Radial growth patterns of Siberian larch in plantations of the Republic Mari El

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Abstract. Based on the measurements of 83 wood cores, the main patterns of changes in the width of the early and late zones in the annual ring of Siberian larch trees (Larix sibirica Ledeb.), as well as their total radial growth indices in the conditions of the Republic of Mari El were identified. It was found that the width of the early wood zone varies in trees from 0.15 to 11.3 mm, late wood – from 0.05 to 4.15 mm, the proportion of latewood – from 1.2 to 82.8 %, and the annual growth indices - from 13 to 423 %. The main factor in the variability of the total width of the annual rings and the layer of early wood is the age of the trees, and the contribution of weather conditions and other unaccounted factors (noise) to the overall variance of the annual growth parameters is no more than 20 %. The variability of the total width of the annual ring also depends on their genotypic features, which determine up to 42.7% of the total variance of the parameter in some cenopopulations. In the dynamics of the growth indices of larch trees, despite the existing specifics of each cenopopulation, the general sharp decline in their values after the droughts of 1972 and 2010, as well as the alternation of the periods of growth and decline, is clearly distinguished.

1. Introduction
The ability of tree plants to be natural monitors and banks for storing information on the environment and dynamics of the biogeocoenotic processes has been widely explored by researchers for quite a long time when addressing scientific and applied challenges [1-4]. Thus, many studies show that after eruptions of big volcanoes trees in many areas of the Northern Hemisphere demonstrate a clear and prolonged drop in the annual growth due to a decrease in air temperatures in summer [5-9]. However, the dynamics of volcanic activity in its turn is directly dependent on some external space factors including solar activity and the Earth rotation rate [10-13]. A literature review, therefore, confirms that the Earth’s climatic system and biosphere acting in a coordinated and automated manner are exposed to heavy impacts by a great number of factors that are different from each other by their nature, power, and scales of consequences as well as by selectivity. When assessing the annual growth of trees dendrochronological studies should consider all of the above mentioned and should be based on certain benchmarks which can be represented by dates of changes in solar activity and powerful volcanic eruptions. The temporal coincidence of such events is particularly dangerous. The effects of delay and attenuation of the signal in the operation of the climatic system and the cumulative effect of all factors as well the peculiarities of their manifestation in different regions of the globe should be also taken into account.

One of the essential aspects of dendrorhronological studies is finding a cycling pattern representing certain repeatability of various events and phenomena. First of all, it refers to the cyclical nature of the
climate. Though many researchers stated the presence of different wave components in the dendrochronological series [14-17], yet, the frequency and amplitude parameters of these components have such broad and variable ranges that it almost eliminates any attempts to identify any general patterns. Nowadays, dendroclimatology cannot give an unambiguous answer to the question about the reasons for comparatively regular periods of depression and expression in tree increment that may be partially explained by an underestimate of the internal properties of the forest ecosystems [18]. The available literature sources give evidence of an ambiguous response of tree increment to the same changes in the environment, thus the question of the existence of strictly periodic components in the dendrochronological series of stands is considered to be an unsolved problem so far.

The goal of this study is to assess the role of the factors influencing the radial growth of Siberian larch (Larix sibirica Ledeb.) plantations in Mari El Republic. Such assessment would comprehensively estimate the ecological and resource potential and growth capacity of this tree species. The study aims to: 1) carry out a literature review on the issues under study, 2) select the relevant test sites and collect wood cores, 3) examine the collected experimental materials in a laboratory, 4) determine the variability of different parameters of the annual ring structure, 5) assess the influence by biocenotic and climatic factors on the width of an annual radial growth of trees, and find some general patterns.

2. Materials and methods
The studies were conducted in six plantations of Siberian larch, which were established at different times and in different forest site types of Mari El Republic (table 1). Using a Pressler increment borer we collected wood cores from 9 to 25 trees in each site at the height of 1.3 m from the ground and measured the width of annual rings using an MBS-10 microscope (with an accuracy up to 0.05 mm).

