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THEORETICAL PRECONDITIONS FOR GROWTH MODELLING OF MODAL STANDS OF HARDWOOD BROADLEAVED TREE SPECIES

O. P. Bala, *Candidate of Agricultural Sciences, Associate Professor, Associate Professor of Department of Forest Mensuration and Forest Management,*
A. Yu. Terentiev, *Candidate of Agricultural Sciences, Associate Professor, Associate Professor of Department of Forest Mensuration and Forest Management,*
I. P. Lakyda, *Candidate of Agricultural Sciences, Associate Professor, Associate Professor of Department of Forest Mensuration and Forest Management,*
National University of Life and Environmental Sciences of Ukraine
E-mail: bala@nubip.edu.ua

Development of reference materials for assessment of dynamics of biometric parameters of modal stands is an important component of research of forests' productivity. In this research, on basis of a stand-level database of IA "Ukrderzhlisproekt" we have statistically justified allocation of pure and mixed stands for hardwood broadleaved tree species by means of cluster analysis and graphical comparison of dendrograms of cluster objects for the main biometric indices (mean height, mean diameter and growing stock per 1 ha). The results prove that for the majority of factors stands with 9 out of 10 units of a certain species in composition belong to the same cluster as those with 3 to 8 units. This has enabled us to allocate pure stands as those featuring 10 units of a certain species in composition. The next stage was to test the null hypothesis on the significance of the difference between the mean values of the main biometric indices of the stand groups allocated from the stand-level database. The groups included pure and mixed stands, stands of natural and artificial, seed and vegetative origin. The statistical toolbox applied includes the Student's t-test and Fisher's F-test. As a result, after an analysis of the calculated indices, considering the structure of the stands in question in terms of their species composition and origin, we have allocated 6 groups for oak, 2 – for beech, 3 – for hornbeam and 3 – for ash stands. Further research of growth and productivity of the hardwood broadleaves linked with the development of yield tables for modal stands should be based on the allocated groups and dynamic site index scales.

Keywords: *composition of a stand, origin of a stand, cluster analysis, biometric indices, Student's t-test, Fisher's F-test.*

Introduction. Improving the information system for assessing forest resources in Ukraine is a rather important task that requires developing the appropriate reference data for estimating and forecasting the growth of the main forest-forming tree species with an account for regional characteristics and growth conditions, origin, and composition. The development of reference materials for assessing the dynamics of biometric indices of modal stands is an important component of the research of forests' productivity. The norms enable objective evaluating the current state of the forest resources in the most widespread tree stands, predicting their growth, and controlling the related forest management activities.

One of the crucial stages in developing growth forecasting standards for modal stands is the analysis, evaluation, and modeling of the dynamic growth processes that occur in them. First and foremost, an important step is to decide which stands have to be considered when developing the yield tables for modal stands. For this, it is required to know which stands of hardwood tree species are the most common. The next step is the study of the possibility for grouping the experimental data into statistically substantiated homogeneous groups, which differ from each other or, conversely, are similar. Actually, it is important to clarify the definition of a pure stand in terms of the presence of an admixture of other tree species in its composition. Also, it is expedient to statistically substantiate the similarity or difference between the pure and mixed, natural and artificial stands, as well as between the stands of seed and vegetative origin for the tree species in question.

Analysis of recent studies. The vast majority of research in the sphere of forest mensuration is accompanied by the use of a large number of methods of mathematical statistics and the systematic approach for establishing dependencies between biometric indices (Nikitin & Shvidenko, 1978). Recent works devoted to the modeling and forecasting growth for the main biometric indices are based on the theoretical preconditions for modeling growth processes in forest stands. In particular, Lakyda P.I and other researchers (Lakyda & Volodymyrenko, 2008, Lakyda & Bala, 2012, Lakyda, Terentiev & Vasylyshyn, 2012, Lakyda & Atamanchuk, 2014, Lakyda & Aleksiiuk, 2017) have applied the methods of cluster analysis and analysis of variance. Similar studies have also been carried out for oak stands in the Forest-Steppe zone and beech stands in the Carpathian region (Bala, Terentiev & Vasylyshyn, 2011, Bala & Terentiev, 2011, Vasylyshyn, 2016). In those studies, hypotheses about the significance of the difference between the main biometric indicators were statistically validated, and also the average values and their mean square deviations were graphically compared. The article by Bala reports on the statistical justification for the choice of a grading factor for hardwood broadleaved tree species that was made by dividing the original experimental material by site index classes and types of forest growth conditions (Bala, 2018). However, consideration should be given to the possibility of separating the studied stands into homogeneous groups by their composition and origin.

Aim of research. Within this research we aim at statistical validation of the null hypothesis about the significance of the difference between the average biometric indices of different groups of hardwood broadleaved stands, separated by origin and composition. Also, our aim is to determine which

of those groups are suitable for further development of yield tables for modal stands oak, beech, ash and hornbeam.

