Modelling the growth tables of the oak stands of seed origin of the Voronezh region by type of forest growing conditions

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Abstract. Growth rate tables (GRT) used by the forest industry, as a rule, are built according to yield class and have a utilitarian focus. Based on forest inventory data, we built multidimensional models and GRTs for oak (Quercus robur L.) stands for 10 types of forest growing conditions, reflecting the dynamics of forest inventory indicators depending on the age and basal area of stands, and the abundance of oak in the overall species composition. The obtained GRTs in the age range of 10-300 years, for the basal area in the range of 0.3-1.0 and the share of oak in the overall species composition of 1-10 units, can be used in surveys of oak stands based on the measurements of the average heights, diameters and sums of cross-sectional areas.

1. Introduction

The doctrine of types of forest growing conditions (TFC) is the basis of forest science. However, it is currently not a vital element of forest assessments. The majority of the growth rate tables (GRT) used in practice are based on “bonitet” (side index); they have a utilitarian focus and do not take into account edaphic conditions [1-3]. In addition, the real forest stands have different values of the basal area, growing stock and other indicators, which are significantly different from those of the fully stocked (normal) stands, the standard indicators of which are now used in the Russian Federation for forest valuation. This method is more than 100 years old, but it has not yet achieved a significant increase in the accuracy of the bulk forest assessments, which is ± 15% with a probability level of 0.68 [1]. We propose to study the dynamics of forest inventory indicators and build GRTs based on the type of forest growing conditions (TFC), which would make them more environmentally and scientifically sound [4-6]. At the same time, in the scale of forest types used in the Voronezh region, each forest type corresponds to one TFC.

2. Material and Methods

As a basis for the development of a new type of standards, we applied an edaphic table by P S Pogrebnyak [6], which has passed practical tests, and in which the soil conditions of forest stands are most successfully linked to forest types and indicators of grass cover. The transition from a general grading scale to a forest typological scale was carried out using statistical models with block dummy variables [4, 5]. When developing the forest typological scale, independent variables represented by quality indicators of TFC: D₀ (very dry oak stand), D₁ (dry oak stand), D₂ (fresh oak stand), D₂P (fresh oak stand on a flood plain), D₃ (wet oak stand), D₃P (wet oak stand on a flood plain), E₀ (very dry oak
stand in a gully), $E_1$ (dry oak stand in a gully), $E_2$ (fresh oak stand in a gully), $C_2D$ (fresh sudubrava, a type of forest growing conditions in transition from a pine to oak forest) \cite{6, 7} were expressed by block dummy variables ($D_1-X_1$, $D_2-X_2$, $D_3P-X_3$, $D_2-X_2$, $D_3P-X_3$, $E_1-X_5$, $E_2-X_6$, $C_2D-X_5$), by building a matrix of binary variables \cite{4, 5}. A combination of the values of variables indicated in the matrix with the data on the age and basal area of oak trees allowed us to form a set of independent variables and build a multiple regression (1) of the age dynamics of average heights expressed by the Korsun-Backman growth function \cite{8}.

3. Results and Discussion

On the basis of the measurements of forest inventory indicators in more than 800 sample plots, we built a model (1) using methods of mathematical-statistical modelling: the model revealed patterns of changes in the average heights ($H$) of oak stands depending on the TFC, age ($A$) and basal area ($P$):

$$H = \exp(-0.07839 + 0.36870243X_1 + 0.5310285X_2 + 0.49612405X_3 + 0.60334283X_4 +$$

$$+ 0.518229X_5 + 0.0493368X_6 + 0.09326359X_7 + 0.5917313X_8 + 0.4398613X_9 -$$

$$- 0.37758lnA + 0.85159lnA - 0.17826lnA + 0.01085lnA + 0.11lnP)$$

(1)

