicators and the dynamics of phenological phases is established (primarily occurring in the spring). With an increase in average annual air temperature by 1 °C and remaining unchanged humidity indicators, the duration of the growing season increases by an average of 4 days. Keeping in mind the emerging tendency of climate change, the cultivation of heat-loving southern forms of Juglans nuts in the Voronezh region will constantly increase.

1. Introduction
Climate changes are an important scientific problem, the solution of which is impossible without assessing the significance of these changes. Phenological observations provide information on the dynamics of plant development during the annual cycle in comparison with meteorological conditions. The crop phenology is a widely used indicator for assessing effects of climate and environmental conditions [1]. An increase in temperature, as a rule, accelerates the phenological development of plants and shortens the growing season, which may affect crop productivity [2, 3]. An analysis of the response of crops to climate change may provide a scientific basis for their adaptation to the effects of climate change [4]. Recent studies conducted at local, regional, and continental scales have shown that phenology of both annual and perennial crops was significantly impacted by climate warming [5, 6]. Therefore, the dynamics study of phenophases occurring under the influence of climate change is an urgent issue.

The selection of trees suitable for various purposes of forestry and agriculture, resistant to adverse external factors, is very important. One of these plants are nuts of the genus Juglans, which were considered in this paper. In the region under study, most species of the genus Juglans have been introduced [7]. It has a good condition, blooms annually and bears fruit stably.

The nut species are unique plants of food, medicinal and forestry importance, and therefore, they are widely used in forestry and fruit growing [8]. Given the multifunctional nature of the nut species,
they should be used not only as fruit trees, but also for the creation of forest crops, planting, increasing sustainability of plantations and increasing their ecological functions [9]. In particular, black walnut can be successfully used to create forest crops [10], have good quality of fruit [11, 12] and can regulate the ecological balance in plantations [13] because it has strong antibacterial effect [11].

Most species of the genus Juglans are common in moderately warm, subtropical and partly tropical regions of the Northern Hemisphere, where mixed deciduous forests grow throughout the mountains. The changes in climatic conditions can favorably affect the cultivation of heat-loving tree species, which will increase the scale of cultivation of Juglans nuts in the Voronezh region. The aim of the study is to establish the patterns of development of the phenological phases of Juglans nuts plants, taking into account the influence of climatic changes.

2. Material and methods

The objects of the study were fruit-bearing plantations, aged 30-50 years, growing in similar forest conditions (figure 1). The work has examined for 5 species of genus Juglans – these are walnut (Juglans regia L.), manchurian walnut (Juglans manshurica Max.), black walnut (Juglans nigra L.), grey walnut (Juglans cinerea L.) and heartnut (Juglans cordiformis Max.). Research on these objects was carried out in the period from 2002 to 2019, which was reflected in the previous works of the author [7, 14].

Figure 1. The layout of the study objects.
The taxation indicators of plantations growing on the objects under study are given in table 1. It should be noted that all objects are located in identical types of forest and soil. The relief is flat, the height above sea level varied from 80 to 200 m. The distance between plants varied from 6 × 6 m to 10 × 10 m. Agrotechnical maintenance was carried out at all sites (except 5).

**Table 1.** Silvicultural and taxation characteristics of the study objects.

| Object | Plantation composition | Trunk diameter (1.3 m), cm | Height, m | Crown diameter, m | Age, years | Forest site type |
|--------|------------------------|-----------------------------|-----------|-------------------|------------|-----------------|
| 1      | 4Mw4EBw1Gw1Hn         | 42                          | 15.8      | 5.5               | 50         | D2              |
| 2      | 5Cw3Gw1Mw1Ac          | 32                          | 11.3      | 4.0               | 45         | D2              |
| 3      | 4Mw2Cw2EBw2Hn         | 36                          | 14.2      | 5.0               | 45         | D2              |
| 4      | 4Gw4EBw2Cw            | 32                          | 12.6      | 4.5               | 40         | D2              |
| 5      | 8Mw2Mp+Ln             | 32                          | 11.4      | 4.0               | 35         | C2D             |
| 6      | 5Cw4Hn1EBw+Gw         | 34                          | 12.8      | 4.5               | 30         | D2              |
| 7      | 6Cw4Tp                | 32                          | 12.5      | 3.5               | 50         | D2              |
| 8      | 5Hn3EBw1Mp1Ac         | 36                          | 12.0      | 5.5               | 45         | D2              |
| 9      | 10Cw                  | 34                          | 12.8      | 4.5               | 42         | D2              |
| 10     | 3Cw3Mw2EBw2Gw         | 32                          | 13.3      | 4.0               | 40         | C2D / D2        |

Where: Cw – walnut; Hn – heartnut; EBw – black walnut; Mw – manchurian walnut; Gw – grey walnut; Ac – acacia; Ln – linden; Mp – maple; Pp – poplar.

