**ЛІСІВНИЦТВО І АГРОЛІСОМЕЛІОРАЦІЯ**
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# *ЛІСІВНИЦТВО*

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## METHODOLOGICAL BACKGROUND FOR DEVELOPMENT OF A SYSTEM OF GROWTH AND PRODUCTIVITY MODELS FOR STANDS OF THE MAIN FOREST-FORMING TREE SPECIES OF UKRAINE

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The article presents the results of scientific research on development of a system of growth and productivity models for stands of the main forest-forming tree species of Ukraine on basis of the yield tables proposed by Ukrainian scientists. The fundamental prerequisites for creating the system and ways for its further development and improvement are grounded. The methodological ground is formed by the developments of Ecosystems Services and Management Program of the International Institute for Applied Systems Analysis in modeling growth, productivity and bioproductivity of forests. Von Bertalanffy's growth function serves as a mathematical basis for the research, by means of which fitting of series of dynamics of stand mean height, diameter, basal area sum, growing stock and total productivity was secured for the studied stands. Perspectives for further application of the results and developments described in the article lie in sphere of integration of the updated description of dynamics Ukrainian forests to regional and global models of dynamics of forest ecosystems to account for impact of global climate change and forecast their state middle- and long-term prospect.

K e y w o r d s : growth, productivity, stand, modeling, system of models, main forest-forming tree species.

**Introduction.** The modern changing world brings to life substantial challenges for world forests and forestry. During a prolonged period of forest management, scientific research and practice of forestry have accumulated a substantial amount of regulatory and information support, which is actively used for describing dynamics of forest stands when carrying-out forest inventory and planning activities. The distinctive feature of the current circumstances for forestry branch is impossibility of trustworthy application of the existing description of forests' growth and productivity patterns under climate change conditions and variability of other environmental factors. Accounting for influence of climatic changes on growth and bioproductivity of Ukrainian forests implies fulfillment of a series of stages towards systematization and improvement of the existing forestry-related regulatory and information support, and its embedding into one or several existing global or regional models of forest ecosystems dynamics.

*The main research aim is* to develop a unified system of growth and productivity models for stands of the main forest-forming tree species of Ukraine. Processes of growth of stands of the main forest-forming tree species are t*he object of research*, while peculiarities of modeling of dynamics of mensurational indices of the abovementioned forest stands define the *subject of research*.

In order to enhance compatibility of the national models with international scientific developments, and to test a conceptual methodological approach, it was proposed to undertake a research on elaboration of a system of growth and productivity models for modal stands of the major forest forming tree species of Ukraine. The system shall provide description of dynamics of the main mensurational indices in a unified way by means of a single type of models and mathematical support. Compliance with the named principles and approaches ensures possibilities for future enhancement of the system by inclusion of growth models for fully stocked stands and modal stands composed by other tree species taking into account regional peculiarities of forest growth and productivity.

**Materials and methods.** Within the scope of the first stage of this scientific research, the following growth and yield tables of modal stands of the major forest-forming tree species were identified as an input data (specification of tree species and the corresponding authors of growth and yield tables is provided in brackets):

- Scots pine (*Pinus sylvestris* L., Ukrainian Polissya, pure and mixed stands of artificial origin – A. Yu. Terentyev [7], stands of natural origin – I. L. Aleksiyuk [1]),
- European spruce (*Picea abies* (L.) Karst., Ukrainian Carpathians, stands of natural and artificial origin – R. D. Vasylyshyn [4]),
- Pedunculate oak (*Quercus robur* L., mixed stands of artificial origin, Right- and Left-bank Forest-Steppe – O. P. Bala [2]),
- European beech (*Fagus sylvatica* L., Ukrainian Carpathians – R. D. Vasylyshyn [4]),
- Silver birch (*Betula pendula* Roth., Ukrainian Polissya – A. M. Bilous [3]),
- Common aspen (*Populus tremula* L., Ukrainian Polissya – A. M. Bilous [3]),
- Black alder (*Alnus glutinosa* (L.) Gaerth., Ukrainian Polissya – A. M. Bilous [3]).

