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Ecological Aspects and Methodology for Assessing the Forests of the Ural Floodplain

Mira Elekesheva [1,*], Vitaly Khlyustov [2] and Yerassyl Dulatbay [1]

[1] Agrotechnological Institute, Zhangir Khan West Kazakhstan Agrarian Technical University, 090009 Uralsk, Kazakhstan; eros.kz@wkau.kz
[2] Institute of Land Reclamation, A.N. Kostyakova Water Management and Construction, Russian State Agrarian University-Moscow Timiryazev Agricultural Academy, 127550 Moscow, Russia; khlyustov@rgau-msha.ru
* Correspondence: mira1989@wkau.kz; Tel.: +7-776-914-7271

Abstract: The floodplain forests in West Kazakhstan's Urals are challenging to study due to complex growth patterns. Existing tables estimate the trunk volume and wood size but lack comprehensive data for effective forest management. A developed research methodology focuses on creating growth and productivity models for forest-forming species across diverse forest types. Multidimensional linear growth models, with dummy variables for species and forest types, offer reliable insights into the average height and diameter changes at different ages. These models facilitate statistical analyses of asynchronous growth with high reliability. Three-level growth models detail regression lines for individual forest-forming species within specific forest types. This article illustrates the construction of a model for black poplar stands in a central floodplain's medium-level conditions. Furthermore, it highlights the potential for a regional planting classification based on average height gradients at the base age of stands. The presented methodology aims to address the challenges in forest management and forestry in the region.

Keywords: growth course; floodplain forests; forest vegetation formation; forest types; sedge plants; forest typological classes of average heights; models of growth course

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1. Introduction

The Ural River in its upper course is a natural water boundary between Asia and Europe. In the middle reaches, this is the border between the Russian Federation and the Republic of Kazakhstan. The southern part of the river flows through the territory of the Republic of Kazakhstan, flowing into the Caspian Sea. The total length of the Urals is 2530 km and the basin area is 220 thousand square kilometers. Forests along the river form a spatially organized system that supports the ecological stability of the territory, preserving biodiversity and preventing landscape degradation. The northern part of the river basin is characterized by the foothill landscapes of the Southern Urals on the territory of the Republic of Bashkortostan with the presence of coniferous and deciduous plantations. Then the river basin smoothly passes into the central part with plateaus, and then into the steppe zone of the Orenburg and West Kazakhstan regions. The forest fund in these regions within the river basin primarily consists of tree species that can withstand prolonged submersion during the spring high water. The development of forest ecosystems in such challenging environmental conditions has complicated the study of the productivity dynamics of stands with various species compositions according to groups of forest types. The absence of regional models, as well as tables of the growth and productivity of stands, did not allow us to justify optimal programs of selective logging in the floodplain forests of Kazakhstan. It became possible to solve this problem on the basis of a large number of trial plots with the number of trees by thickness classes, materials with the instrumental taxation of stands and new methods of statistical data analysis. The existing methods of modeling the growth of individual trees and stands are based on calculating the parameters of linear or nonlinear regression equations. In this case, the linear regression equations are obtained by the least-squares method. Nonlinear models are obtained by the method of the nonlinear estimation of the equation parameters with an initial approximation. An example of a linear regression equation is the three-parameter Korsun growth function. Examples of nonlinear growth models are the three- and five-parameter growth functions of Levakovich, [1]. It is known from modeling theory that only one predictor can be included in nonlinear growth models—this is age. The inclusion of several qualitative predictors in the nonlinear growth model along with age makes it much more difficult to obtain the parameters of the equation. In accordance with the above, the purpose of this study was formulated, which provided for the development of a methodology for the multidimensional modeling of growth indicators of stands by average height (H, m), average diameter (D, cm) and stock (M, m^3/ha), depending on the names of the forest-forming species and the names of the groups of forest types.

The research hypothesis of the study was to prove the possibility of obtaining a statistical model of the growth of stands depending on the qualitative characteristics of plantations representing several groups of forest types and several tree species over the entire range of changes in average heights and average diameters. An analytical review of publications on modeling the age dynamics of the taxation indicators of stands indicates the special interest of scientists in this topic. Since the 1980s and 1990s, large-scale studies have been conducted to improve forest taxation methods in a significant part of the USSR, including Kazakhstan. The reference books "All-Union reference books on forest taxation" have been published, Zagreev V.V. [2], and also "Reference books on the taxation of forests of Kazakhstan" [3]. In order to systematize all the varieties of growth curves of stands, it was proposed to streamline the age-related changes in taxation indicators, calling them standard growth lines. The first attempt to create unified growth scales was made by B.B. Zeide [4]. This work was continued by V.V. Zagreev [5] and his colleagues on the main forest-forming species of Russia [2]. For the first time, the mathematical analysis and systematization of linear and nonlinear growth models of the obtained unified growth-type scales were carried out by A.K. Keviste [6]. The interpretation of the parameters of nonlinear models of the growth of stands is given in the works of Yu.P. Demakov [7], A.Z. Shvidenko and co-authors [8], Yu.P. Demakov in co-authorship [9], Yu.P. Demakov and co-authors [10] and Yu.P. Demakov [11]. V.A. Usoltsev widely uses multidimensional regressions based on the Korsun function in modeling the growth of stands [12]. The possibility of the large-scale application of multidimensional linear growth models is shown by V.K. Khlyustov [13]. A.R. Weiskittel and co-authors have published a monograph describing the classification and methodology of modeling the growth of stands [14]. H.E. Burkhart and co-authors published a reference book on modeling the development of forest plantations [15]. Over the past decade, significant research has been conducted in the field of growth modeling theory. These are the works of H. Andrés [16], Nunifu, T.K. [17], Davidian, M. [18] and McCullagh, P. [19]. In accordance with the above classification [13], our proposed growth models belong to the class of linear statistical models.

At the end of the 20th century, forestry scientists were faced with two tasks. The first task was related to the development of growth models and the forecasting of current growth for specific stands in the same types of forest. Individual stands have different numbers of trees at the initial age of the stand (NA, pcs/ha). Consequently, with age, they show a different increase in their average height (H, m), average diameter (D, cm) and a decrease in the number of trees (pcs/ha). To solve this problem, the experimental material should be presented with data from periodic (after 5–10 years) measurements of trees at long-term experimental sites. This issue was successfully addressed by the research of V.K. Khlyustov [20], as well as by G.S. Razin, who studied and modeled the growth of artificial stands with various planting densities: Methodological recommendations. L.:

LenNIILH, 1977, 43 p. [21], G.S. Razin in co-authorship [22] and M.V. Rogozin in co-authorship [23].

The second task was related to the development of growth models for closed (normal) stands growing in various types of forest or groups of forest types. In the last decade, this field of research has become especially popular. The reason is that qualitative predictors can be included in statistical growth models along with age. Qualitative predictors can be represented by a list of groups of forest types with tree species growing in them. The experimental material can be represented by data from temporary test areas, as well as materials from a mass inventory of plantings. The presented article reveals methodological techniques for constructing models of the growth and productivity of stands of various tree species growing in different groups of forest types. Possible solutions to this problem are shown in the works of Y.P. Demakov [9,24]. New methodological solutions to this problem are shown by V.K. Khlyustov [25].

The development of stand growth models for forest-forming species requires the classification of plant growth conditions. In the conditions of the Ural floodplain with a rugged terrain, a detailed description of the landscapes and their accompanying elements of the hydrological network was required. The Kazakh Scientific Research Institute of Forestry and Agroforestry has developed a classification of groups of forest types for the corresponding forest formations. The author of the classification is a senior researcher at the Institute A.D. Tokarev [26]. The scheme of groups of forest types is described in detail in the publication by V.N. Biryukov [27].

2. Materials and Methods

2.1. Objects of Research

The objects of study were plantings of the main forest-forming species of floodplain forests of the river. The Urals are on the territory of the West Kazakhstan region. Figure 1 shows a geographical map of the Republic of Kazakhstan and fragments showing the borders of the West Kazakhstan region, the basin of the Ural River and the coastline of floodplain forests. The collection of field material was carried out in the Ural and Yanvartsevo state institutions for the protection of forests and wildlife in the region. The forest vegetation formation—sedge gardens—was adopted as the classification basis of forest objects. The formation was represented by groups of forest types confined to different parts of the river profile from its riverbed part to the upper levels of the floodplain. The following groups of forest types are covered by the research: High-level Black poplar stand near the riverbed (HLSG); Lowland Black poplar stand of the central floodplain (near oxbow) (LOSG); Middle-level Black poplar stand of the riverine floodplain (MLSG); and Middle-level Black poplar stand of the central floodplain (MLSCG). In each group of forest types, a list of tree species was defined, representing specific forest elements that were subject to full-scale taxation. To study age-related changes in the average heights and average diameters of forest elements in groups of forest types, an array of target-measurement inventory data was generated. The volume of taxation materials met the requirements of variation statistics. Thus, the accuracy of determining the average statistical values of the average height over five years falls within the range of ±2.5%/±6.5%, and the average diameter, respectively, ±3.0%/±7.0%, which indicates the reliability of the data for constructing age model changes.

Figure 1. Geographical Placement of Research Objects in the Ural River Basin.

