Simulation of forest ecosystems dynamic processes message

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Abstract. Dynamic characteristics of changes in the diameter of larch forests in the Lower Angara region are being analyzed. Larch stands of the herbal group of fox types is the object of the present research. This research is based on the data of field inventory 858 forest areas with larch predominance. The structure of the forest average diameter is approximated by the exponential function, statistical analysis of which has been carried out using a non-linear least-squares method and simulation methods by conducting 50000 statistical tests. Regularities of error distribution, parameters and calculation accuracy of approximating function have been defined. Estimations of parameter correlations approximating function have been suggested. Holetsky’s method helped to receive two dimensional parameter generator. The defined regularities of the dynamics of average diameters allow to design economic activities in forest stands of larch herbal groups types in the region under study.

1. Introduction

Dynamics of forest stands is one of the main factors responsible for taking actions aimed at forestry development. Features of growth and formation of forest stand is determined by several factors, the main one is their growth conditions. Classification of stands productivity is valid within the territory with the same climate.

Productivity assessment of vegetation conditions for the forest stands is the basis for studying their dynamic patterns. In the domestic forestry for these purposes, the bonitet scale (usually M. M. Orlov's scale) and typological classifications (V. N. Sukachev, P. S. Pogrebnyak, etc.) are employed. Methods of dynamic simulation of plant communities have been considered in the works of J. K. Vanclay, P. J. Sands [1], A. Porte, H. H. Bartelink [2], Ch. Peng, X. Wen [3], V. V. Kuzmichev [4] etc. V.V. Kuzmichev [4] gives the following classification of methods to describe the dynamics of forest communities:

- simulation development model;
- eco-physiological simulation and application of stochastic models;
- tables of forest growth progress.

A distinctive feature of simulation is consideration of dynamics of separate elements of a complex biological system with a certain level of confidence without explaining the mechanism of their functioning.

Eco-physiological simulation pursues the achievement of a relatively complete understanding of trends in the dynamics of the object under study, by describing the mechanisms of its elements’ functioning. At present eco-physiological models do not account for "all or even a large part of influencing the process of growth (forest) individual factors and their interactions" [4], therefore they cannot be regarded as a model which adequately captures the dynamic processes of forest stands and trees.
The tables of growth which present taxation regulations, despite repeatedly expressed doubts concerning their impartiality and adequacy of processes of forest vegetation dynamics, still remain the only effective tool in domestic forestry practices which allows the use of regularities of dynamic processes in forest stands for the purposes of practical forestry.

One of the major shortcomings of growth tables is application of simplified methods of curves alignment, characterizing the dynamics of inventory performance, without logical analysis of obtained results; another one is weakness of the used mathematical tools.

Regularities of the dynamics of inventory indices of larch stands in Central Siberia were investigated by B. N. Tikhomirov and A. I. Tishenkov [5], E. N. Falaleev and V. S. Polyakov [6], I. I. Krasikov and S. L. Shevelev [7], N. N. Kulakova, and S. L. Shevelev [8]. In their work N. N. Kulakov and S. L. Shevelev [8] note the relevance of growth tables in the study of quite an extensive herbal group of larch forests. The purpose of this study was to develop the method for establishing the patterns of inventory indices of forest stands on the example of average diameters, using mathematical tools of data processing and computer modeling in the construction of forest growth tables.

2. Materials and methods
The object of the study was stands of Siberian larch on the territory of Nizhneangarsk taiga area [9] where the tree stands with a predominance of this breed is about 24% of the total forested area.

Based on inventory materials, selection of 858 taxation plots applying typological approach was made. Forest stands are characterized by productivity, corresponding to bonitet class III. According to N. I. Tretyakov and I. V. Semechkin [10] recommendations, a series reflecting dynamics of average diameters of forest stands has been obtained; their variability (W, %) and accuracy of the test (P, %) (table 1).