The authors have used diverse approaches when conducting their research. Moreover, modeling of different mensurational indices, even within one research, is done using dissimilar mathematical expressions. This corresponds to the common practice of carrying out research on forest growth and yield modeling. However, in its current state, national description of forest growth and productivity is hardly possible to embedded into any of the existing regional or global models of dynamics of forest ecosystems.

Within this research, modeling activities were performed with the best possible consideration of the groundwork of Ecosystems Services and Management program of the International Institute for Applied Systems Analysis (Laxenburg, Austria) stated in the respective publications. [6, 13].

The following mensurational indices from growth and yield tables were taken as primary ones for further modeling:

- mean stand height *H*,
- mean stand diameter *D*,
- stand basal area *G*,
- growing stock *M*,
- total productivity *TP*.

The rest of mensurational indices, which traditionally are included into growth and yield tables, could be taken as derivative ones, since they may be calculated based on the well-known "classic" formulas of forest mensuration.

Development of stands by the indices listed above was fitted using Bertalanffy's growth function [8]. This function is also referred to as Drakin-Vuyevsky growth function [5] or Chapman-Richards growth function [11]. The integral equation of the applied function is of the following form:

$$y = a_1(1 - \exp(-a_2 \cdot x))^{a_3}, \quad (1)$$

where $y$ – dependent variable,

$x$ – independent variable,

$a_1$, $a_2$, $a_3$ – regression coefficients.

Using equation (1) it is possible to describe the accumulated value of a mensurational index as a function of age within a site index class. Coefficients of this model have biological meanings: $a_1$ depicts a maximal value of the growth function (asymptote), in other words, it characterizes a value of utilized potential of growth conditions; $a_2$ is used for scaling of temporal axis, it describes rate of stand growth and is proportional to age of culmination of an increment. Expression $a_1a_2 \cdot (1 - 1/a_3) \cdot \exp(a_3 - 1)$ describes maximum of a current increment, and $(\ln(a_3)/a_2)$ circumscribes inflection point of the growth function. Modeling of numerous growth and yield tables done by scientists abroad has shown that sets of coefficients $a_1$, $a_2$, $a_3$ depict growth peculiarities of diverse tree species in a good manner for different site conditions and management regimes, and create prerequisites for accounting for impacts of different nature upon forest stands, including those induced by climatic changes [6].

Approximation of coefficients of equation (1) for stands composed by the forest-forming tree species within the scope of this research was implemented by means of a statistical software *StatSoft Statistica* [14], version 12.5 (Fig. 1).