2.2. Research Methodology

Field research consisted of establishing 135 trial plots in accordance with the requirements of the industry standard OST 56-69-83 "Test forest management areas. Establishment methods." The sizes of the trial plots varied depending on the distribution of trees across the area. The collection of primary forest taxation data was carried out in a landscape-oriented group of forest types of the forest vegetation formation, *Osokorniki*, relative to the river bed. Primary information was collected by conducting a complete count of trees with an accuracy of measuring trunk diameters up to 0,1 cm. In total, 27,231 changes in diameter and 1282 changes in tree height were made. In the sample plots, the plantings were represented, as a rule, by mixed stands with a predominance of black poplar (*Populus nigra*) and accompanying species—white poplar (*Populus alba*), white willow (*Salix alba*) and smooth elm (*Ulmus laevis*). Additionally, the analysis included data from 3204 sections of targeted and measuring forest stand inventory. A statistical analysis of field materials was carried out on MS Excel using the multiple regression method, combining the Korsun–Bakman growth function and predictors encoding the names of groups of forest types and the names of tree species according to the method of Draper and Smith [28]. The distribution of forest plots and trial areas with a complete list of trees by groups of forest types is shown in Table 1. A total of 23,046 changes in tree diameter and 929 changes in tree height were recorded. In the experimental plots, stands were generally mixed stands dominated by black poplar (Populus nigra) and associated species such as white poplar (Populus alba), white willow (Salix alba) and smooth elm (Ulmus laevis). In addition, data from 2352 forest plots where an instrumental stand inventory was conducted were included in the analysis.

Table 1. The number of objects for conducting statistical data analysis.

Forest Vegetation Formation	A Group of Forest Types	Plantings for Measuring Taxation, Units	Number of Test Areas, Units	Trees Measured, Pieces	
				Diameter	Height
Black poplars (the popular name *Osokorniki*)	HLSG—high level near the riverbed	50	-	-	-
	LOSG—the low level of the area near the central floodplain	434	8	1809	53
	MLSG—the average level near the riverbed in the floodplain	1281	47	11,109	648
	MLSCG—the average level of the central floodplain	587	48	10,128	228
	Total	2352	103	23,046	929

First of all, to model the growth and productivity of the stands, the variability of the average heights and average diameters (V, %) in the age of the stands from 10 to 60 years was estimated, as well as the accuracy of their determination (±P, %) by groups of forest types.

2.3. Matrix for Obtaining a Species-Forest Typological Model of Growth Progress

To develop a species-forest typological model of the growth of the average statistical indicators of the average height and average diameter of forest stands, a matrix of binary variables was compiled that encodes landscape-typological groups of forest conditions and the entire variety of tree species growing in a particular formation (Table 2). In our case, these are the names of 4 groups of forest types and 4 forest-forming species. To ensure the informativeness of qualitative predictors, it is necessary to follow point No. 2 and fill in the matrix of binary variables. To do this, qualitative predictors are encoded by dummy variables, assigning them the value "1". The colored cells of the matrix indicate to the reader the spatial distribution of fictitious variables encoding groups of forest types (Xi) and forest-forming species (Zi).

Table 2. Coding matrix for groups of forest types and tree species of forest vegetation formation—black poplar stand.

Forest Type Group (Xi)	Tree Species	False Block Variables					
		X_1	X_2	X_3	Z_1	Z_2	Z_3
High-level Black poplar stand near the riverbed (HLSG)	*Ulmus laevis*	0	0	0	0	0	0
	Salix alba (Z_1)	0	0	0	1	0	0
	Populus alba (Z_2)	0	0	0	0	1	0
	Populus nigra (Z_3)	0	0	0	0	0	1
Lowland Black poplar stand of the central floodplain (near oxbow) (LOSG) (X_1)	*Ulmus laevis*	1	0	0	0	0	0
	Salix alba (Z_1)	1	0	0	1	0	0
	Populus alba (Z_2)	1	0	0	0	1	0
	Populus nigra (Z_3)	1	0	0	0	0	1
Middle-level Black poplar stand of the riverine floodplain (MLSG) (X_2)	*Ulmus laevis*	0	1	0	0	0	0
	Salix alba (Z_1)	0	1	0	1	0	0
	Populus alba (Z_2)	0	1	0	0	1	0
	Populus nigra (Z_3)	0	1	0	0	0	1
Middle-level Black poplar stand of the central floodplain (ОСЦ) (X_3)	*Ulmus laevis*	0	0	1	0	0	0
	Salix alba (Z_1)	0	0	1	1	0	0
	Populus alba (Z_2)	0	0	1	0	1	0
	Populus nigra (Z_3)	0	0	1	0	0	1

The modeling of age-related changes in statistical average heights and diameters was carried out using the Korsun–Bakman growth function:

$$H_{av}^{av}, D_{av}^{av} = exp(a_0 + a_1 lnA + a_2 \ln^2 A) \quad (1)$$

Combining the growth function with dummy variables coding forest type groups (X) and tree species (Z) gave the regression model the following general form:

$$H_{\text{cp}}^{\text{cp}}, D_{\text{cp}}^{\text{cp}} = \exp\left(\sum_{k=0}^{2} ln^k A \left(a_k + \sum_{i=1}^{n} b_{k,i} X_i + \sum_{j=1}^{m} c_{k,j} Z_j\right)\right) \quad (2)$$

where:

$H_{\text{cp}}^{\text{cp}}$, $D_{\text{cp}}^{\text{cp}}$—average height (m), average diameter (cm) of tree species;
A—age of the forest stand, years;
X, Z—dummy variables coding groups of forest types and tree species;
a, b, c—model parameters;
k, i, j—indices.

2.4. Matrix for a Three-Level Growth Model

At the next stage, the range of variation in $H_{(average)}$ and $D_{(average)}$ was included in three-level models of the growth course of these morphometric indicators. Models of growth progress include the entire complex of landscape-typological forest vegetation formations of the floodplain: 4 groups of forest types, 3 levels of productivity and 3 names of tree species. The coding matrix of the variables included in the model is presented in Table 3. The different colors in the table are explained by the fact that the models were built on the basis of a matrix of block binary variables encoding three levels of average heights (H_I–H_{III}) and average diameters (D_I–D_{III}), (X_i), four groups of forest types, (Z_i), and three tree species, (F_i).

Table 3. Matrix for coding productivity levels, groups of forest types and tree species of the forest vegetation formation—black poplars.

Productivity Level (X_i)	Forest-Type Group (Z_i)	Tree Species (F_i)	False Block Variables						
			X_1	X_2	Z_1	Z_2	Z_3	F_1	F_2
Level I—higher	HLSG	WW	0	0	0	0	0	0	0
		WP (F_1)	0	0	0	0	0	1	0
		BP (F_2)	0	0	0	0	0	0	1
	LOSG (Z_1)	WW	0	0	1	0	0	0	0
		WP (F_1)	0	0	1	0	0	1	0
		BP (F_2)	0	0	1	0	0	0	1
	MLSG (Z_2)	WW	0	0	0	1	0	0	0
		WP (F_1)	0	0	0	1	0	1	0
		BP (F_2)	0	0	0	1	0	0	1
	MLSCG (Z_3)	WW	0	0	0	0	1	0	0
		WP (F_1)	0	0	0	0	1	1	0
		BP (F_2)	0	0	0	0	1	0	1
Level II—middle (X_1)	HLSG	WW	1	0	0	0	0	0	0
		WP (F_1)	1	0	0	0	0	1	0
		BP (F_2)	1	0	0	0	0	0	1
	LOSG (Z_1)	WW	1	0	1	0	0	0	0
		WP (F_1)	1	0	1	0	0	1	0
		BP (F_2)	1	0	1	0	0	0	1
	MLSG (Z_2)	WW	1	0	0	1	0	0	0
		WP (F_1)	1	0	0	1	0	1	0

		BP (F_2)	1	0	0	1	0	0	1
	MLSCG (Z_3)	WW	1	0	0	0	1	0	0
		WP (F_1)	1	0	0	0	1	1	0
		BP (F_2)	1	0	0	0	1	0	1
Level III—lower (X_2)	HLSG	WW	0	1	0	0	0	0	0
		WP (F_1)	0	1	0	0	0	1	0
		BP (F_2)	0	1	0	0	0	0	1
	LOSG (Z_1)	WW	0	1	1	0	0	0	0
		WP (F_1)	0	1	1	0	0	1	0
		BP (F_2)	0	1	1	0	0	0	1
	MLSG (Z_2)	WW	0	1	0	1	0	0	0
		WP (F_1)	0	1	0	1	0	1	0
		BP (F_2)	0	1	0	1	0	0	1
	MLSCG (Z_3)	WW	0	1	0	0	1	0	0
		WP (F_1)	0	1	0	0	1	1	0
		BP (F_2)	0	1	0	0	1	0	1

The combination of Equations (4) and (5) with Equations (7)–(11) made it possible to obtain data for constructing three-level species-forest typological models of age-related changes in the average heights and average diameters of tree stands in the entire range of their variation. The construction of the models was carried out on the basis of a matrix of binary variables encoding three levels of average heights (HI–HIII) and average diameters (DI–DIII),(X_i), four groups of forest types,(Z_i), and three tree species, (F_i) (Table 3).

2.5. Matrix of Binary Variables to Model the Extreme Values of Mean Heights and Diameters

The second objective of this study included the development of a three-level species-forest typological model of growth progress according to the average height and average diameter of dendrocenosis elements. A matrix of binary variables was used to model the extreme values of mean heights and diameters (Table 4).

Table 4. Matrix of binary variables coding tree species in models of limiting values of average heights and diameters of tree stands.

Tree Species	False Block Variables		
Ulmus laevis	0	0	0
Salix alba	1	0	0
Populus alba	0	1	0
Populus nigra	0	0	1

The regression model of the range of variation in the average heights of tree stands from the average statistical values for the data array for the coded forest-forming species is represented by a general expression:

$$H_{\min}^{cp}, H_{\max}^{cp} = \exp\left(a_0 + a_1 lnH_{cp}^{cp} + lnH_{cp}^{cp}\left(\sum_{i=1}^{n} b_i X_i\right)\right) \quad (3)$$

where:

$H_{\min}^{cp}, H_{\max}^{cp}$—minimum and maximum values of average heights of constituent tree species, m;

H_{cp}^{cp}—statistical average value of average height of tree stands, m;

X_i—coded tree species.