Table 1. General information on test sites in the Siberian larch plantations.

| Site locationa | FSTb | Space coordinates | Year established | Sampling size (units) |
|----------------|------|-------------------|------------------|----------------------|
|                |      | north latitude    | east longitude   |                      |
| 1. Oak Grove urban forest | D3,4 | 56°38'53.88" | 40°56'05.72" | 25 | 710 |
| 2. Pine Grove urban forest | D3,4 | 56°37'30.94" | 47°55'05.04" | 9 | 492 |
| 3. Nolka forestry enterprise | C2,3 | 56°35'31.44" | 47°53'48.51" | 14 | 634 |
| 4. Sernur forestry enterprise | C2  | 56°55'28.68" | 49°21'39.25" | 11 | 757 |
| 5. Dubravnaya forestry enterprise | D2   | 56°06'51.17" | 46°02'48.39" | 10 | 939 |
| 6. Krasny Most forestry enterprise | A2   | 56°33'51.60" | 47°00'15.54" | 14 | 1391 |

a The Oak Grove and Pine Grove urban forests are situated in the plain of the Small Kokshaga River, which is temporarily flood-prone.
bForest site type.

The empirical materials were collected based on the developments of reputable dendrochronology scientists like [19-21]. The collected materials were then processed using the standard methods of mathematical statistics in Excel and Statistica-6 software [22]. To assess a tree response to environmental changes, dendrochronology uses a series of growth index values, which represent the interrelation between actual and theoretical values calculated by the parameters of an age trend function. In order to remove some inherent noise from the original series and to identify the general patterns of tree growth more specifically we applied smoothing by a moving average method [23]. The obtained series of annual tree growth values were compared to the data of the solar and geomagnetic activity and to publicly available weather details from the Yoshkar-Ola Meteorological Agency.
3. Results and discussion
The study showed that the annual radial growth value of the Siberian larch tree varies within a rather great range (0.2mm to 11.5mm). However, its mean values in a number of ecotopes significantly differ from each other (table 2). The widest annual rings are observed in the trees from the Oak Grove urban forest situated in the flood-plain of the Small Kogshaga River, while the narrowest ones in Quarter 59 of the Krasny Most forestry enterprise on sandy soils with ground waters at the depth of about 120cm. The standard deviation (SD) of the annual ring width varies from 1.04mm to 2.50mm, while the coefficient of variation (CV) varies from 59.7% to 84.7%. The annual ring width of early wood varies from 0.15mm to 11.3mm, that of latewood from 0.05mm to 4.15mm, and the proportion of latewood from 1.2% to 82.8%, with the greatest mean value of the latter in the Nolka forestry enterprise. The SD value for the proportion of late wood is 19%, and CV is from 25.6% to 61.5%.

Table 2. Variability patterns of annual radial growth of dominant Siberian larch trees in the test sites of plantations.