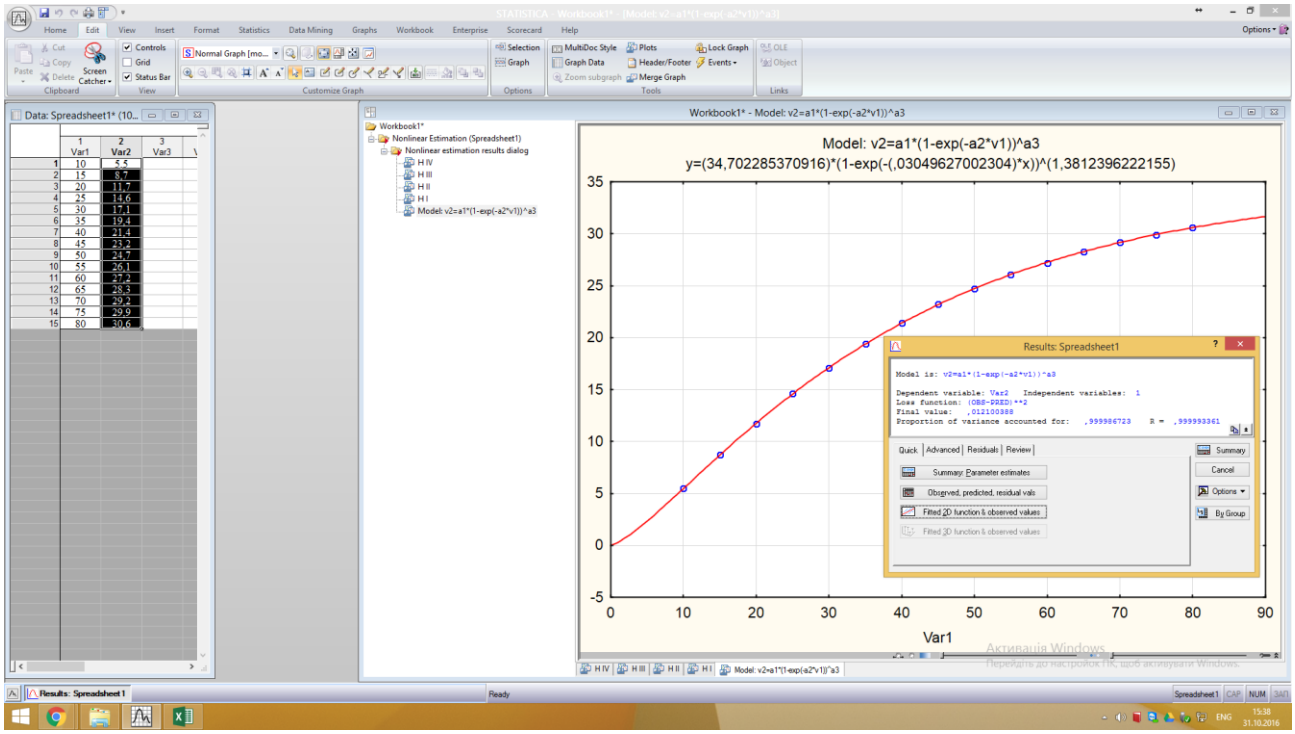


**Fig. 1 – Implementation of modelling approach**
**by means of a statistical software *StatSoft Statistica*, version 12.5**

As an approximation method for determining numerical values of regression coefficients, it was decided to apply Quasi-Newton method [9, 12]. This is a first-order optimization method, grounded on accumulation of information on curvature of an objective function through gradient change observation. The applied approach has enabled to speed-up the modeling process significantly compared to a widely applied simplex-method of optimization. By applying the described approach, we have determined values of coefficients $a_1$, $a_2$, $a_3$ of the equation (1) differentiated by forest-forming tree species, mensurational parameters and site index classes.

The generally applied practice of growth and yield modeling also includes a stage of approximation of the determined for each site index class values of regression coefficients using a polynomial function. Within the scope of this research, this step was omitted due to technical reasons – tables of coefficients are easier to embed into the existing regional or global functions of forest ecosystems dynamics. However, it is planned to implement this stage in further research in order to fulfill national requirements to forestry regulatory and information support.

**Results and discussion.** As a result of implementation of the previously described methodology to the initial data, we have obtained tables of values of regression coefficients for equation (1) in the context of forest-forming tree species, mensurational indicators and site index classes. An example of such kind of a table for mixed modal Scots pine stands of artificial origin for zone of Ukrainian Polissya is presented in table 1.

Currently the system of growth and productivity models for modal stands of the main forest-forming tree species of Ukraine includes information on dynamics of mensurational indices from 11 separate yield tables.

*Table 1*

**Values of regression coefficients of the model for mixed modal Scots pine stands of artificial origin for zone of Ukrainian Polissya**