2.6. Selection of a Forest Typological Model for Differentiating the Course of Growth by Classes of Average Heights (H_{30})

The solution to the third problem was to develop a forest typological model of the growth of forest stands according to classes of average heights (H_{30}) using the example of black poplar (*Populus nigra*) growing in sedge forests at the middle levels of the central floodplain (MLSCG). The data for constructing regressions of forest typological classes of average heights were the tabulated values of the three-level species-forest typology model of average heights (12), corresponding to the group of forest types—the black poplar stand average levels of the central floodplain.

3. Results

3.1. Measuring Results of Tree Heights and Diameters

The change in the coefficient of variation and the accuracy of determining average heights and diameters with increasing age is shown in Figures 2–5. The empirical and theoretical (according to the equation) lines shown in the figures indicate a natural decrease in the coefficient of variation and an increase in the accuracy of determining the average heights and diameters of the black poplar with the age of stands in different groups of forest types. Judging by the figures, the variability of the average height in the range from young to ripe stands has halved from 32% to 17%. At the same time, the accuracy of determining the average statistical indicators of average heights increased from ± 6.5 to ± 2.5%. A similar pattern is observed when analyzing the variability of the average diameter of the stands. There is a decrease in the variability between the ages of 10 and 60 years from 40% to 16% with an increase in the accuracy of determining the average value from ± 7% to ± 3%. The statistical parameters of the taxational indicators of stands in the entire data set should be considered sufficiently reliable to characterize a specific forest formation by groups of forest types. Thus, it became possible to use data from experimental plots and instrumental taxation to develop growth models of the average heights and diameters of stands growing in various groups of forest types.

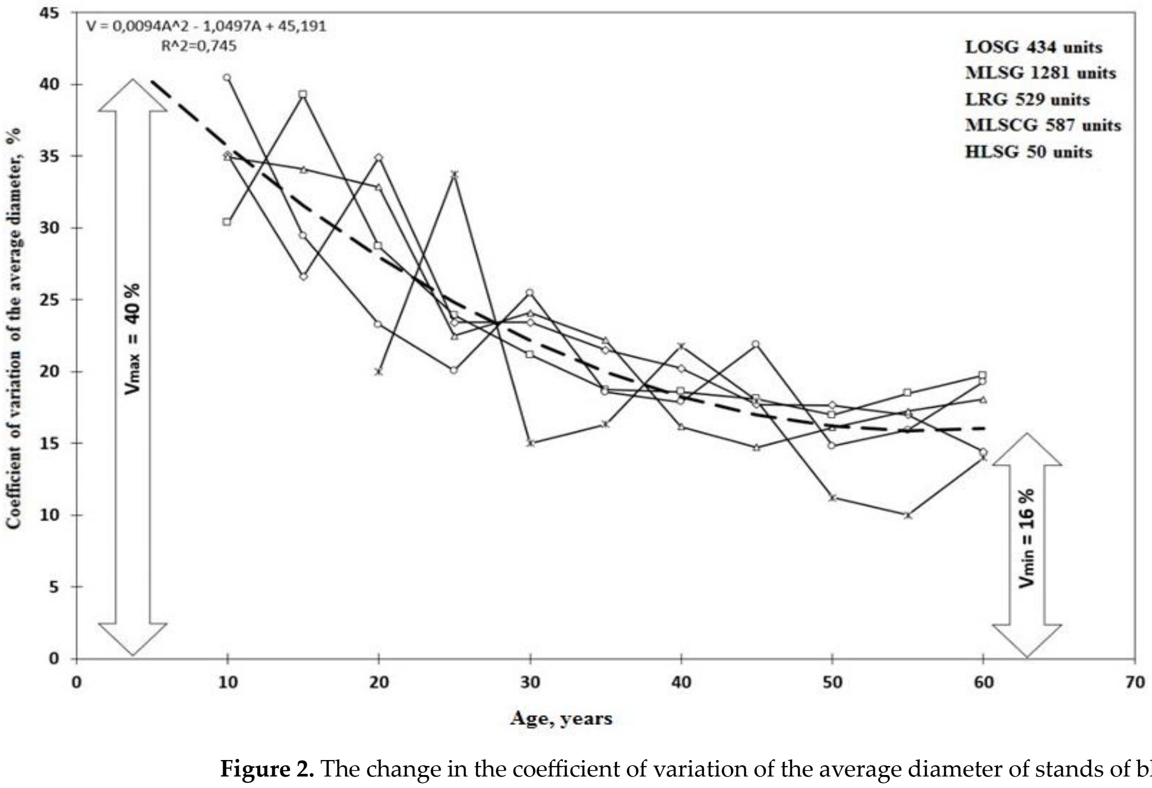

Figure 2. The change in the coefficient of variation of the average diameter of stands of black poplar with age by groups of forest types.

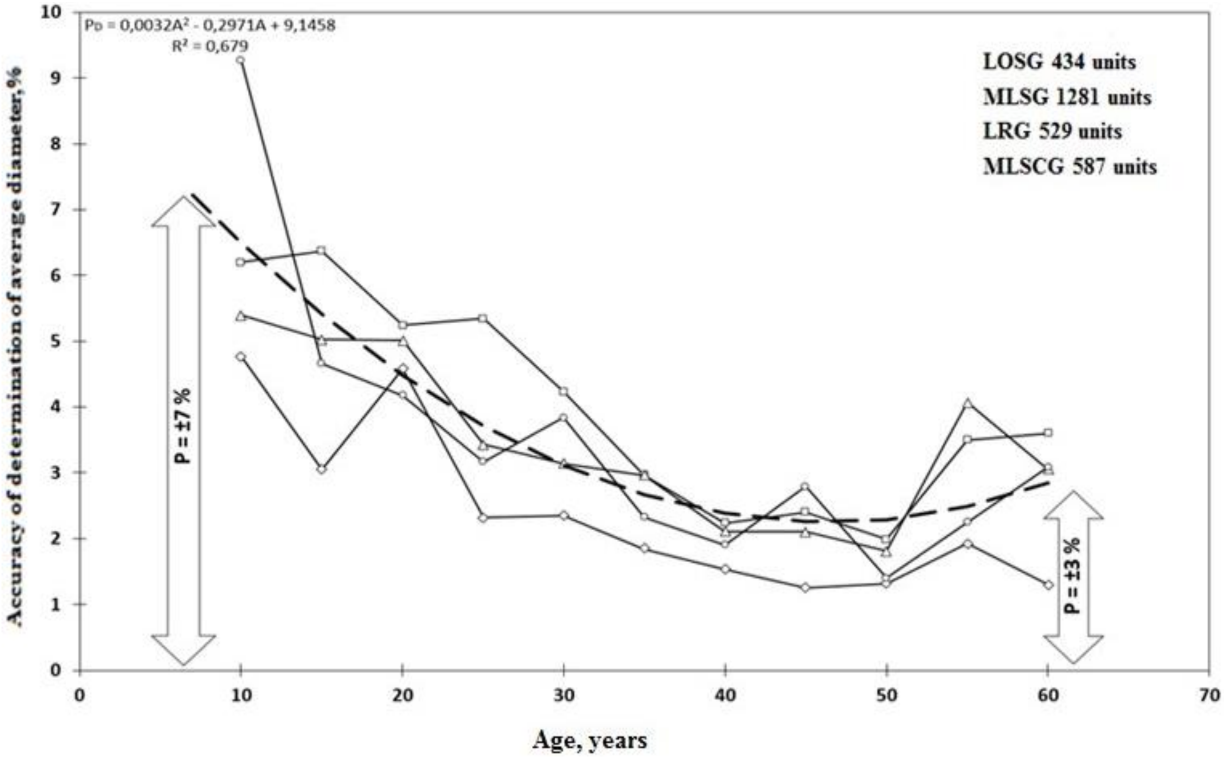

Figure 3. The change in the accuracy of determining the average diameter with the age of stands of black poplar by groups of forest types.