When carrying out phenological observations, the used technique developed by A A Rikhter [15], with the recommendations of F L Schepotiev [16] and J Marion [17]. Phenological phases were determined by the date of its onset. The following phases of plant growth and development were noted:

1. The swelling of the buds (renal scales began to diverge and parted). The date of the onset of the phenophase was recorded at the moment when lighter stripes were noticeable between the renal scales.
2. Breaking of buds (the scales of the buds are opened, and green leaves are visible from the ajar apex).
3. Leaf-unfolding (beginning of leaves formation) and complete leafing (leaves reach their maximum size).
4. End of shoot growth (apical bud at the top).
5. The appearance of flower buds.
6. Flowering (formation of male and female inflorescences), as well as the beginning and end of dusting.
7. Ripening of fruits (the period from the beginning of formation to the moment of full ripening).
8. Falling of fruits - beginning and end of the process of falling (the beginning of the falling process was recorded, when the first fallen fruits were noticeable, and the end when all the fruits fell).
9. Autumn leaf color (date of change of leaf color) and leaf fall (duration of leaf fall).

A review of climatic factors was made on the basis of hydro-meteorological observations at the stations of the state monitoring network of Roshydromet [18, 19]. To calculate the deviations of the observed values, as the “climatic norm”, the average values of meteorological elements for the period 1961-1990 are used. “Climatic norm” 1961-1990 taken as a historical base period. This will allow for a long-term assessment of climate change over the observation period. The observation results were processed via analysis of variance and correlation analysis using computer programs STATISTICA-
6.0 and Microsoft Office Excel 2007-2010 for Windows, according to the recommendations of B A Dospekhov [20].

3. Results and discussion
The rhythms of the seasonal development of plants are an important component of ontogenesis, which largely determines their stability, and, consequently, the prospects for cultivating. It is of paramount importance for tree species, which under the new conditions are forced to change not only the timing, but also the duration and nature of the occurrence of individual phenological phases [5, 7].

The nuts of the genus *Juglans*, grown in the Voronezh region, in most cases have a shorter growing season compared to their southern counterparts. The same thing is observed with respect to growth and development – forms develop faster, earlier complete growth and form the apical kidney. Such dynamics of development characterizes forms as more winter-hardy. According to phenological observations for the period from 2002 to 2019, a phenospectrum was compiled (figure 2).

![Figure 2](image.png)

**Figure 2.** The phenospectrum of nut species of the genus *Juglans* in the Voronezh region.

To construct the phenospectrum (figure 2), at least 200 trees of each species of the genus *Juglans* were examined. The timing of the start of leaf-unfolding, depending on the species features and the weather conditions of the spring period, ranges from 12 April to 4 May. Moreover, within the same species, no early or late blooming forms were distinguished. The difference in several days is due to the fact that trees, with shoots more dehydrated during the winter, are delayed with leaf-unfolding. The end of the growing season can be either transient or prolonged, depending on climatic factors and species characteristics of woody species. Manchurian walnut has the shortest duration of the growing season – from 145 to 160 days, and the growing season of heartnut can vary from 155 to 180 days.

Figure 3 shows the factors that have the greatest effect on the intensity of the onset of phenological phases. The degree of influence of climatic factors on the phenological phases of plants, expressed in relative units, was determined using multivariate analysis of variance. The most significant meteorological factors that have the greatest impact on the timing of the onset of phenological phases are air temperature and rainfall.
Figure 3. The degree of influence of various factors on the phenology of Juglans nuts in the Voronezh region, %.

Non-climatic factors (illumination, hereditary properties, state of plantings, etc.) also have a high degree of influence on plant phenology and necessarily must be taken into account. The dynamics of the average annual air temperature in the Voronezh region is shown in figure 4.

Figure 4. Dynamics of average air temperature in the Voronezh region.