| Mensurational index | Site index class | Regression coefficients | | |
|---|---|---|---|---|
| | | $a_1$ | $a_2$ | $a_3$ |
| Mean stand height | V[a] | 13.101 | 0.0177 | 1.220 |
| | V | 17.618 | 0.0181 | 1.237 |
| | IV | 22.196 | 0.0183 | 1.248 |
| | III | 26.830 | 0.0183 | 1.243 |
| | II | 31.611 | 0.0180 | 1.233 |
| | I | 36.143 | 0.0183 | 1.242 |
| | I[a] | 40.959 | 0.0181 | 1.235 |
| | I[b] | 45.437 | 0.0183 | 1.245 |
| | I[c] | 50.202 | 0.0182 | 1.239 |
| | I[d] | 54.680 | 0.0183 | 1.242 |
| Mean stand diameter | V[a] | 15.274 | 0.0151 | 0.959 |
| | V | 19.091 | 0.0173 | 1.110 |
| | IV | 22.403 | 0.0197 | 1.249 |
| | III | 25.005 | 0.0229 | 1.410 |
| | II | 27.171 | 0.0260 | 1.553 |
| | I | 28.699 | 0.0292 | 1.670 |
| | I[a] | 29.628 | 0.0328 | 1.791 |
| | I[b] | 29.959 | 0.0367 | 1.906 |
| | I[c] | 29.740 | 0.0405 | 1.998 |
| | I[d] | 28.831 | 0.0453 | 2.113 |
| Stand basal area | V[a] | 11.680 | 0.1317 | 6.280 |
| | V | 13.781 | 0.1130 | 4.936 |
| | IV | 16.276 | 0.0986 | 4.125 |
| | III | 19.172 | 0.0885 | 3.568 |
| | II | 22.206 | 0.0821 | 3.145 |
| | I | 24.238 | 0.0786 | 2.759 |
| | I[a] | 24.842 | 0.0781 | 2.463 |
| | I[b] | 24.986 | 0.0779 | 2.136 |
| | I[c] | 25.010 | 0.0791 | 1.886 |
| | I[d] | 24.987 | 0.0811 | 1.681 |
| Growing stock | V[a] | 230.089 | 0.0053 | 0.918 |
| | V | 285.242 | 0.0115 | 1.386 |
| | IV | 302.020 | 0.0211 | 1.988 |
| | III | 335.820 | 0.0284 | 2.406 |
| | II | 364.394 | 0.0348 | 2.726 |
| | I | 386.576 | 0.0404 | 2.916 |
| | I[a] | 402.420 | 0.0460 | 3.093 |
| | I[b] | 413.921 | 0.0517 | 3.251 |
| | I[c] | 421.715 | 0.0575 | 3.406 |
| | I[d] | 427.524 | 0.0630 | 3.520 |
| Total productivity | V[a] | 478.843 | 0.0047 | 1.113 |
| | V | 398.298 | 0.0154 | 1.842 |
| | IV | 469.019 | 0.0220 | 2.345 |
| | III | 549.113 | 0.0264 | 2.595 |
| | II | 627.324 | 0.0297 | 2.635 |
| | I | 691.688 | 0.0328 | 2.585 |
| | I[a] | 739.054 | 0.0361 | 2.512 |
| | I[b] | 781.240 | 0.0398 | 2.433 |
| | I[c] | 823.063 | 0.0436 | 2.351 |
| | I[d] | 864.653 | 0.0475 | 2.259 |

The calculated values of coefficients of determination $R^2$ (0.95–0.99) attest to high precision of fitting the models to the existing dynamics series of mensurational indices using Bertalanffy's growth function due to flexibility and universality of the latter. For better visualization, it is

worthwhile to consider Fig. 2, which presents graphical comparison of dynamics series of selected mensurational indicators for stands, composed by selected tree species.