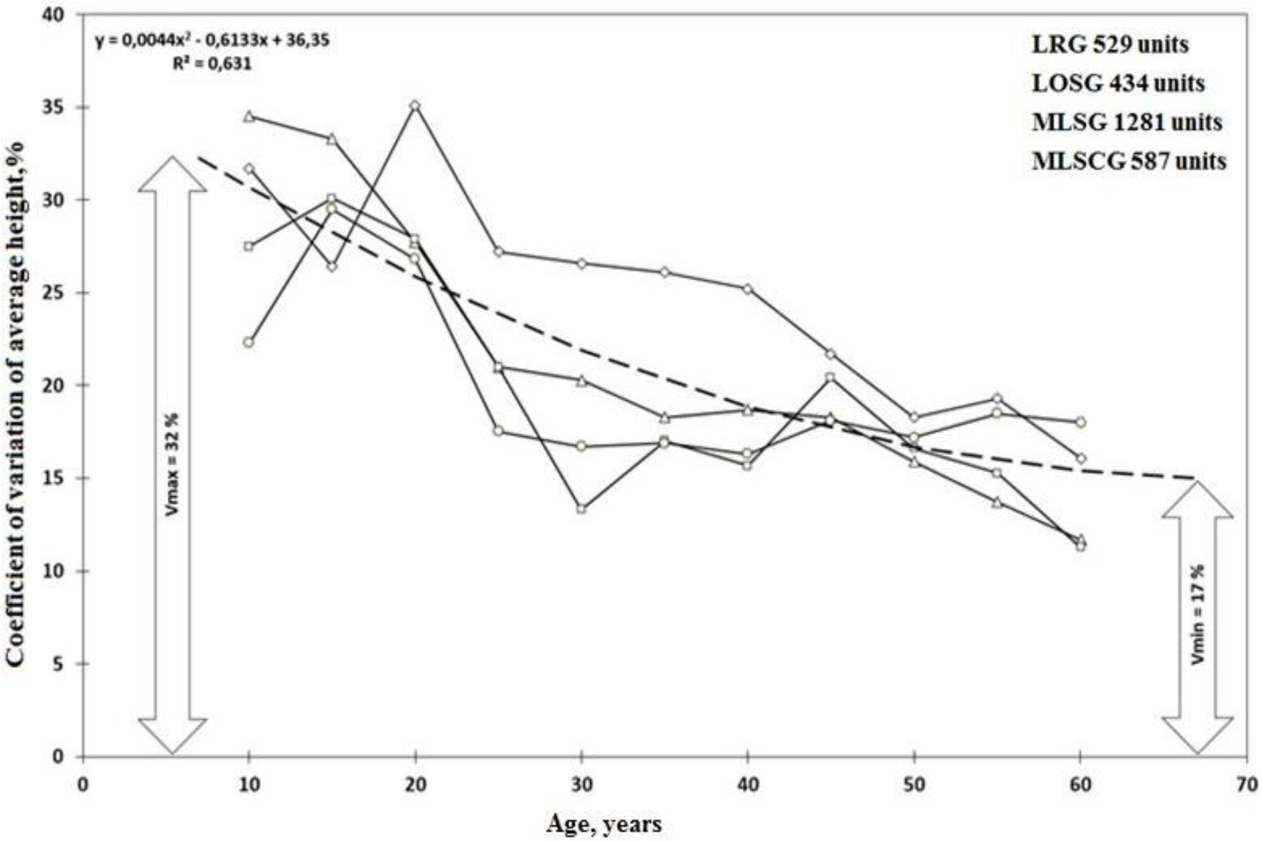

Figure 4. The change in the coefficient of variation of the average height of stands with the age of black poplar by groups of forest types.

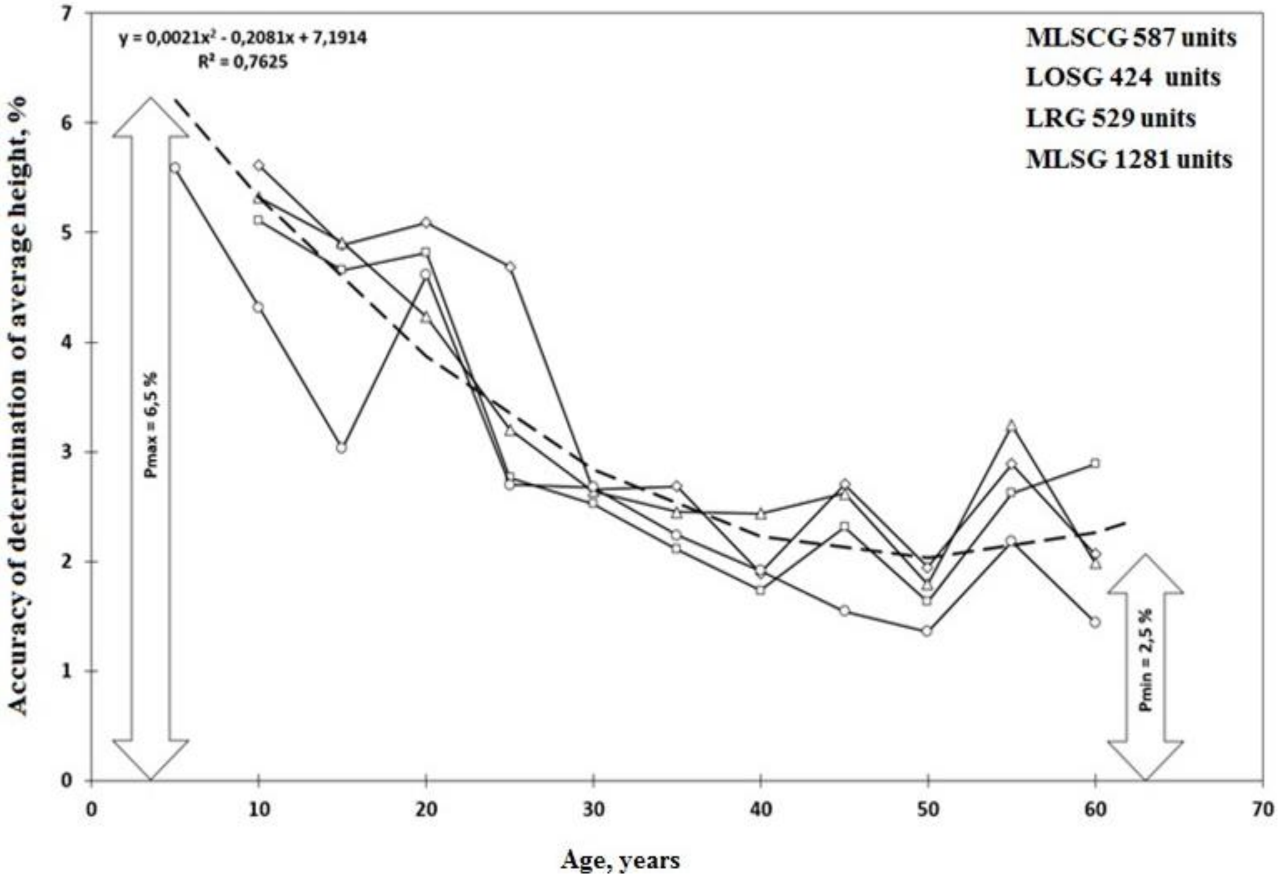

Figure 5. The change in the accuracy of determining the average height of stands with the age of black poplar by groups of forest types.

3.2. Species and Forest Typological Models of the Growth of Forest Stands

The final regression models look like this:

$$H_{sr}^{sr} = exp(-1.93563 + 1.62630 lnA - 0.11616\, ln^2 A + lnA(0.01928X_1 + 0.1393X_2 + 0.00805X_3) + ln^2 A(-0.00684X_1 - 0.04022X_2 - 0.00374X_3) + lnA(0.41436Z_1 + 0.53407Z_2 + 0.47131Z_3) + ln^2 A(-0.08784Z_1 - 0.11224Z_2 - 0.09995Z_3)) \quad (4)$$

$$R^2 = 0.983;\ ES \pm 6.3\%;\ t_{\text{cal}} > t_{05} = 1.96.$$

$$D_{sr}^{sr} = exp(-2.02555 + 1.73997 lnA - 0.11685\, ln^2 A + lnA(0.12332X_1 - 0.00696X_2 + 0.10079X_3) + ln^2 A(-0.03324X_1 + 0.00073X_2 - 0.02495X_3) + lnA(0.19099Z_1 + 0.23436Z_2 + 0.25165Z_3) + ln^2 A(-0.02363Z_1 - 0.03075Z_2 - 0.03795Z_3)) \quad (5)$$

$$R^2 = 0.990;\ ES = \pm 6.8\%;\ t_{\text{cal}} > t_{05} = 1.96.$$

The obtained values of the coefficients of determination (R^2 = 0.983–0.990) and other statistical parameters of the equations indicate the high reliability of the models. Averaged by species and by groups of forest types, the regression lines for the growth of the average heights and average diameters of forest stands are shown in Figures 6 and 7.

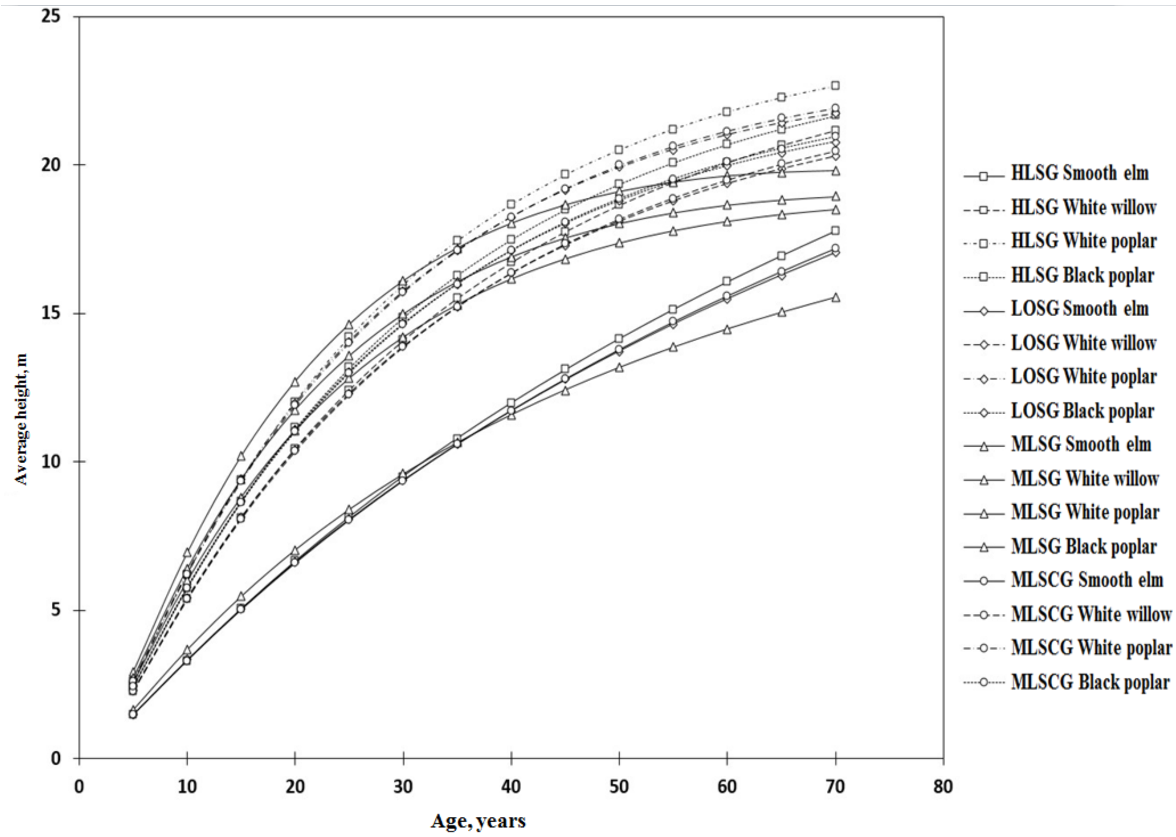

Figure 6. Changes with age in the averaged average height.