$$R^2=0.923; \, m_8=0.1104 \, m; \, t_p> t_{0.05}=2.0; \, F=816.7; \, P<0.05$$

The reliability of the obtained model is confirmed by the value of the Fisher criterion of 816.7 at a probability level of 0.95 \cite{9}. Digital interpretation was performed for all TFC, in the age range from 10 to 300 years, in the basal area range from 0.3 to 1.0, and in the range of the share of oak in the composition of forest stands from 1 to 10 units. The results demonstrate (table 1) that the best increase in height is typical for TFC $D_1$, reaching 31.7 m in 180 years. TFC $E_2$ (31.3 m) turned out to be very similar to the above, followed by TFC $D_2$ (29.5 m), $D_3P$ (29.1 m) and $D_2P$ (28.5 m). With the deterioration of the quality of edaphoses (edaphic conditions), the height decreases: in TFC $C_2D$, to 26.9 m; and in TFC $D_1$, to 25.1 m. In the Voronezh region, the least favourable for oak forests conditions are found in TFC $E_1$ (19.0 m), $E_0$ (18.2 m) and $D_0$ (17.3 m).

**Table 1.** Forest typological scale of average heights. Basal area equals 1.0.

| A, years | $D_0$ | $D_1$ | $D_2$ | $D_3$ | $C_2D$ | $D_3P$ | $D_2P$ | $E_0$ | $E_1$ | $E_2$ |
|----------|-------|-------|-------|-------|--------|-------|-------|-------|-------|-------|
| 20       | 4.5   | 6.6   | 7.7   | 8.3   | 7.1    | 7.5   | 7.6   | 4.8   | 5.0   | 8.2   |
| 60       | 11.8  | 17.0  | 20.0  | 21.5  | 18.3   | 19.3  | 19.8  | 12.4  | 12.9  | 21.3  |
| 100      | 15.1  | 21.8  | 25.6  | 27.6  | 23.4   | 24.8  | 25.3  | 15.8  | 16.6  | 27.2  |
| 140      | 16.6  | 24.0  | 28.3  | 30.4  | 25.8   | 27.3  | 27.9  | 17.5  | 18.2  | 30.0  |
| 180      | 17.3  | 25.1  | 29.5  | 31.7  | 26.9   | 28.5  | 29.1  | 18.2  | 19.0  | 31.3  |
| 220      | 17.7  | 25.5  | 30.0  | 32.3  | 27.4   | 29.0  | 29.6  | 18.5  | 19.4  | 31.9  |
| 260      | 17.8  | 25.7  | 30.2  | 32.5  | 27.6   | 29.2  | 29.8  | 18.7  | 19.5  | 32.1  |
| 300      | 17.8  | 25.7  | 30.2  | 32.5  | 27.6   | 29.2  | 29.9  | 18.7  | 19.5  | 32.1  |

When the average heights of all TFCs with the best of them for oak growth, $D_1$, were compared, we came to a conclusion that in TFC $E_2$ the average height was 1.2\% lower; in TFC $D_2$, 7.1\% lower, in TFC $D_3P$, 8.0\% lower; in TFC $D_3P$, 10.2\% lower; in TFC $C_2D$, 15.1\% lower; in TFC $D_1$, 20.9\% lower; in TFC $E_1$, 40.0\% lower; and in TFC $D_0$, 45.2\% lower (Table 1). These data reflect, among other things, the features of growth and the validity of segregation of the upland, gully and floodplain ecotypes of oak forests based on differences in the mean height. The resulting model allows us to numerically demonstrate the effect of soil moisture on the absolute values of the average heights of the studied oak stands: with the decrease in soil moisture, the height decreases significantly, by 7.1%, 20.9% and 45.2% in TFC $D_2$, $D_1$ and $D_0$, respectively, compared with TFC $D_1$; and by 39.5% and 41.7% in TFC $E_1$ and $E_0$, respectively, compared to TFC $E_2$.  

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Our calculations demonstrate that the differences in the average height of tree stands within one TFC with a change in the basal area from 1.0 to 0.3 reach 11.2–11.4%, in absolute terms from 2.0 m in TFC D0 to 3.8 m in TFC D3, which is a substantial difference that can influence the accuracy of the growing stock assessments [4].