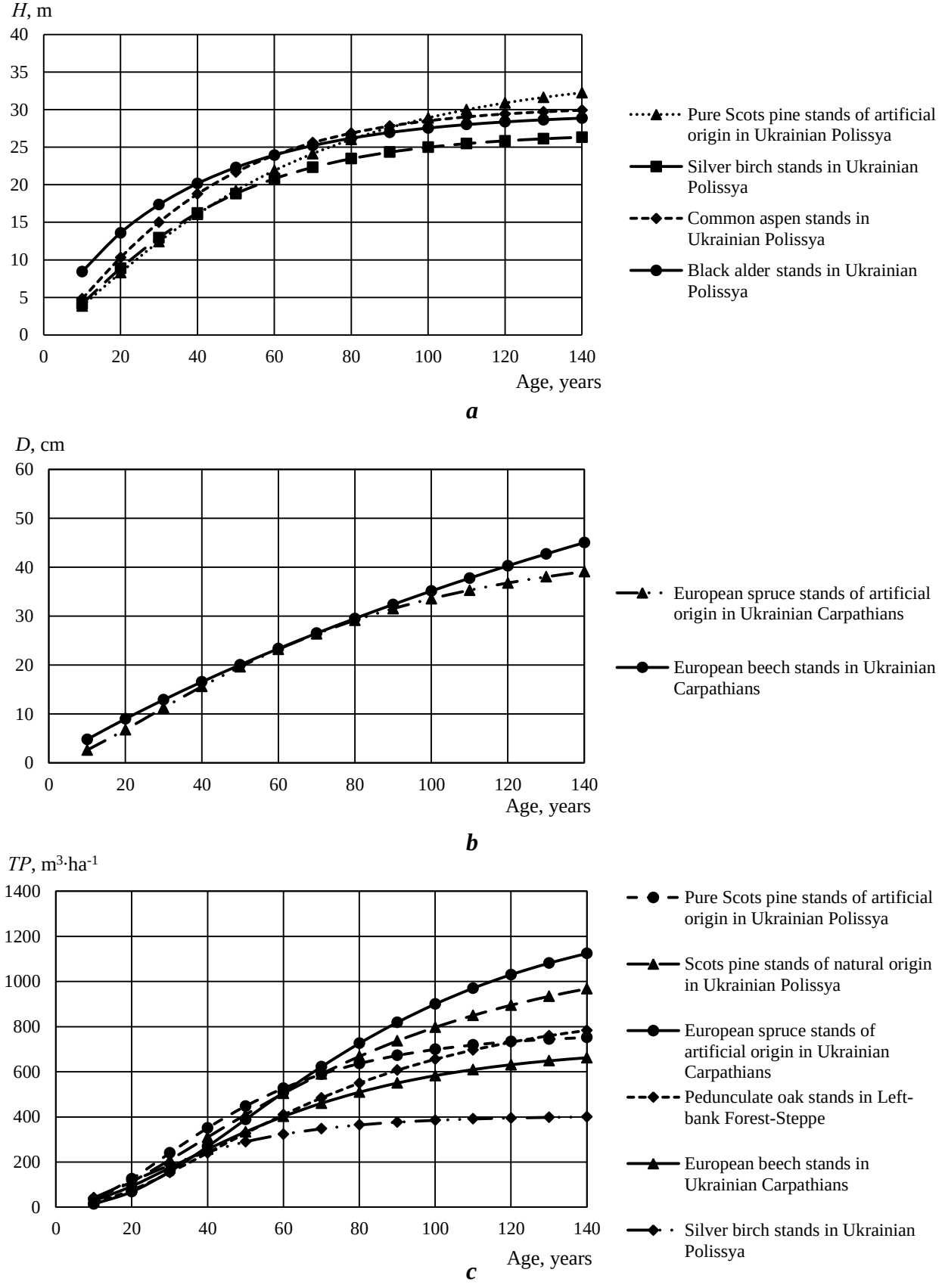


**Fig. 2 – Visual demonstration of functioning of the developed system of growth and productivity models for selected mensurational indices and stands composed by selected tree species: *a* – for mean stand height (*H*), *b* – for mean stand diameter (*D*), *c* – for total productivity (*TP*)**

The main perspectives of application for the developed system is its integration to regional and global models of forest ecosystems dynamics in order to forecast state of Ukrainian forests for a middle- and long-time prospect. A representative of this kind of models is a Global Forest Model (G4M), developed at the International Institute for Applied Systems Analysis (IIASA) [10]. The developers of the model have included a functionality for assessing forest land productivity based on site height above sea level, geographical latitude, soil type, moisture regime, $CO_2$ concentration, monthly precipitation, and monthly average temperature. Today there is a positive experience of its application for analysis of changes in forest stands productivity driven by changing environmental factors, above all – by climatic changes. IIASA scientists have demonstrated capabilities of G4M to account for impact of changes of temperature regime upon forest ecosystems in the course of the international scientific project EURO-CORDEX.