Over the past 30 years, only positive deviations of the average annual air temperature from the climatic norm have been noted on the territory of the Voronezh Region (figure 4). A continuous intensive increase in the average annual air temperature is observed, to a greater extent due to an increase in winter temperatures. From 1961 to 1990 an increase in the temperature amplitude is observed, whereas since 1988 the amplitude has decreased, but an intensive growing trend has appeared. Since 2007, the average annual temperature did not fall below 7 ºC and only twice did not
exceed the mark of 7.5 °C. The average annual air temperature for the period from 1990 to 2019 increased by 1.2 °C in comparison with the climatic norm and amounts to 7.3 °C.

The average annual values of air humidity, determined from 1991 to the present, coincide with the values of the climatic norm (Table 2). This pattern is characteristic of both the northern (Voronezh) and the southern (Boguchar) parts of the studied region.

**Table 2.** The average monthly indicators of air relative humidity in the Voronezh region.

| A period of time | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | Year |
|------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Voronezh         |     |     |     |     |     |     |     |     |     |     |     |     |      |
| 1961-1990        | 84  | 82  | 80  | 70  | 59  | 64  | 67  | 67  | 71  | 80  | 85  | 87  | 74.6 |
| 1991-2019        | 83  | 81  | 78  | 66  | 61  | 66  | 68  | 68  | 73  | 79  | 82  | 83  | 74.0 |
| Deviation        | –1  | –1  | –2  | –4  | +2  | +2  | +1  | +1  | –1  | –3  | –4  | –0.6|      |
| Boguchar         |     |     |     |     |     |     |     |     |     |     |     |     |      |
| 1961-1990        | 85  | 83  | 82  | 67  | 59  | 60  | 62  | 62  | 66  | 76  | 84  | 86  | 72.8 |
| 1991-2019        | 84  | 81  | 76  | 64  | 60  | 62  | 63  | 62  | 68  | 76  | 83  | 84  | 71.9 |
| Deviation        | –1  | –1  | –6  | –3  | +1  | +2  | +1  | 0   | +2  | 0   | –1  | –2  | –0.9 |

At the same time, a slight negative trend is observed (0.3 % / 10 years), indicating a slight decrease in humidification in the Voronezh region. It should be noted that a decrease in air humidity occurs exclusively in the winter months. Another major climatic factor determining the development of woody vegetation is precipitation. The average annual rainfall in the Voronezh region in relation to the climatic norm (%) is shown in figure 5.

**Figure 5.** Dynamics of annual precipitation for the period 1961-2019 in the Voronezh region in relation to the average value.

From the analysis of the data shown in figure 5, it follows that the average amount of precipitation in the Voronezh region has not changed significantly in recent years - there is a cyclical pattern in their fluctuations. The annual precipitation over this time increased on average by 6.6 mm/10 years relative to the climatic norm. Therefore, despite the fluctuations, this climate indicator remains virtually unchanged.
The tightness of correlation between climatic indicators and the dynamics of the phenological phases of nut species by season of the year in the Voronezh region is shown in figure 6.

Figure 6. Correlation between the dynamics of climatic indicators and phenological changes characteristic of species of nuts depending on the season.

A direct correlation was found between the air temperature and the timing of the onset of phenological phases (especially pronounced in spring). It should be noted the moderate strength of the correlation relationship between of the moisture indicators and swelling of the buds, complete leaf disclosure and flowering. This dependence is typical for all types of nuts. The reliability indicator of studies ($t$) exceeds the standard value ($t_{st}$) at a probability level of 0.95, which indicates the accuracy of the data.

The factor influence of climatic indicators on the duration of the growing season is shown in figure 7. The confidence factor ($F$) exceeds the standard value of the Fisher test ($F_{st}$) for the probability level (0.95).

Figure 7. The factor influences of climatic factors on the duration growing season of nut species in the Voronezh region.
4. Conclusion
In the course of the work, it was revealed that in the Voronezh region there was a significant change in climatic conditions, which, first of all, is characterized by an increase in the temperature regime. The average annual air temperature over the past 30 years has increased by 1.2 °C (20 %) compared with the climatic norm. The greatest correlation of the increase in air temperature was noted between the spring phenological phases (r = 0.68). An increase in temperature in the autumn period weakly correlates with the duration of the phenological phases (yellowing of leaves and leaf fall). It has been established that with an increase in the average annual air temperature by 1 °C and remaining unchanged humidity indicators, the duration of the growing season increases by an average of 4 days. The emerging trend will allow increasing the cultivation of heat-loving southern forms of Juglans nuts in the Voronezh region, which are characterized by a prolonged vegetation period.

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