Alongside with the study of the age dynamics of the average height of stands, in studying the patterns of growth, it is necessary to consider their age variation in thickness [1, 2]. Based on the collected initial data, as a result of multivariate statistical modelling of diameters \( D \), a regression equation of the following form was built:

\[
D = \exp(-0.6224884 + 0.19782609X_1 + 0.3432783X_2 + 0.39198115X_3 + 0.3948874X_4 + \\
+ 0.544034X_5 + 0.2347975X_6 + 0.14925188X_7 + 0.5011764X_8 + 0.3279976X_9 + \\
+ 0.1585797\ln A + 0.2703163\ln^2 A - 0.02778458\ln^3 A - 0.2435761\ln P)
\]

(2)

The reliability of the model (2) is confirmed by a high value of the coefficient of determination \( R^2 = 0.918 \) and a significant value of the actual Fisher criterion of 769.8 at a probability level of 0.95 [9]. The analysis of the modelling results shows that the average diameter of oak stands decreases with the deterioration of TFC, from the maximum value of 63.0 cm observed in floodplain wet oak forests (TFC D3,P) to the minimum value of 36.6 cm observed in very dry oak forests (TFC D0).

At the same time, all TFCs can be divided into four groups by age dynamics of the analysed indicator: the first group includes TFC D3,P and E2, characterized by the highest rate of increase in diameter; the second group includes TFC D1, D2, C2D and D2,P, characterized by a good rate of increase in diameter; the third group (TFC D1, E0 and E1), by lower rate of increase in diameter; and the fourth (TFC D0), by a slow rate of increase in diameter in the worst growing conditions for oak.

The conducted studies allowed us to reveal specific patterns of changes in the average diameter of the oak element of forests depending not only on the age, but also on the basal area of stands. The results of calculations for plantations with a basal area of 0.3 show that with the increase in the basal area, the average diameter also increases and can reach 34.1%, which is very important and should be taken into account in valuation of forest stands. Thus, the obtained model of the age dynamics of the average diameter of the oak element according to TFC allowed the multidimensional regression (2) to differentiate its values within the established ecological niches of growth of the studied forests in the conditions of the Voronezh region.

Table 2. Dynamics of the average diameter by TFC. The basal area is 1.0.

| A, years | D₀ | D₁ | D₂ | D₃ | C₂D | D₂P | D₃P | E₀ | E₁ | E₂ |
|----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 20       | 4.6 | 5.6 | 6.5 | 6.9 | 6.4 | 6.8 | 8.0 | 5.8 | 5.4 | 7.6 |
| 60       | 14.2| 17.3| 20.0| 21.0| 19.7| 21.0| 24.4| 17.9| 16.5| 23.4|
| 100      | 22.8| 27.8| 32.1| 33.8| 31.7| 33.7| 39.3| 28.8| 26.5| 37.6|
| 140      | 30.2| 36.9| 42.6| 44.9| 42.0| 44.8| 52.1| 38.3| 35.1| 49.9|
| 180      | 36.6| 44.6| 51.6| 54.3| 50.8| 54.1| 63.0| 46.3| 42.5| 60.4|
| 220      | 42.0| 51.2| 59.2| 62.3| 58.3| 62.1| 72.3| 53.1| 48.7| 69.3|
| 260      | 46.5| 56.7| 65.6| 69.1| 64.6| 68.9| 80.2| 58.9| 54.0| 76.8|
| 300      | 50.4| 61.5| 71.1| 74.8| 70.0| 74.6| 86.9| 63.8| 58.5| 83.2|