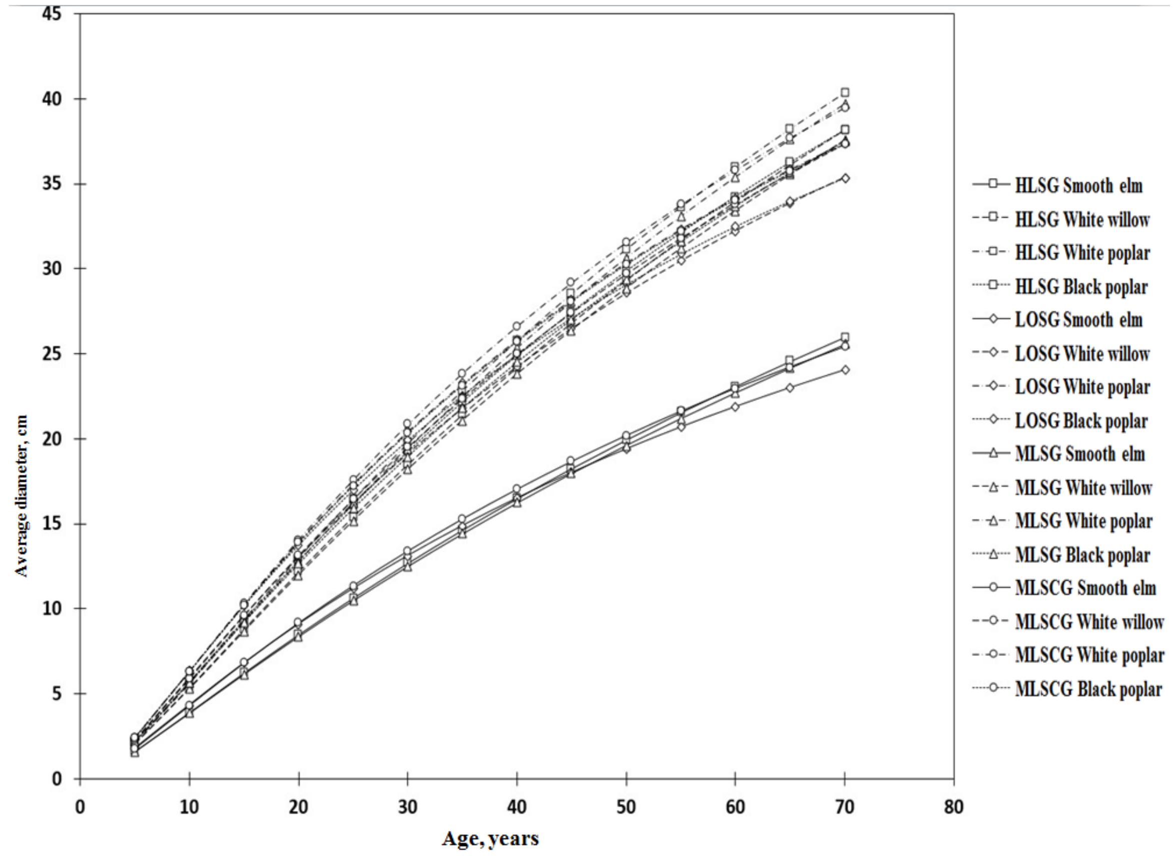

Figure 7. Changes with age in the average diameter (bottom) of forest-forming species of tree stands by groups of forest types.

The regression lines related to smooth elm are significantly lower than those of other forest-forming species, regardless of the group of forest types. The low ecological resistance of this tree species to pathogenic diseases and insect pests significantly worsens the sanitary condition of trees, which must first be cut down when caring for plantings.

To determine the range of variation in average heights, Equation (6) was obtained, and to determine the range of the average diameters, Equations (10) and (11) were used.

$$H_{\min}^{cp} = \exp\left(-0.8883 + 1.21605 lnH_{cp}^{cp} + lnH_{cp}^{cp}(-0.07897X_1 - 0.25315X_2 - 0.14635X_3\right) \quad (6)$$

$R^2 = 0.870$; ES = ±22.0%; t > t05 = 1.96; F = 63.5 when $p < 0.05$

$$H_{max}^{cp} = \exp\left(1.06077 + 0.68393 lnH_{cp}^{cp} + lnH_{cp}^{cp}\left(0.09182X_1 + 0.11500X_2 + +0.11904X_3\right)\right) \quad (7)$$

$R^2 = 0.954$; ES = ±10.0; t > t05 = 1.96; F = 199.3 when $p < 0.05$

The regression model of the range of variation in the average diameters of tree stands for the coded forest-forming species is represented by a general expression:

$$D_{\min}^{cp}, D_{max}^{cp} = \exp\left(a_0 + a_1 lnD_{cp}^{cp} + lnD_{cp}^{cp}\left(\sum_{i=1}^{n} b_i X_i\right)\right) \quad (8)$$

where:

$D_{\min}^{cp}, D_{max}^{cp}$—minimum and maximum values of average diameters of tree stands of constituent tree species, cm;

D_{cp}^{cp}—statistical average value of the average diameter of tree stands, cm.

$$D_{\min}^{cp} = \exp\left(-1.38969 + 1.3666 lnD_{cp}^{cp} + lnD_{cp}^{cp}(-0.09540X_1 - 0.16327X_2 - 0.15484X_3\right) \quad (9)$$

$R^2 = 0.946$; $ES = \pm 21.0\%$; $t > t_{05} = 1.96$; $F = 172.3$ when $p < 0.05$

$$D_{max}^{cp} = \exp\left(1.01252 + 0.74166 lnD_{cp}^{cp} + lnD_{cp}^{cp}(0.10983X_1 + 0.11872X_2 + +0.10846X_3\right) \quad (10)$$

$R^2 = 0.977$; $ES = \pm 9.0\%$; $t > t_{05} = 1.96$; $F = 411.5$ when $p < 0.05$

The statistical parameters of the equations indicate a high degree of reliability of the maximum values of the average heights and diameters obtained from them.

3.3. Three-Level Models of Forest Growth Progress

Thus, three-level species-forest typological models of growth progress in terms of the average height (12) and average diameter (13) of tree stands are represented by regressions of the form:

$$\begin{aligned} H_{sr} = \exp(&-0.49901 + 1.37916 lnA - 0.02418 \ln^3 A + lnA(-1.08091X_1 - 2.06770X_2) \\ &+ \ln^2 A(0.45443X_1 + 0.82467X_2) + \ln^3 A(-0.05289X_1 - 0.09499X_2) \\ &+ lnA(0.14381Z_1 + 0.25777Z_2 \\ &+ 0.13315Z_3) + \ln^2 A(-0.08487Z_1 - 0.11657Z_2 - 0.08193Z_3) \\ &+ \ln^3 A(0.01177Z_1 + +0.01177Z_2 + 0.01177Z_3) \\ &+ lnA(+0.20737F_1 + 0.14947F_2) + \ln^2 A(-0.10770F_1 - 0.07742F_2) \\ &+ \ln^3 A(0.01294F_1 + 0.009918F_2)) \end{aligned} \quad (11)$$

$R^2 = 0.984$; $ES = \pm 9.0\%$; $t > t_{05} = 1.96$; $F = 1268.6$ when $p < 0.05$

$$\begin{aligned} D_{sr} = exp(&-0.86401 + 1.52981 lnA - 0.01960 \ln^3 A + lnA(-1.05469X_1 - 2.64443X_2) + \\ &\ln^2 A(+0.41629X_1 + 1.08970X_2) + \ln^3 A(-0.04596X_1 - 0.12416X_2) + lnA(0.25823Z_1 + 0.12435Z_2 + \\ &0.23508Z_3) + \ln^2 A(-0.11628Z_1 - 0.08138Z_2 - 0.10777Z_3) + \ln^3 A(0.01233Z_1 + 0.01233Z_2 + 0.01233Z_3) + \\ &lnA(+0.14797F_1 + 0.16575F_2) + \ln^2 A(-0.08109F_1 - 0.08880F_2) + \ln^3 A(0.01093F_1 + 0.01098F_2)) \end{aligned} \quad (12)$$

$R^2 = 0.997$; $ES = \pm 5.5\%$; $t > t_{05} = 1.96$; $F = 6679.9$ when $p < 0.05$

A graphical interpretation of the three-level models clearly shows the discrepancy in the growth rates of tree species both among themselves and in groups of forest types for each level of the average heights and diameters of the tree stands (Figures 8 and 9). Each level shows how productive different tree species are in different types of growing conditions.