| Site location                  | Statistic parameters of annual ring width a |
|-------------------------------|--------------------------------------------|
|                               | M ± m | min | max | Sx   | CV, % |
| Total width of the annual ring of wood (mm) |       |      |      |      |       |
| Oak Grove urban forest        | 2.95 ± 0.15 | 0.50 | 11.5 | 2.50 | 84.7  |
| Pine Grove urban forest       | 2.28 ± 0.09 | 0.25 | 14.7 | 1.94 | 84.8  |
| Nolka forestry enterprise     | 2.23 ± 0.06 | 0.30 | 9.0  | 1.56 | 70.2  |
| Sernur forestry enterprise    | 2.72 ± 0.06 | 0.30 | 9.9  | 1.62 | 59.7  |
| Dubravnaya forestry enterprise| 2.16 ± 0.05 | 0.25 | 11.5 | 1.61 | 74.6  |
| Kransy Most forestry division | 1.42 ± 0.03 | 0.20 | 7.8  | 1.04 | 73.0  |
| Annual layer of earlywood (mm)                           |       |      |      |      |       |
| Oak Grove urban forest        | 2.37 ± 0.15 | 0.25 | 11.3 | 2.50 | 105.4 |
| Nolka forestry enterprise     | 1.30 ± 0.05 | 0.15 | 7.75 | 1.16 | 89.5  |
| Sernur forestry enterprise    | 1.75 ± 0.05 | 0.20 | 8.90 | 1.37 | 78.2  |
| Annual layer of latewood (mm)                           |       |      |      |      |       |
| Oak Grove urban forest        | 0.63 ± 0.03 | 0.05 | 3.50 | 0.49 | 77.9  |
| Nolka forestry enterprise     | 0.94 ± 0.02 | 0.05 | 4.15 | 0.57 | 61.3  |
| Sernur forestry enterprise    | 0.96 ± 0.02 | 0.10 | 3.20 | 0.53 | 55.4  |
| Latewood proportion in the annual layer (%)                      |       |      |      |      |       |
| Oak Grove urban forest        | 30.8 ± 1.2  | 1.2  | 81.3 | 19.0 | 61.5  |
| Nolka forestry enterprise     | 46.6 ± 0.5  | 11.1 | 82.8 | 12.0 | 25.6  |
| Sernur forestry enterprise    | 37.1 ± 0.5  | 6.3  | 75.3 | 12.8 | 34.6  |

aThe statistics legend: M ± m is the arithmetic mean value of annual growth and its error; min, max is the minimal and maximal value of increment; Sx is the root mean square (standard) deviation of increment; CV is the coefficient of variation of values.

The calculations confirmed that the key factor of variability in the total width of annual rings and an early wood layer is the age of trees, while a contribution of the weather conditions and other unaccounted factors (noises) into the total variance of annual growth parameters is only 17.3% to 18.1% (table 3). On the other hand, the latewood layer value varies mainly due to the environmental conditions and genotypic characteristics of tree cenopopulations in the ecotopes, while their age does not make any significant difference.

In general, the dynamics of the annual ring width has a clear trend (figure 1) which can be best described with the Zipf-Pareto equation:
\[ Y_t = K \times \exp(-a \times 10^2 \times t) + m \]  

where the values of all the parameters with certain biophysical meanings (\( K \) as an original potential of tree growth, \( m \) as a stabilization level of the annual ring width or a lower limit of a tree’s sustainable functioning; \( a \) as a mean rate of the annual ring width decrease over the tree age) are highly specific for each ecotope (table 4). The pair correlation coefficient for the age series of dominant tree growth in different ecotopes varies from 0.58 to 0.95 (table 5). The greatest correlation between the tree growth series is observed in the Pine Grove urban forest and in the Dubravnaya forestry enterprise situated on the hilly right bank of the Volga River. The least relation between the tree growth series is observed in the Oak Grove urban forest and in the Sernur forestry enterprise where the development characteristics of the larch cenopopulation significantly differ from the other ecotopes (figure 2).

Table 3. Results of variance analysis of the factors determining the variability of annual radial growth of dominant Siberian larch trees in the test sites.

| Variance           | Sums of squares | Degrees of freedom | Mean square value | Fisher’s criterion | Contribution (%) |
|--------------------|-----------------|--------------------|-------------------|--------------------|------------------|
|                    |                 |                    |                   | F_{\text{actual}} | F_{0.05}         |
| Total width of the annual layer |                 |                    |                   |                    |                  |
| Age                | 446.569         | 32                 | 13.9553           | 15.2               | 1.52             | 54.8             |
| Ecotopes           | 220.363         | 5                  | 44.0726           | 47.9               | 2.27             | 27.1             |
| Noise              | 147.300         | 160                | 0.9206            |                    |                  | 18.1             |
| Total              | 814.232         | 197                |                    |                    |                  | 100.0            |
| Early wood layer   |                 |                    |                   |                    |                  |
| Age                | 302.765         | 33                 | 9.1747            | 6.97               | 1.61             | 60.2             |
| Ecotopes           | 113.515         | 2                  | 56.7575           | 43.1               | 3.14             | 22.6             |
| Noise              | 86.849          | 66                 | 1.3159            |                    |                  | 17.3             |
| Total              | 503.128         | 101                |                    |                    |                  | 100.0            |
| Late wood layer    |                 |                    |                   |                    |                  |
| Age                | 3.770           | 34                 | 0.1109            | 1.09               | 1.60             | 22.6             |
| Ecotopes           | 6.005           | 2                  | 3.0026            | 29.6               | 3.13             | 36.0             |
| Noise              | 6.905           | 68                 | 0.1015            |                    |                  | 41.4             |
| Total              | 16.679          | 104                |                    |                    |                  | 100.0            |