The obtained regression models indicate that in all the studied TFCs the average diameter of the elements of the oak forests will increase with the increase in age and the decrease in basal area. Along with the study of patterns of changes in average heights and diameters, we performed a simulation of the age dynamics of the average growing stock per 1 ha of the studied tree stands. As a result, a multiple regression model (3) of changes in the growing stock of oak stands \( M \) depending on
the average height ($H$), basal area ($P$) and the share of oak in the overall species composition ($S$) was obtained:

$$M = 0.885*\exp(-0.60621 + 1.19093\ln H + 0.05244\ln^2 H + 1.0\ln P + 1.0\ln S)$$

$$R^2 = 0.9999; \ m_R = 0.01252; t_p > t_{0.05} = 2.0; F=14401001.0; P<0.05$$

The reliability of the model (3) is confirmed by a high value of the multiple coefficient of determination ($R^2 = 0.9999$) and the actual value of the Fisher criterion of 14401001.0 at a probability level of 0.95 [9]. All coefficients of the regression equation and the synchrony of the regression lines also confirm the reliability of the simulation, the results of which are shown in Table 3.

**Table 3.** Dynamics of the average growing stock by TFC. The basal area is 1.0.

| A, years | $D_0$ | $D_1$ | $D_2$ | $D_3$ | $C_2$ | $D_2P$ | $D_3P$ | $E_0$ | $E_1$ | $E_2$ |
|---------|-------|-------|-------|-------|-------|--------|--------|-------|-------|-------|
| 20      | 33    | 55    | 69    | 76    | 60    | 65     | 67     | 35    | 37    | 75    |
| 60      | 125   | 215   | 274   | 306   | 239   | 260    | 269    | 134   | 143   | 300   |
| 100     | 180   | 312   | 399   | 446   | 347   | 379    | 392    | 193   | 206   | 438   |
| 140     | 207   | 361   | 464   | 518   | 403   | 439    | 454    | 223   | 238   | 509   |
| 180     | 221   | 386   | 495   | 554   | 430   | 469    | 485    | 238   | 254   | 544   |
| 220     | 227   | 397   | 509   | 570   | 442   | 482    | 499    | 245   | 261   | 559   |
| 260     | 229   | 401   | 514   | 575   | 447   | 487    | 504    | 247   | 264   | 565   |
| 300     | 230   | 401   | 515   | 576   | 447   | 488    | 505    | 247   | 264   | 566   |

As shown by our calculations (Table 3), the obtained models of the dynamics of productivity of the oak elements of forests of seed origin for all TFCs are within the existing boundaries of the lb - V yield classes [2, 3], which also indicates their correspondence to the grading scales, at the same time they indicate distinctiveness of the accumulation of the growing stock in the studied stands. Thus, the average values of the growing stock in the most productive TFCs, $D_3$ and $E_2$, fall within the boundaries of the 1st yield class, but have the absolute values 5.1–9.9% lower than in the applied GRT [3], and the accumulation curves, both theoretical and actual (3), do not overlap, but gradually diverge with age. The growing stock accumulation dynamics in the worst forest growing conditions of very dry oak forests ($D_0$) also does not correspond to that given in the standards [3], differing from it by 19.2–19.8% in the age range from 100 to 200 years, which is a substantial difference.

When other age trends were considered, a similar pattern was observed. In addition, GRT used by the industry [3] contains information on the dynamics of forest inventory indicators for up to 200 years and, of course, does not cover all oak stands of the forest fund of the region.

The calculations show that the group of the most productive in terms of the growing stock stands includes oak stands growing in TFC $D_3$ and $E_2$, the age trends in accumulation of the growing stock of which differ by no more than 1.7–1.8%. The group of high productivity includes tree stands growing in TFC $D_2$, $D_3P$ and $D_3P$, which accumulate growing stock on average 11.0%, 13.8% and 17.5% slower than tree stands in $D_3$, respectively. The group of average productivity includes tree stands growing in TFC $C_2$ with the growing stock 27.8% less than the growing stock in TFC $D_3$. The group of low productivity includes tree stands growing in TFC $D_1$ with the growing stock 40.9% less than the growing stock in $D_3$, and the group of the lowest productivity, $D_0$ and $E_0$, with the growing stock 2.3–2.4 times less than that of the most productive stands.