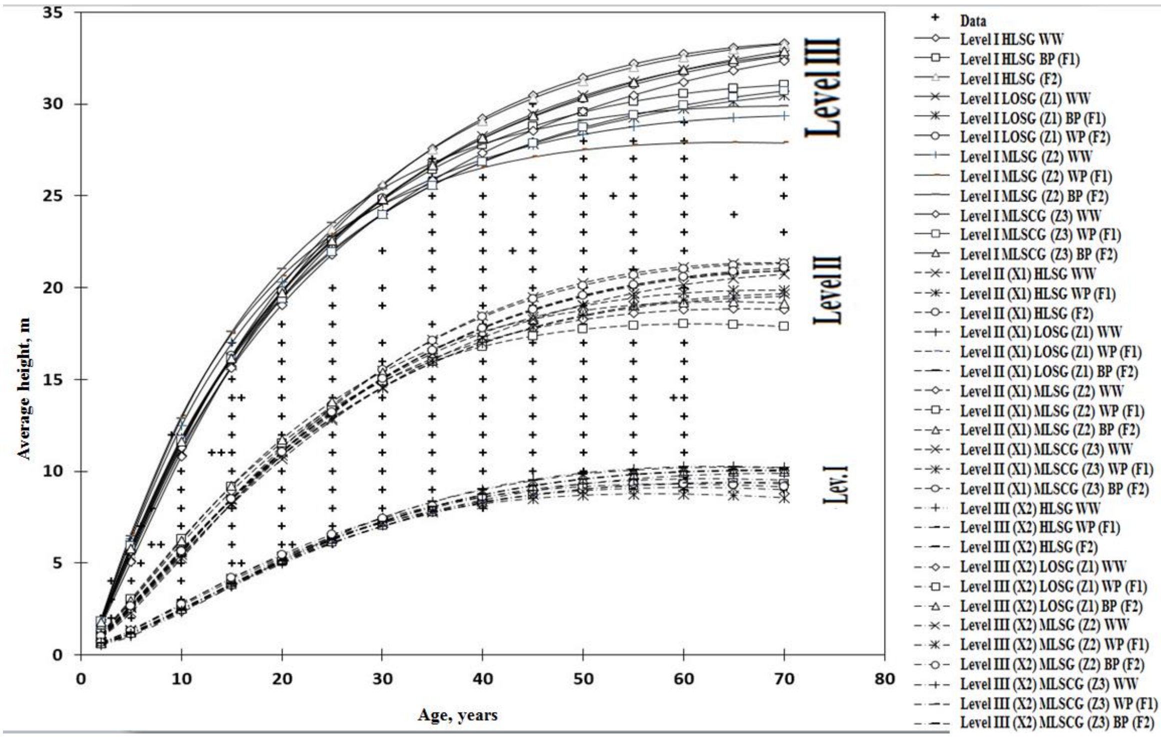

Figure 8. Changes with age in three levels of average height of three tree species in four forest-type groups.

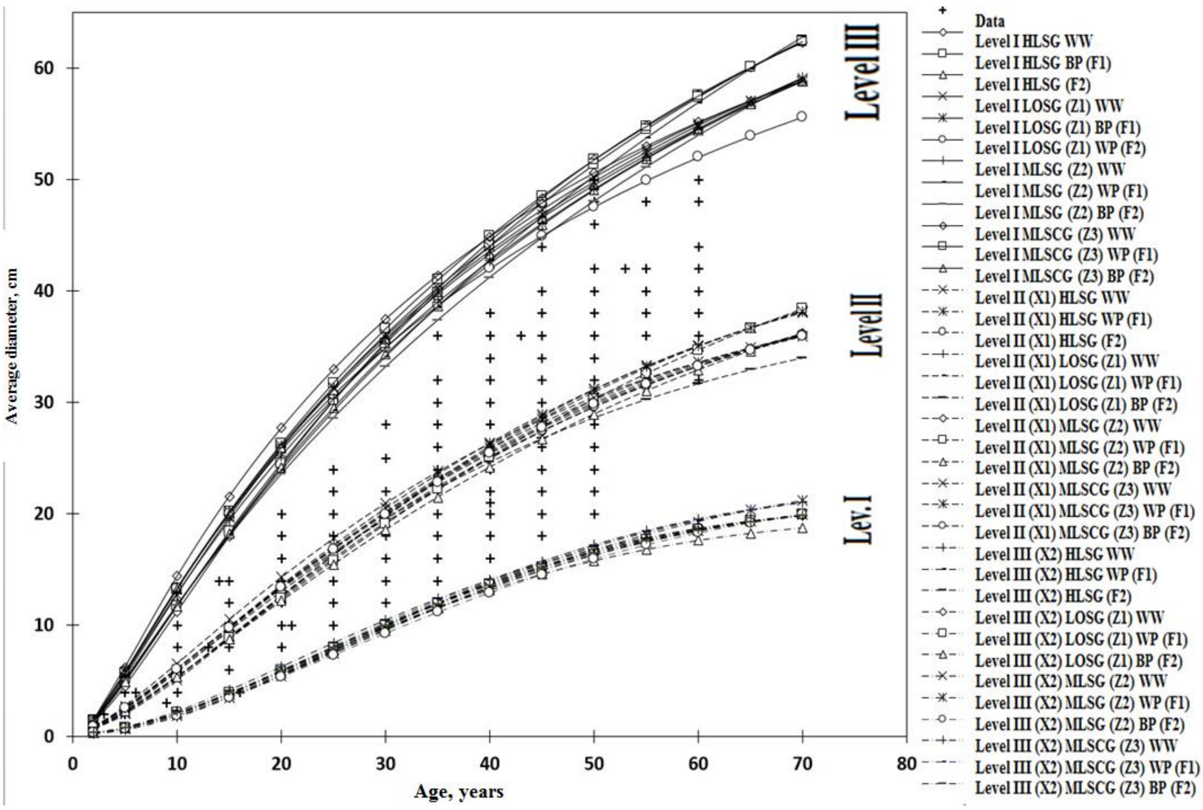

Figure 9. Changes with age in three levels of average diameter of three tree species in four forest-type groups.

A graphical interpretation of the three-level models of age-related changes in average heights and average diameters clearly shows the discrepancy in the growth rates of tree species both among themselves and in groups of forest types for each level of the average heights and diameters of tree stands. A graphic comparison of the actual and theoretical values of average heights and a presentation of the multidimensional patterns of changes in the average height of forest stands allows us to compare the obtained growth curves with the general grading scale related to tree species of rapid growth (poplar, white willow and white acacia), RSRIFFM [2].

3.4. Forest Typological Models of the Growth of Forest Stands by Classes of Average Heights (H30)

Thus, the model of the relationship between the average height of black poplar stands and age for a conditionally given gradation of average height levels at the base age of 30 years is represented by a regression equation of the form:

$$H_{\text{cp}} = exp(-0.49901 + 0.44530 lnA - 0.08061\, ln^2 A - 0.00211\, ln^3 A - -1.73172 lnAlnH_{30} + 0.65722 lnAln^2 H_{30} + 1.02238\, ln^2 AlnH_{30} - -0.32601\, ln^2 Aln^2 H_{30} - 0.12548\, ln^3 AlnH_{30} + 0.03904\, ln^3 Aln^2 H_{30}) \quad (13)$$

$$R^2 = 1.0$$

The functionally derived model of average heights (14) with a given gradation of 1 m at 30 years of age is shown in Figure 10. Along with forest typological curves of classes of average heights, the figure shows curves corresponding to the RSRIFFM bonitet scale [2] for tree species of rapid growth (poplar, white willow and white acacia). Bonitet characterizes the growth and potential productivity of plantings of a certain species, age and height for given growing conditions. A comparison of the regression lines with the curves of average heights constructed according to the data of the quality scale indicates the possibility of using the quality scale only in the highest-quality classes. From the figure, you can see that the forest typological curves of the middle height classes coincide with the quality scales Ib, I and III and the quality scale can only be used in the highest quality classes.

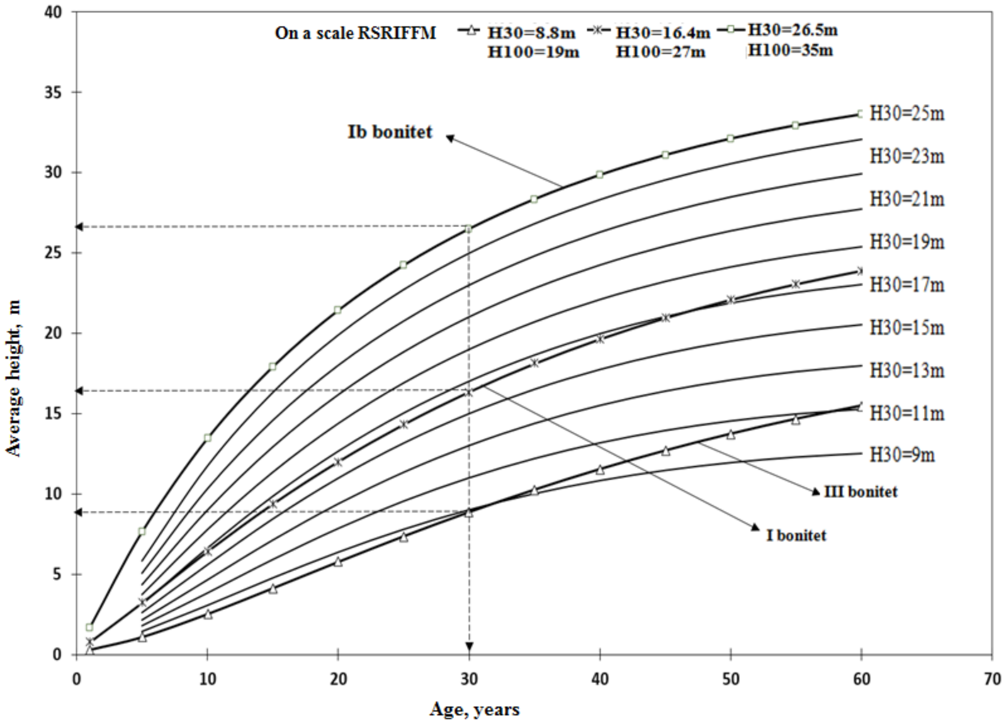

Figure 10. Changes with age in the average height of black poplar stands by average height classes in the MLSCG group of forest types.