| age, number of years | 10  | 30  | 50  | 70  | 90  | 110 | 130 | 150 | 170 | 190 | 210 | 230 | 250 | 270 |
|----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| diameter, cm         | 1.7 | 8.7 | 16.0| 19.5| 23.1| 25.9| 27.8| 30.2| 35.3| 38.6| 41.0| 41.6| 40.7| 46.0|
| W, %                 | 72.1| 45.2| 18.6| 23.8| 11.3| 10.0| 8.0 | 7.6 | 13.4| 16.4| 12.8| 13.7| 8.8 | 7.3 |
| P, %                 | 13.9| 11.0| 3.6 | 3.1 | 1.3 | 0.9 | 0.8 | 0.9 | 1.8 | 2.9 | 2.4 | 2.5 | 1.3 | 2.3 |

For mathematical description of the deterministic component or temporary trend of forest growth series different models have been used [11]. In the 30s of XX century L. von Bertalanffy (Von Bertalanffy, 1938) [12] formulated a scientific hypothesis, according to which the increase (growth rate) by the volume of the body is expressed by the difference between anabolic (synthesis of substances) and catabolic (decomposition of matter) growth rates. Anabolic growth rate is proportional to the surface area of the body, while catabolic - to the size of the biomass.

A preliminary analysis of the experimental data is presented in table 1. It allowed to describe age-related changes in the average diameter larch stands employing the Robertson-Ostwald (Robertson, Ostwald, 1908) [13, 14] model, namely its particular case - Bertalanffy model:

\[ D(t) = D_{max} \times (1 - \exp(-t/T)) \],

where \( D(t) \) is the average diameter of larch stands, cm; \( t \) – the age of forest stands, years; \( D_{max} \) – the maximum rating value of diameter, cm; \( T \) – time constant characterizing the rate of diameter change, years. Under \( t = T \) diameter equals 63%, and under \( t = 3T \) – 95% of the maximum value \( D_{max} \).

3. Results and Discussion
While differentiating (1) we evaluate the annual rate of average diameter change:

\[ V_D(t) = V_{max} \times \exp(-t/T), \]
where \( V_D(t) \) is the estimate of the average annual larch stands diameter increase cm/year; \( V_{\text{max}} = D_{\text{max}}/T \) is the estimate of the initial (maximum) velocity, cm/year.

Switching to generalized variables \( D_0(t) = D(t)/D_{\text{max}}, \tau = t/T \) in expression (1) we obtain:

\[
D_0(\tau) = 1 - \exp(-\tau),
\]

(3)

Evaluation of the rate of generalized variables \( V_0(\tau) = V_D(\tau)/V_{\text{max}} \) is:

\[
V_0(\tau) = \exp(-\tau).
\]

(4)

From (4) it follows that under \( t = T \), the annual diameter growth rate reduces to 37%; under \( t = 3T \) – to 5% from initial (maximum) value.

Evaluation of equation coefficients (1) was performed with a nonlinear least-squares method [16], their standard errors and 95% confidence intervals of changes were defined in the simulation modeling by implementation of 50,000 statistical tests [16,17,18]. Statistical characteristics of model (1) are presented in table 2.

**Table 2. Statistical characteristics of model (1).**

| Index                                           | Symbol            | Value               |
|------------------------------------------------|-------------------|---------------------|
| Freedom degrees number                          | \( f \)           | 12                  |
| Least-squares estimate of time constant, cm     | \( D_{\text{max}} \) | 57.3 ± 3.9          |
| Least-squares estimate of time constant, years  | \( T \)           | 180 ± 21            |
| Least-squares estimate of maximum velocity, cm/year | \( V_{\text{max}} \) | 0.32 ± 0.02        |
| Standard error of the model, cm                 | \( S \)           | 1.5 ± 0.3           |
| 95% confidence variation rate, \( D_{\text{max}} \), cm |                | [51.2 66.5]         |
| 95% confidence variation rate \( T \), years    |                   | [146 229]           |
| 95%-confidence variation rate \( S \), cm       |                   | [0.9 2.1]           |
| Determination coefficient of the model          | \( R^2 \)         | 0.988               |

Figure 1 presents the empirical and theoretical (normal) distribution function of errors of model (1). The normality of error distribution was checked according to the Frozini consent criteria [19] for cases of complex hypotheses testing, where parameters of distribution are estimated based on empirical data. Statistics of consent criteria and critical values under 5% level of significance were evaluated based on 50000 statistical tests [17].