Thus, for the seed oak plantations of the Voronezh region, models of growth of the main forest inventory indicators by TFC were obtained for the first time, allowing us to numerically reflect the patterns of changes in forest inventory indicators depending on the age and basal area of tree stands (1-3).

Regression models (1-3) built as a result of multivariate modelling allowed us to construct tables of the age dynamics of forest inventory indicators based on forest typology and reflecting the actual
growth of the stands under study, which can form the basis of an ecological approach to the inventory of oak forests in the Voronezh region in particular. The developed standards are classified as regional and should be applied by the industry in forest valuation [4]. However, significant progress in this area has not, as yet, been achieved, due to the lack of consistency and a uniform methodology in their development. The new GRT class being developed will make it possible to take into account the growth characteristics of oak stands such as forest elements with a different basal area and share of oak in the forest composition in the conditions of the Voronezh region.

Features of the construction of growth rate tables based on forest typology have a number of distinctive features in comparison with classical approaches [1, 2]. The GRT modelling work has started with calculations using the obtained regression models of the average height values (1) and diameters (2), as well as the stock of stem wood per 1 ha (3) for each TFC in the age range from 10 to 300 years and the share of oak in the forest composition from 10 to 1 units with the entry of data in the grid of an electronic spread sheet (Table 4 - fragment). The validation of the obtained data confirmed the reliability of the simulation results. In the next step, on the basis of the obtained indicators of heights (√) and diameters (D) according to the trunk volume model (√) of a growing tree (4), we calculated the average volume for the corresponding age, height and diameter of the trunk and also listed it in the simulated table 4. The obtained values of √, D, M1ha (standing volume per 1 ha) and Vst formed the basis for calculating all the remaining forest inventory characteristics of the growing part of stands, while in other classical methods [1, 2] these are √, D, M1ha and G1ha (the sum of the areas of the cross-sections of stands per 1 ha).

In our approach, the developed system of standards based on the value of the volume of the growing tree trunk (√) found from the previously developed [10] model of the oak trunk volumes (4). Additionally, according to the formula for the upper height (√) (5), obtained by the method proposed by V K Khlyustov [5], its values are calculated and also listed in table 4:

\[
V_{st} = \exp(-9.00391 - 0.74478\ln H + 0.098371\ln^2 H - 0.00421\ln^2 D + 1.01415\ln HD)^2 \quad (4)
\]

\[
R^2=0.999996; m_R=\pm0.003596; t_p> t_{0.5}=2.0; F = 31556907.8; P<0.05
\]

\[
H_B = \exp(1.77312\ln H - 0.363699\ln^2 H + 0.04615\ln^3 H - 0.005203\ln^3 A + 0.000704\ln^4 A) \quad (5)
\]

\[
R^2=0.935; m_R=0.1008; t_p> t_{0.5}=2.0; F=934.7; P<0.05
\]

After performing all the necessary preparatory calculations for the growing part of the stand, the forest inventory indicators missing in GRT were determined using the well-known formulas [1]:

\[
F = M / (G \cdot H) \quad (6)
\]

\[
H = F \cdot N \quad (7)
\]

\[
G_1ha = 3.14D^2N / 10000 \quad (8)
\]

\[
G^2 = M / A \quad (9)
\]

\[
G^{\text{cr}} = (M_A - M_{A-n}) / A \quad (11)
\]

where \( F \) - species number, \( H \) - species height (m), \( N \) - number of stems (unit/ha), \( G_{1ha} \) - the sum of the areas of cross-sections (m²/ha), \( Z^{av} \) - average stock change (m³/(ha*year)), \( Z^{cr} \) - current growing stock change, m³/(ha* year).