In the floodplain of the Ural River, there were mainly plantations of average productivity levels at which the values of the quality scale do not coincide with the forest typological curves of classes of average heights (H_{30}). The relationship between the productivity of forest elements and their average height is well known. The final indicators of forest stand productivity were the available stock and the stock of dying trees, which together characterize the overall productivity (productivity). The stock of available forest stands (M, m^3/ha) is determined, as a rule, by three indicators: the average height (H, m), relative completeness (C), and the share of the tree species in the forest stand (Ds). Graphically, the age-related change in the stock of pure-composition, closed stands of black poplar in the group of forest types characterizing the sedge forests of the middle levels of the central floodplain is shown in Figures 11 and 12. The inventory regression equation obtained in the data of standard tables has the form:

$$M = \exp(-0.39351 + 1.16608 lnH + 0.0399 \ln^2 H + 0.9999 lnC + +0.9999 lnD_s) \quad (14)$$

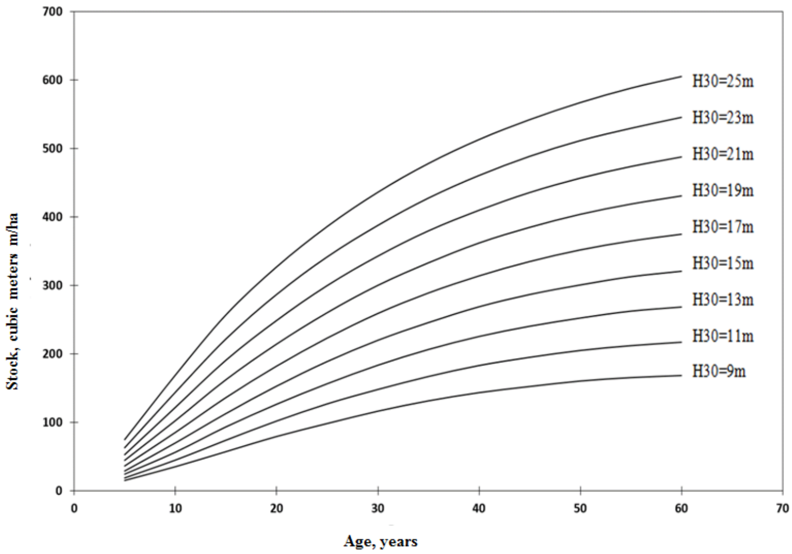

Figure 11. Changes with age in the stock (top) of pure, closed stands of black poplar by average height classes (H_{30}) in the MLSCG group of forest types.

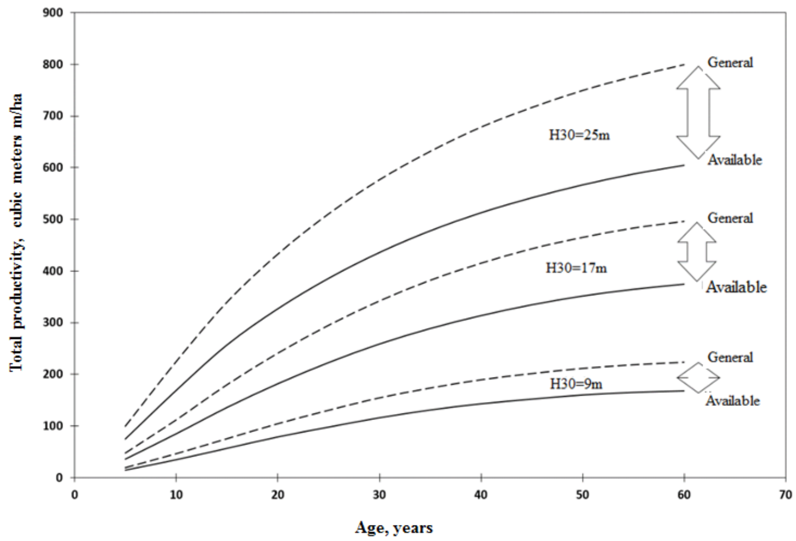

Figure 12. Changes with age in the total productivity (bottom) of pure, closed stands of black poplar by average height classes (H30) in the MLSCG group of forest types.

The maximum potential and theoretically calculated productivity of fully mature black poplar stands at the age of cutting when H_{30} = 25 m can reach 500 cubic meters per hectare. To transition from available stock to total productivity, a direct reduction coefficient (1.3215), derived from the work of A.Z. Shvidenko and others [8], was used. This coefficient allows for an approximate relationship between the total productivity of the stand, considering decay, and the stock of the full stand according to the equation: MOP = 1.3215×M. Figure 12 (bottom) shows a comparison of graphs of changes in the stock and total productivity of pure and maximally full black poplar stands. Figure 13 (top) shows the culminating curves of the current and average change in the stock of full plantations, as well as the age of quantitative maturity corresponding to the intersection of the curves for the maximum (H_{30} = 25 m) and minimum (H_{30} = 9 m) class of the average height of stands, respectively, at 17 and 27 years. The curves of the total current increase in stock for the same classes of average heights are shown in Figures 13 and 14. With a class of average heights H_{30}= 25 m at the age of the culmination of the current growth—10 years—the maximum annual productivity of closed tree stands can reach 25 cubic meters, m/ha, and the minimum at H_{30} = 9 m at the age of 15 years is 6 cubic meters, m/ha.

The presented methodological solutions and the obtained results of modeling the course of growth of tree stands using the example of floodplain forests of the Urals made it possible to significantly supplement the theory of the course of growth with new results that take into account the diversity of environmental conditions, the species and the spatial structure of plantings. The resulting models and new normative and reference materials on growth and productivity indicators allow us to continue scientific and practical work on optimizing the use of wood when caring for forests, ensuring its environmental sustainability. To date, forestry organizations and scientists of our region are raising the problem of the state of the floodplain forests of the Ural River and are trying to find solutions to it.

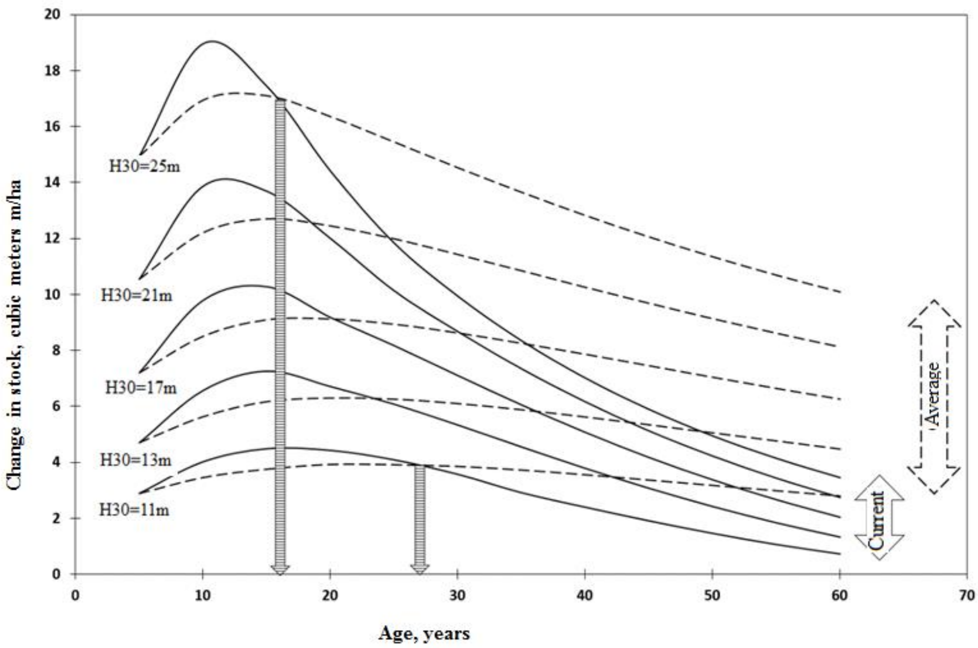

Figure 13. Age dependency of current and average changes in stock of fully mature black poplar stands, with a mention of the age of quantitative maturity.

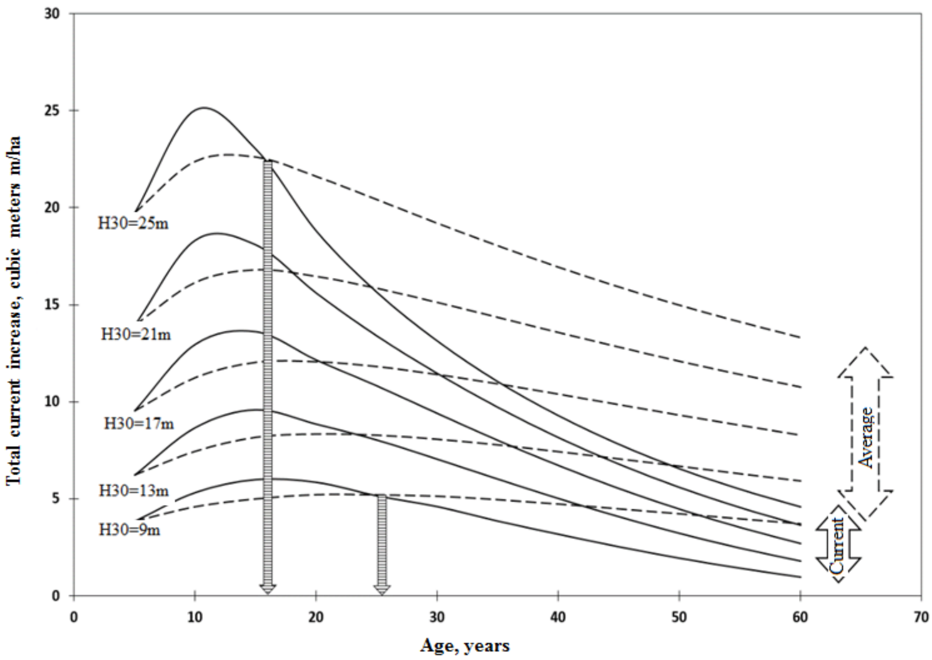

Figure 14. Age dependency of total current growth and average change in stock, considering decay, of fully mature black poplar stands, indicating the age of quantitative maturity.