The analysis showed that the hypothesis of error distribution normality is not rejected at 5% significance level as under Frozini criteria and \( \sigma^2 \) (figure 2).

**Figure 1.** Cumulative error distribution function of the model (1).
Figure 2. Hypothesis test of error distribution normality under Frozini criteria and \( \omega^2 \).

Since the hypothesis of error distribution normality is not rejected, estimates of model parameters distributions can be obtained by the simulation method conducting the following computer experiments: for each age group (table 1) random variables (errors) are superimposed on the results of diameter calculation according to the model (1) distributed under the law \( N(0, S^2) \). To obtain the values module parameters estimates are determined (1) [16].

Figure 3 - 6 present the results of distribution parameters functions estimation \( D_{max}, T, V_{max} \) and standard error of the model \( S \) based on the results of 50000 statistical tests.

The obtained results characterize statistical distribution of relevant variables and allow simulation modeling of larch stands' diameters.

Figure 3 Estimates of coefficient distribution function \( D_{max} \) with statistical tests method.
There is a close correlation between values of the maximum diameter $D_{\text{max}}$ and the time constant $T$ (correlation coefficient $R_{\text{DT}} = 0.981$). The correlation cloud of 95% confidence interval of these parameters variation is shown in figure 7a.

![Figure 4. Estimates of coefficient distribution function $T$ with statistical tests method.](image)

![Figure 5. Estimates of coefficient distribution function $V_{\text{max}}$ with statistical tests method.](image)
Figure 6. Estimates of the modal standard error distribution function $S$ with statistical tests method.

Figure 7. Evaluation of 95%-confidence interval of coefficients variations $D_{\text{max}}$ and $T$: (a) method of statistical tests, (b) random values generator (5) – (7).

Applying the method of multidimensional random variables formation based on the Cholesky transformation generator of pseudo-random values to determine the $D_{\text{max}}$ and $T$ has been obtained:

$$
\begin{align*}
\begin{cases} 
D_{\text{EEH}} \\ T_{\text{EEH}}
\end{cases} &= \begin{cases} 
M_{\text{Dmax}} + S_{\text{Dmax}} \times D_f \\ M_f \times S_f \times T_f
\end{cases}, \\
\begin{cases} 
D_f \\ T_f
\end{cases} &= \begin{cases} 
D_f \\ R_{gf} \times D_c + \sqrt{1 - R_{gf}^2} \times T_c
\end{cases},
\end{align*}
$$

(5)
where $D_{\text{gen}}, T_{\text{gen}}$ – generated values of the maximum diameter and time constant; $D_r, T_r$ – generated normalized values of the maximum diameter and time constant; $D_\varepsilon, T_\varepsilon$ – normalized values of maximum diameter and a time constant corresponding to $\varepsilon D_m, \varepsilon T$; $\varepsilon D_m, \varepsilon T$ – randomly selected values from the array of coefficients of $T$ and $D_{\text{max}}$ obtained by the method of statistical tests (figure 3-4); $M_{D_m} = 57.3, M_T = 180$ – least-squares estimate of the maximum diameter and time constant (table. 2); $S_{D_m} = 3.9, S_T = 21$ – standard estimate errors of the maximum diameter and time constant (table. 2); $R_{DT} = 0.981$.

Figure 7 b presents the results of 10000 pseudo-random values formation obtained with generator (5) to (7).

Experimental calculated values and 95% confidence variation interval of average larch stands diameters of the forest-type herbal group depending on the age of the stand is shown in figure 8. The cumulative distribution function of the average larch stands herbal groups of forest types diameters depending on the age of forest stands is shown in figure 9.

![Figure 8. Dynamics of the average larch stands of the forest-type herbal group diameters](image)

![Figure 9. Integral function of the average larch stands of the forest-type herbal group](image)
Conclusion

The proposed scheme estimates the dynamics of the average inventory indices, allowing to estimate the most probable values of the Robertson-Ostwald model coefficients, statistics of variations in these ratios, change statistics of projected inventory indices.

The use of the proposed scheme will improve the methods of constructing tables of growth and designing forest management activities.

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