Figure 1. Dynamics of the total width of the annual layer in dominant Siberian larch trees in the test sites.
**Table 4.** Values of the parameters included into the equation of the age trend of the annual radial growth of dominant Siberian larch trees in the test sites of the plantations.

| Site location                          | Total width of the annual wood layer (mm) | $K$  | $a$   | $m$  | $R^2$ |
|----------------------------------------|------------------------------------------|------|-------|------|-------|
| Oak Grove urban forest                 | 10.1                                     | 11.58| 0.64  | 0.959|
| Pine Grove urban forest                | 6.96                                     | 13.59| 1.22  | 0.950|
| Nolka forestry enterprise              | 5.52                                     | 4.425| 0.13  | 0.894|
| Sernur forestry enterprise             | 7.35                                     | 3.517| 1.28  | 0.766|
| Dubravnaya forestry enterprise         | 6.46                                     | 9.060| 1.43  | 0.937|
| Krasny Most forestry enterprise        | 3.85                                     | 6.509| 0.87  | 0.922|
| Total for all the ecotopes             | 5.67                                     | 7.743| 1.45  | 0.950|

**Table 5.** Correlations between the age range of the annual growth of dominant Siberian larch in the test sites.

| Site location                          | Coefficient of correlation between the ecotopes |
|----------------------------------------|-----------------------------------------------|
|                                         | No. 1          | No. 2      | No. 3      | No. 4      | No. 5      |
| Total annual wood layer                |                                           |            |            |            |            |
| 1. Oak Grove urban forest              | 1.00          |            |            |            |            |
| 2. Pine Grove urban forest             | 0.86          | 1.00       |            |            |            |
| 3. Nolka forestry enterprise           | 0.85          | 0.84       | 1.00       |            |            |
| 4. Sernur forestry enterprise          | 0.58          | 0.61       | 0.87       | 1.00       |            |
| 5. Dubravnaya forestry enterprise      | 0.92          | 0.95       | 0.90       | 0.75       | 1.00       |
| 6. Krasny Most forestry enterprise     | 0.88          | 0.91       | 0.92       | 0.84       | 0.91       |
| Earlywood layer                        |                                           |            |            |            |            |
| 1. Oak Grove urban forest              | 1.00          |            |            |            |            |
| 3. Nolka forestry enterprise           | 0.94          |            |            | 1.00       |            |
| 4. Sernur forestry enterprise          | 0.66          |            | 0.81       | 1.00       |            |
| Latewood layer                         |                                           |            |            |            |            |
| 1. Oak Grove urban forest              | 1.00          |            |            |            |            |
| 3. Nolka forestry enterprise           | 0.42          |            |            | 1.00       |            |
| 4. Sernur forestry enterprise          | -0.18         |            | -0.06      | 1.00       |            |
Figure 2. Similarity dendrogram of the age series of annual growth of dominant Siberian larch trees in the test sites (with the ecotope numbers described in tables 1 and 5).

One of the factors, which influence the variability of trees' annual growth, is their genotypic characteristics determining up to 42.4% of the total variance of this parameter in some cenopopulations (table 6). It is proved by the correlation analysis results (table 7) which showed non-synchronicity in the growth of trees responding to fluctuations in the environment. In this relation, larch cenopopulation growing in the plantations of the Sernur forestry enterprise mixed with pine and spruce demonstrated the highest inhomogeneity.