When constructing complete growth tables, calculations were also made for the second part of any growing stand, that is, for the dead timber. Its main characteristics, as is known [1, 2], are \( N_{dec} \) - number of dead trees, \( V_{dec} \) - the volume of an average dead tree, \( M_{dec} \) - the volume of dead timber for the period of growth, and \( \Sigma M_{dec} \) - the total volume of the dead timber.
The number of dead trees is calculated as the difference between the number of trees in the growing part at the age of \( A-n \) (n = 10) and \( A \) years:

\[
N_{\text{dec}} = N_{A-n} - N_A
\]  

(12)

The volume of an average dead tree \( (V_{\text{dec}}) \) in the developed GRT (table 4) for all ages and basal areas was determined on the basis of the regression equation (13):

\[
V_{\text{dec}} = \exp(0.8368539 - 0.597222504\ln H_{100} + 1.206094\ln V_{\text{st}} - 0.009706\ln V_{\text{st}}^2)
\]  

\[
R^2=0.9996; \ m_R = 0.06127; \ t_{p}> t_{0.5}=2.0; \ F=23432.5 \text{ at } P<0.05.
\]  

The dead timber stock over a 10-year period is obtained by the formula:

\[
M_{\text{dec}} = V_{\text{dec}} \cdot N_{\text{dec}}.
\]  

(14)

The accumulated dead timber stock \( (\sum M_{\text{dec}}) \) was calculated by the successive summation of \( M_{\text{dec}} \) for each 10 year period.

The final stage of building the growth tables for the oak stands of seed origin of the Voronezh region on a forest typology basis (table 4) was the determination of indicators of the total productivity for all age groups. The total growing stock was calculated as the sum of the stocks of the growing part of tree stands \( (M) \) and the accumulated stock of the dead timber \( (\sum M_{\text{dec}}) \):  

\[
M_{\text{tot}} = M + \sum M_{\text{dec}},
\]  

(15)

the total average increase was determined by the formula:

\[
Z_{\text{av tot.}} = M_{\text{tot}} / A,
\]  

(16)

and the total current average periodic growth, by the equation:

\[
Z_{\text{cr tot.}} = (M_{\text{tot}}A - M_{\text{tot},A-n}) / A
\]  

(17)

4. Conclusions

As a result of the modelling, the regression models were built (1–17) and for the first time, the GRTs of the oak stands of the Voronezh region with different basal areas and the share of oak in the forest composition were built in an electronic form on a forest typology basis, allowing investigation of the patterns of changes in their basic forest inventory indicators for TFC depending on the age and basal area of forest stands. The resulting GRTs for oak as the main forest forming species of the region, in the age range from 10 to 300 years, for the basal area of 0.3-1.0 and the share of oak in the forest composition from 1 to 10 units allow us to perform inventory of modal tree stands and can be used in an electronic form to make estimates with a measuring method according to field measurements of the average height, average diameter, and the sum of areas of cross-sections. A comparison of the obtained GRTs with those developed earlier for the oak stands of seed origin of the Russian Federation by I. M. Naumenko [3] based on yield class showed their correspondence along the main lines of the dynamics of forest inventory indicators.
Table 4. Growth rate table for the oak forests of seed origin of the Voronezh region. TFC D₂.