**Conclusions.** As a result of scientific efforts within the scope of the presented research activity, a system of growth and productivity models for modal stands of the main forest-forming tree species of Ukraine was developed. Application of approbated and internationally recognized and harmonized approaches during its development enables enhancing of the system in the future for better capturing of regional peculiarities of forest stands dynamics and supplementing it with growth models of fully-stocked stands, which are actively used in the practice of forest management and planning. The scientific research creates preconditions for forecasting growth and productivity of forests in Ukraine under the climate change conditions by means of internationally approbated and recognized regional and global models of forest ecosystems dynamics.

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МЕТОДИЧНЕ ПІДҐРУНТЯ ДЛЯ РОЗРОБЛЕННЯ СИСТЕМИ МОДЕЛЕЙ РОСТУ ТА ПРОДУКТИВНОСТІ ДЕРЕВОСТАНІВ ОСНОВНИХ ЛІСОУТВОРЮВАЛЬНИХ ДЕРЕВНИХ ВИДІВ УКРАЇНИ

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У статті висвітлено результати наукової роботи щодо розроблення системи моделей росту та продуктивності модальних деревостанів панівних лісоутворювальних деревних видів України на основі запропонованих вітчизняними дослідниками чинних таблиць ходу росту. Обґрунтовано засадничі передумови створення такої системи, наведено шляхи її подальшого розвитку та вдосконалення. Методичною основою є напрацювання програми Екосистемних послуг та управління Міжнародного інституту прикладного системного аналізу (м. Лаксенбург, Австрія) у сфері моделювання росту, продуктивності та біопродуктивності лісів. Математичним підґрунтям виступає ростова функція Берталанффі, за допомогою якої здійснено вирівнювання рядів динаміки середньої висоти, середнього діаметра, абсолютної повноти, запасу та загальної продуктивності досліджуваних деревостанів. Перспективи подальшого застосування описаних у статті наукових розробок полягають у інтегруванні опису динаміки лісів України до регіональних та глобальних моделей динаміки лісових екосистем задля урахування впливу глобальних кліматичних змін та прогнозування їхнього стану на середньо- та довгострокову перспективу.

К л ю ч о в і  с л о в а: ріст, продуктивність, деревостан, моделювання, система моделей, панівні лісоутворювальні деревні види.

Лакида И. П., Василишин Р. Д.

МЕТОДИЧЕСКОЕ ОСНОВАНИЕ ДЛЯ РАЗРАБОТКИ СИСТЕМЫ МОДЕЛЕЙ РОСТА И ПРОДУКТИВНОСТИ ДРЕВОСТОЕВ ОСНОВНЫХ ЛЕСООБРАЗУЮЩИХ ДРЕВЕСНЫХ ВИДОВ УКРАИНЫ

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В статье отражены результаты научной работы по разработке системы моделей роста и продуктивности модальных древостоев господствующих лесообразующих древесных видов Украины на основе предложенных отечественными исследователями действующих таблиц хода роста. Обоснованы основные предпосылки создания такой системы, приведены пути ее дальнейшего развития и совершенствования. Методической основой являются наработки программы Экосистемных услуг и управления Международного института прикладного системного анализа (г. Лаксенбург, Австрия) в сфере моделирования роста, продуктивности и биопродуктивности лесов. Математическим основанием выступает ростовая функция Берталанффи, с помощью которой осуществлено выравнивание рядов динамики средней высоты, среднего диаметра, абсолютной полноты, запаса и общей продуктивности исследуемых древостоев. Перспективы дальнейшего применения описанных в статье научных разработок заключаются в интегрировании описания динамики лесов Украины в региональные и глобальные модели динамики лесных экосистем для учета влияния глобальных климатических изменений и прогнозирования их состояния на средне- и долгосрочную перспективу.

К л ю ч е в ы е  с л о в а: рост, продуктивность, древостой, моделирование, система моделей, основные лесообразующие древесные виды.

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