Table 6. Factor contribution into the total variance of the annual radial growth of trees in the cenopopulations.

| Ecotope No. | Factor contribution into the total variance (%) | Factor significance level |
|-------------|-----------------------------------------------|---------------------------|
|             | age | trees | noise | age | trees |
| 1           | 84.1 | 1.1   | 14.8  | < 0.001 | 0.03 |
| 2           | 59.1 | 6.9   | 34.0  | < 0.001 | < 0.001 |
| 3           | 71.2 | 10.8  | 18.0  | < 0.001 | < 0.001 |
| 4           | 24.4 | 37.7  | 37.9  | < 0.001 | < 0.001 |
| 5           | 30.8 | 26.5  | 42.7  | < 0.001 | < 0.001 |
| 6           | 66.9 | 5.8   | 28.3  | < 0.001 | < 0.001 |

* Description of the ecotope numbers is provided in tables 1 and 5.

Table 7. Variability of pair correlation coefficient for growth series of dominant Siberian larch trees in the test sites.

| Site location                     | Coefficient of correlation between trees in the ecotopes | M ± m | min | max | Sx | CV, % |
|-----------------------------------|-------------------------------------------------------|-------|-----|-----|----|-------|
| 1. Oak Grove urban forest         | 0.81 ± 0.02                                            | 0.61  | 0.94| 0.09| 11.7|
| 2. Pine Grove urban forest        | 0.83 ± 0.02                                            | 0.58  | 0.95| 0.10| 13.0|
| 3. Nolka forestry enterprise     | 0.83 ± 0.01                                            | 0.49  | 0.98| 0.11| 12.0|
| 4. Sernur forestry enterprise    | 0.49 ± 0.03                                            | -0.11 | 0.86| 0.20| 39.9|
| 5. Dubravnaya forestry enterprise| 0.70 ± 0.04                                            | 0.13  | 0.92| 0.24| 33.5|
| 6. Krasny Most forestry enterprise| 0.70 ± 0.01                                           | 0.41  | 0.95| 0.12| 17.9|
The measurements showed that trees of different rank positions in the cenosis significantly differ from each other since the earliest age both in the overall width of their annual ring and the value of the radial annual growth of latewood (figure 3). In addition, it is determined that the Kraft's Class IV trees do not form annual rings for the period of seven to 18 years while remaining alive and giving the entire reserve of nutrients to new needles and water sprouts growing sometimes along their whole trunk.

In order to assess the response of trees to environmental changes researchers usually refer to the indices representing interrelations between actual and theoretical values calculated using the age trend function parameters rather than the absolute values of their growth. The calculations showed that the values of this parameter in the trees of the cenopopulations vary significantly (table 8), which indicates that the larch trees are exposed to powerful environmental factors and have an excellent adaptive ability that enables larch to grow under environmental conditions of a wide range. The greatest variability of tree growth indices was demonstrated in the oak grove forest growing environment (Ecotope No.5), while the least one was in the pure floodplain and mixed watershed plantations.

![Figure 3. Dynamics of annual radial growth of different Kraft's classes larch in the Oak Grove urban forest: (a) the total annual layer, (b) the late wood layer.](image)

**Table 8.** Variability patterns of the growth index of the total width of the annual ring in dominant Siberian larch trees in the test sites.

| Statistic parameter       | Parameter values of the growth indices in different ecotopes (%)<sup>a</sup> |
|---------------------------|-----------------------------------------------------------------------------|
|                           | No. 1 | No. 2 | No. 3 | No. 4 | No. 5 | No. 6 |
| Minimum value             | 35.2  | 16.3  | 24.8  | 23.6  | 13.3  | 21.7  |
| Maximum value             | 284.2 | 309.6 | 265.8 | 274.7 | 423.3 | 360.6 |
| Mean-square deviation     | 39.1  | 46.5  | 44.8  | 37.7  | 51.7  | 47.2  |

<sup>a</sup> Description of the ecotope numbers is provided in tables 1, 5 and 7.