| A, years | Hₚ, m | H₂, m | H₃, m | F | H₅, m | N, unit*ha⁻¹ | H₆, m | V, m³ | H₇, m | Growing stock change, m³*ha⁻¹*year⁻¹ |
|----------|-------|-------|-------|---|-------|-------------|-------|------|-------|-------------------------------------|
|          |       |       |       |   |       |             |       |      |       | Z⁺w | Z⁻w |
| 1        | 2     | 3     | 4     | 5 | 6     | 7           | 8     | 9    | 10    | 11  | 12  |
| 20       | 11.2  | 7.7   | 6.7   | 0.59 | 4.6  | 4244       | 15.1  | 0.016| 69    | 3.43 | 4.62 |
| 40       | 18.6  | 15.0  | 13.7  | 0.511| 7.7  | 1573       | 23.3  | 0.114| 179   | 4.47 | 5.49 |
| 60       | 22.9  | 20.0  | 20.6  | 0.485| 9.7  | 848        | 28.2  | 0.323| 274   | 4.57 | 4.49 |
| 80       | 25.6  | 23.4  | 27.1  | 0.473| 11.1 | 544        | 31.3  | 0.637| 347   | 4.33 | 3.35 |
| 100      | 27.4  | 25.6  | 33.1  | 0.467| 12.0 | 387        | 33.3  | 1.033| 399   | 3.99 | 2.42 |
| 120      | 28.5  | 27.2  | 38.8  | 0.464| 12.6 | 294        | 34.6  | 1.488| 437   | 3.64 | 1.72 |
| 140      | 29.3  | 28.3  | 44.0  | 0.462| 13.1 | 234        | 35.5  | 1.979| 464   | 3.31 | 1.21 |
| 160      | 29.8  | 29.0  | 48.7  | 0.461| 13.4 | 193        | 36.1  | 2.491| 482   | 3.01 | 0.84 |
| 180      | 30.2  | 29.5  | 53.2  | 0.460| 13.6 | 164        | 36.5  | 3.010| 495   | 2.75 | 0.58 |
| 200      | 30.4  | 29.8  | 57.2  | 0.460| 13.7 | 143        | 36.7  | 3.527| 504   | 2.52 | 0.39 |
| 220      | 30.5  | 30.0  | 61.0  | 0.460| 13.8 | 126        | 36.9  | 4.032| 509   | 2.31 | 0.25 |
| 240      | 30.6  | 30.2  | 64.5  | 0.460| 13.9 | 113        | 37.0  | 4.522| 512   | 2.14 | 0.15 |
| 260      | 30.7  | 30.2  | 67.6  | 0.460| 13.9 | 103        | 37.0  | 4.994| 514   | 1.98 | 0.07 |
| 280      | 30.7  | 30.2  | 70.6  | 0.460| 13.9 | 95         | 37.0  | 5.443| 515   | 1.84 | 0.02 |
| 300      | 30.8  | 30.2  | 73.3  | 0.460| 13.9 | 88         | 37.0  | 5.870| 515   | 1.72 | 0.00 |

Table 4. Growth rate table for the oak forests of seed origin of the Voronezh region. TFC D₂ (cont.).

| A, years | Nₜ, unit*ha⁻¹ | Vₜ, m³ | M₀, m³*ha⁻¹ | M₀, m³*ha⁻¹ | Mₓ, m³*ha⁻¹ | Increment, m³*ha⁻¹*year⁻¹ | Z⁺ | Z⁻ |
|----------|---------------|--------|-------------|-------------|-------------|-----------------------------|----|----|
|          |               |        |             |             |             |                             |    |    |
| 1        | 13            | 14     | 15          | 16          | 17          |                             | 18 | 19 |
| 20       | 5885          | 0.002  | 11          | 11          | 80          | 4.01                        | 5.77 |
| 40       | 831           | 0.023  | 19          | 46          | 225         | 5.62                        | 7.40 |
| 60       | 274           | 0.084  | 23          | 91          | 365         | 6.09                        | 6.80 |
| 80       | 125           | 0.193  | 24          | 139         | 485         | 6.07                        | 5.75 |
| 100      | 67            | 0.346  | 23          | 186         | 585         | 5.85                        | 4.75 |
| 120      | 41            | 0.537  | 22          | 231         | 668         | 5.56                        | 3.91 |
| 140      | 27            | 0.755  | 20          | 272         | 736         | 5.25                        | 3.23 |
| 160      | 19            | 0.993  | 18          | 310         | 792         | 4.95                        | 2.69 |
| 180      | 13            | 1.243  | 17          | 344         | 839         | 4.66                        | 2.25 |
| 200      | 10            | 1.499  | 15          | 375         | 878         | 4.39                        | 1.89 |
| 220      | 8             | 1.756  | 14          | 403         | 912         | 4.14                        | 1.61 |
| 240      | 6             | 2.010  | 12          | 428         | 940         | 3.92                        | 1.37 |
| 260      | 5             | 2.259  | 11          | 451         | 965         | 3.71                        | 1.18 |
| 280      | 4             | 2.499  | 10          | 471         | 986         | 3.52                        | 1.02 |
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