4. Discussion

The modeling of growth patterns of the whole diversity of forest-forming species of stands in landscape-ecological groups of forest types of the Ural River floodplain is an urgent theoretical and practical task facing foresters of the Republic of Kazakhstan.

The analytical review of the literature sources allowed us to note the increasing interest to the problem of modeling the growth and productivity of forest plantations due to the introduction of modern computer technologies and data analysis methods into the scientific process. According to the accepted classification and methodology of statistical modeling [13], growth models are divided into a class of linear models obtained by the least-squares method and nonlinear models obtained by the nonlinear estimation of the equation parameters. Of particular interest are statistical methods of multivariate modeling using regression analysis, including independent predictors along with numerical values of qualitative variables. It is most appropriate to obtain a multivariate least-squares regression of growth by combining the combination of stand age with qualitative predictors expressed by dummy variables such as the names of forest-forming species and the names of the forest-type groups. In this case, it was necessary to form the structure of regression models of a linear type, allowing to display the dependence of the morphometric indices of growth on the whole complex of quantitative and qualitative variables.

This article details the methodology for the development of growth models of forest-forming species of stands growing in the conditions of groups of forest types, representing the forest formation dominated by black poplar—black poplars (folk name Osokorniki). Forest-forming rocks for building growth models were represented by smooth elm (Ulmus laevis), white willow (Salix alba), white poplar (Populus alba) and black poplar (Populus nigra). In accordance with the objective and working hypothesis, the methodology of multivariate growth modeling was divided into four stages. Each stage included a logical list of tasks, the order of solving which allowed obtaining the results of modeling the stand growth taking into account the names of tree species and their growing conditions. Draper Smith's textbook on regression analysis was used in the development of the methodology. The essence of the technique is to form a structure of regression equations of a general type, including age as the main indicator characterizing the growth process and dummy variables coding qualitative attributes. It should be noted that models describing the growth process can be of two kinds. The first type of model describes a synchronized change in growth rates for different characteristics of a qualitative variable. In our case, these are names of forest-forming species and names of forest-type groups. But, as a rule, in nature, the synchrony of changes in the growth of objects is not manifested because each forest-forming species has its own growth energy, different from others. Therefore, to show the asynchrony of the growth curves of stand morphometric traits, the product of age and the qualitative predictor encoded by the dummy variable in the corresponding matrices was added to the general form of the equation.

The essence of the first stage is to obtain regression models of changes with age in the average statistical indices of the average height and average diameter of four forest-forming species in four landscape-ecological groups of forest types. Consun's growth function was used in conjunction with the specified qualitative variables to construct growth models. Multiple regression analysis provided array-averaged data for the construction of growth regression lines characterized by the following parameters: for average statistical stand heights (R^2H = 0.983; ESH = ±6.3%) and for average statistical stand diameters (R^2D = 0.990; ESD = ±6.8%). The second stage of the methodology was devoted to modeling the change with the age of the maximum and minimum values of average heights and diameters as a function of the average stand heights and diameters obtained in the first stage of modeling. The change with the age of the regression line boundaries was estimated from the growth model data of the mean values of heights and diameters and dummy variables encoding names of forest-forming species. The asynchrony of the marginal growth curves is provided as a result of the product of the mean statistical values of the morphometric growth curves by dummy variables encoding the names of forest-forming tree species. The final regression equations of the maximum and minimum values of the mean heights and diameters were characterized by the following statistical parameters: R^2Hmin = 0.946, R^2Hmax= 0.954, R^2Dmin = 0.870, R^2Dmax = 0.977, and the errors of the equations (ESmax = ±22.0%, ESHmax = ±10.0%, ESDmin = ±21.0% and ESDmax = ±9.0%). Thus, the fulfillment of the first and second stages of the methodology allowed us to obtain data for three levels of changes in growth indices: for average statistical values for the data set, as well as for the limit values of the range of variation of the average heights and average diameters of the stands. The obtained data set allowed the construction of a three-level regression model of the general type, including qualitative predictors along with age: three levels of average heights and average diameters, four groups of forest types and three forest-forming tree species, coded by dummy variables. The processing of the data set by multiple regression analysis allowed us to obtain statistical growth models with the following parameters: for the average height (($R^2 = 0.984$; ES = ±9.0%)) and for the average diameter ($R^2 = 0.997$; ES = ±5.5%). The presence of these qualitative variables in multivariate growth models in combination with stand age, while observing the rule of the asynchrony of the growth curves, allowed us to proceed to the fourth stage of modeling. The fourth step involves detailing growth models for a particular tree species growing in a particular group of forest types. To demonstrate the detailed modeling of the growth and productivity of stands and to draw up practical standards, the dominant species—black poplar (Populus nigra)—growing in the group of forest types (folk name Osokorniki) of the middle level of the central floodplain, was selected.

In the fourth step, we obtain gradient growth curves with a given level of the average stand height at a certain age. In our case, it is 30 years. The model of average stand height growth is functional ($R^2 = 1.0$), as all data for its construction were obtained in the third stage of modeling. The known range of the limit values obtained from the third stage of modeling allowed us to order the changes in the mean heights into eight classes of mean heights with a two-meter gradation in a 30-year stand from 9 m to 25 m. The availability of a regional model of the dependence of the stock of closed stands of black poplar on the average height (Hsr) with statistical parameters ($R^2 = 1.0$) allowed us to proceed to the estimation of stand productivity. Thus, the theoretical model of stand growth by 2 m forest-typological classes of average heights at 30 years of age allowed us to solve the problems of modeling stand productivity in the whole range of stock variation. The graphical interpretation of age-related changes in the stock of closed stands of black poplar by 2 m classes of average height in the group of forest types Osokorniki of the central floodplain (Figure 4 from top) indicates the possibility of compiling similar models and taxation norms for other groups of forest types.

As a result, the lines of age-related changes in total stand productivity were obtained for the whole growth period. A comparison of the dynamics of available stand stock and total productivity is presented in Figure 4 below. The presence of the regression lines M and OD made it possible to calculate the values of the current change in the stock of the existing stand (Figure 5, top) and the total current growth taking into account the falling off (Figure 5, bottom) and to obtain the necessary data for the development of an optimization program of thinning in accordance with the methodology proposed by V.K. Khlyustov [13]. Thus, the methodology of the step-by-step modeling of growth and productivity indicators of forest stands allowed us to digitize normative and reference materials for the whole variety of tree species and groups of forest types by forest-typological classes of average heights with a 2 m gradation in 30-year stands. The developed methodology of the multidimensional modeling of the growth and productivity of forest plantations has practical realization, connected with further development of information and reference systems of forest taxation norms for forest inventory, as well as with the development of programs for the optimization of forest maintenance cuttings. The described methodological solutions and the obtained results of modeling the growth and productivity of stands on the example of floodplain forests of the West Kazakhstan part of the Ural River basin allowed us to significantly supplement the growth theory with new results, taking into account the diversity of the ecological conditions of the places of growth of forest-forming species

5. Conclusions

The conducted scientific research allows us to draw the following main conclusions:

The growth of average heights and diameters of forest elements is successfully described by asynchronous forest-typological and species–species regressions, combining the synergy of the growth function with binary variables encoding groups of forest types and tree species. The determination coefficients R^2H = 0.983 and R^2D = 0.990 and equation errors ESN = ±6.3% and ES*D* = ±6.8% indicate the reliability of the models.

The average maximum and minimum heights and average maximum and minimum diameters of the forest elements are closely related to the average statistical values for the massif in the context of forest-forming tree species. The determination indicators of equations (R^2Hmin = 0.946, R^2Hmax = 0.954, R^2Dmin = 0.870 and R^2Dmax = 0.977) and errors of equations ES*H*min = ±22.0%, ES*H*max = ±10.0%, ES*D*min = ±21.0% and ES*D*max = ±9.0% indicate a reliable determination of the maximum values of the average heights and average diameters of tree stands.

The three-level models of growth progress make it possible to assess changes in the taxation indicators of forest stands with an age over the entire range of the forest conditions, species and spatial structure. Model accuracy indicators for the average heights (R^2 = 0.984; ES = ±9.0%) and average diameters (R^2 = 0.997; ES = ±5.5%) indicate a high degree of reliability of the modeling results.

Based on the models of the limiting values of the average height and average diameter, forest typological scales of classes of average heights and diameters with a given gradation at 30 years of age of the forest stands for individual tree species were constructed. Using the example of sedge gardens at the middle levels of the central floodplain, tables of growth progress were constructed for the closed stands of black poplar.

The introduction into the statistical models of the taxation indicators of forest typological classes of average heights (H30) and a relative average diameter (*D*rel30) makes it possible to construct tables of growth progress and tables of the stock of forest stands with different densities. The function of the stock model M = f(H30, Hav, *D*rel30) allows us to build a regression with the determination index $R^2 = 0.998$ and the error ESM = ±3.4%.

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