The analysis of the obtained data showed that the dynamics of the annual tree growth indices in each ecotope is highly specific as indicated by the low values of the pair correlation coefficient for the temporal series, being -0.52 to 0.53 (table 9). The greatest correlation is observed between the growth index series of the cenopopulation trees in the Oak Grove urban forest and the Nolka forestry enterprise of the Volgatech Scientific Experimental Forestry Company. No correlation is observed in these cenopopulations in regard to the plantations in the Dubravnaya and Krasny Most forestry enterprises are included into the same cluster with the mixed species in the Sernur forestry enterprise (figure 4). The dynamics of the growth indices of the Siberian larch trees in the Republic of Mari El, despite the existing specificity of each cenopopulation, has a clear general trend of a sharp drop in their values after the droughts of 1972 and 2010 as well as alteration of increasing and decreasing trends (figure 5). Favourable conditions for their increase were observed in 1917-1930, 1945-1952 and 1959-1970, and
unfavourable ones in 1934-1943, 1953-1958, 1984-1992 and 1996-2015 (figure 6). In general, these data indicate a decrease in the fifteen-to-twenty-five-year fluctuation amplitude of the growth index values.

Table 9. Correlation between the age series of the annual layer total width index of dominant Siberian larch trees in the test sites.

| Site location                          | Coefficient of correlation between the ecotopes |
|----------------------------------------|-----------------------------------------------|
|                                        | No. 1  | No. 2  | No. 3  | No. 4  | No. 5  |
| 1. Oak Grove urban forest              | 1.00   |        |        |        |        |
| 2. Pine Grove urban forest             | 0.45   | 1.00   |        |        |        |
| 3. Nolka forestry enterprise           | 0.53   | 0.34   | 1.00   |        |        |
| 4. Sernur forestry enterprise          | -0.14  | 0.13   | 0.05   | 1.00   |        |
| 5. Dubravnaya forestry enterprise      | 0.09   | 0.21   | 0.21   | 0.41   | 1.00   |
| 6. Krasny Most forestry enterprise     | -0.52  | 0.20   | 0.04   | 0.43   | 0.44   |

Figure 4. Similarity dendrogram of the age series of the annual layer total width indices of dominant Siberian larch trees in the test sites (description of the ecotope numbers is provided in tables 1, 5, 7 and 9).
Figure 5. Dynamics of the mean total width index of the annual layer of Siberian larch trees in the different ecotopes of Mari El Republic (description of the ecotope numbers is provided in tables 1, 5, 7 and 9).

Figure 6. The seven-year smoothed and generalized dynamics of the annual growth index of Siberian larch in Mari El Republic.

4. Conclusion
Based on the field measurements of 83 wood cores we have found the boundaries and key patterns of changes in the width of the early and late zones in the annual ring of Siberian larch trees as well as indices of their total radial growth in the conditions of the Republic of Mari El and compiled a generalized chronological series from 1915 to 2015. We determined that the annual radial tree growth value significantly varies within a great range (0.2mm to 11.5mm), however, the mean values in the cenopopulations significantly differ from each other due to the type of the forest-growing environment and the stand thickness and composition. The width of the early wood zone varies from 0.15mm to 11.3mm, the width of the latewood - from 0.05mm to 4.15mm, the proportion of latewood varies from 1.2% to 82.8%, and the annual growth indices vary from 13% to 423%.

The key variability factor of the total width of the annual rings and the early wood layer is the tree age, and the contribution of weather conditions and other unaccounted factors (noise) into the total variance of the annual growth parameters is not more than 20%. The age trend of the annual ring width dynamics is best of all approximated with the Zipf-Pareto (equation 1), where the values of all the parameters are highly specific for each ecotope. On the other hand, the late wood layer value has almost no changes over the tree age.
One of the variability factors of the annual growth of trees along their age is their genotypic characteristics determining up to 42.7% of the total variance of this parameter in some cenopopulations. In addition, this study showed that oppressed trees do not form any annual rings for the last seven to 18 years while remaining alive and giving the entire reserve of nutrients to new needles and water sprouts growing sometimes along their whole trunk.

The dynamics of the growth indices of the Siberian larch trees in the Republic of Mari El, despite the existing specificity of each cenopopulation, has a clear general trend of a sharp drop in values after the droughts of 1972 and 2010 as well as alteration of rising and falling trends. Favourable conditions for their increase were observed in 1917-1930, 1945-1952 and 1959-1970, and unfavourable in 1934-1943, 1953-1958, 1984-1992 and 1996-2015. In general, these data indicate a decrease in the fifteen-to-twenty-five-year fluctuation amplitude of the growth index values.

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References
[1] Demakov Iu P 2001 Dendrochronology possibilities in indication and prediction of natural and human-induced processes Mathematical and Physical Methods in Ecology and Natural Environment Monitoring (Moscow: MGUL) pp 257–263
[2] Malik I and Wistuba M 2012 Geochronometria 39 180–196
[3] Tumajer J and Treml V 2015 Dendrochronologia 34 1–9
[4] Stoffel M. and Bollschweiler M 2008 Natural Hazards and Earth System Sciences 8 187–202
[5] Gervais B R and MacDonald G M 2001 The Holocene 11 499-505
[6] Sidorova O V, Naurzbaev M M and Vaganov E A 2005 The response of the tree-ring chronologies of northern Eurasia to powerful volcanic eruptions Issues of Ecological Monitoring and Ecosystem Modelling
[7] Borzenkova I I, Zhiltsova E L and Lobanov V A 2011 Climate variations of the extratropical zone of the northern hemisphere over the past 1000 years: analysis of data and possible causes Issues of Ecological Monitoring and Ecosystem 24 131–152
[8] D’Arrigo R and Wilson R 2013 Journ. of Geophys. Res. 118 9000–9010
[9] Kasatkina E A, Shumilov O I, Timonen M and Kanatev A G 2013 Izvestiya RAN. Fizika Atmosfery i Okeana 49 469–476
[10] Sidorenkov N S 2004 Herald of the Russian Academy of Sciences 74 701–715
[11] Fridman A M, Klimenko A V, Polyachenko E V and Fridman M V 2005 Volcanology and Seismology 1 67–74
[12] Utkin V I and Tsurko I A 2010 Ural Geophysical Bulletin 17 53–60
[13] Levin B V and Sasorova E V 2015 Doklady Akademii nauk 464 351–355
[14] Komin G E 1974 Russian Journal of Forest Science (Lesovedenie) 2 21-27
[15] Olenin S M 1976 Russian Journal of Forest Science (Lesovedenie) 2 35-41
[16] Berr B L, Liberman A A and Shiyatov S G 1979 Ecology 6 22–26
[17] Vaganov E A, Shiyatov S G and Mazepa V S 1996 Dendroclimatic Studies in the Ural-Siberian Subarctic (Novosibirsk: Nauka) 246 p
[18] Iuknis R A, Shipenite D A and Zhiliavichus A I 1985 Issues of Ecological Monitoring and Ecosystem Modelling 8 145–157
[19] Shiyatov S G 1973 Dendrochronology, its principles and methods Notes of All-Union Botanic
Society 6 53–81

[20] Shiyatov S G, Vaganov E A, Kirdyanov A V, Kruglov V B, Mazepa V S et al 2000 Methods of Dendrochronology. Part 1. Fundamentals of Dendrochronology. Collecting and Receiving Tree-Ring Information (Krasnoyarsk: KrasGU) 80 p

[21] Rumyancev D E 2010 History and Methodology of Forestry Dendrochronology (Moscow: MGUL) 109 p

[22] Grinin A S, Orekhov N A and Novikov V N 2003 Mathematical Modeling in Ecology (Moscow: YUNITI-DANA) 269 p

[23] Hemming R V 1980 Digital Filters (Moscow: Sovetskoe Radio) 224 p