Materials and methods of research. To carry out the research, we have used the data on the mean biometric indices from the stand-level database of IA "Ukrderzhlisproekt" for the entire territory of Ukraine separated by the studied hardwood broadleaved tree species, by stand composition, and origin. The research was based on the principles of the systematic approach, employed modern information technologies and software (IBM SPSS Statistics). The research combines general scientific and special (silvicultural, mensurational, and biometric) methods of cognition.

Results and discussion. At the first stage of the research, we carried out a comparison of pure and mixed stands of the studied tree species and determined the definition of pure and mixed stands in terms of percentage of the main tree species in the species composition. In accordance with DSTU 3404-96 "Silviculture. Terms and definitions" (DSTU 3404-96, 1997) pure stands are those consisting of a certain tree species with individual trees of other species. However, in forest management planning practice, in particular, according to the draft "Instruction on inventory of forest fund of Ukraine" (State Agency of Forest Resources of Ukraine, 2014) stands are divided into separate compartments when there is a difference equal to or greater than 2 units (20 %) in the composition coefficients. Also, this document regulates the determination of the number of relascopic and circular enumeration sites under the applied mensuration technique, in which one category includes pure stands and stands with the presence of 8 to 9 units (80-90 %) of the dominant tree species. In fact, in practice of forest management planning and forest mensuration, nominally pure stands are defined as those with 8 to 10 units (80-100 %) of the main tree species in their composition.

For statistical validation of the null hypothesis about the significance of the difference between the mean biometric indices of stands with different composition, the database was separated into three groups for each tree species according to the following features:

– the first group – stands that consist of 10 composition units (100 %) of the investigated tree species (hereinafter referred to as 10);
– the second group – stands with the share of 9 units (90 %) of the investigated tree species in the stand composition (hereinafter referred to as 9);
– the third group – stands that consist of 30 to 80 % (from 3 to 8 units) of the tree species in question (hereinafter referred to as 38).

Stands featuring less than 3 units (30 %) of the studied tree species in composition were not considered.

To compare the above groups, we employ cluster analysis methods (Shmoilova, Mynashkyn, Sadovnikova & Shuvalova, 2005), which is used for data classification and grouping. Cluster analysis is a statistical procedure that, based on information from certain samples, organizes objects in relatively homogeneous clusters. The algorithm of calculations involves combining objects according to certain features into sufficiently large clusters, using a certain degree of similarity or distance between the objects.

When defining clusters, the following concepts are used:

– distance measure – calculates distance matrices by a certain chosen method;

– association rule – chooses the methods of combining objects into different clusters.

When conducting cluster analysis, we calculate the matrix of distances using a certain distance measure, depending on the chosen association rule (method). Further, the assignment of objects to certain clusters and the formation of a tree-like structure takes place.

The most widely used type of distance measure for the calculations is the "Euclidean distance". It is calculated as a simple geometric distance in a multidimensional space, following the special procedure, namely, the formula below (Shmoilova et al., 2005):

$$dist\,(x, y) = \left[\sum (x_i - y_i)^2\right]^{1/2}, \quad (1)$$

where x_i – values of indices for the first group;

y_i – values of indices for the second group.

The calculations were carried out using the IBM SPSS Statistics software package. We defined Ward's method with the interval measure of the squared «Euclidean distance» as an association rule. The selected method employs the approaches of analysis of variance to estimate the distance between clusters. The method minimizes the sum of squares for any two clusters that can be formed at each step.

We have carried out grouping into clusters for the following biometric indices: average height, average diameter and growing stock per hectare. The results have been obtained in the form of a dendrogram that reflects separation of the research data into the two clusters. That is, from the three initial data groups, the most similar two are identified and grouped into one cluster.

The calculations described above enable us to draw a conclusion that by average height and diameter of the stands, those with the share of 3 to 8 units (30 to 80 %) of the investigated tree species in its composition are in the same cluster with a group of stands with 10 units (100 %). A separate cluster is formed by the stands, which feature 9 units (90 %) of the studied tree species in composition. Since clusters are formed by groups that are not adjacent, this is a prerequisite to assert that there is no need for the separation of pure and mixed oak stands. By the average growing stock, the "38" group of stands is associated with the "9" group into a single cluster. This can serve as another confirmation for allocation of pure stands as those featuring exclusively 10 units of oak (100 %) in their composition.

A similar analysis was carried out for other hardwood broadleaved tree species. The results prove that for beech stands, the pure ones should be defined as those with 9 and 10 units (90 and 100 %) of beech in composition, and according to average height and growing stock – exclusively 10 units (100 %). For ash and hornbeam stands, the "38" group is associated with the "9" group into a single cluster for all biometric indices in question. This testifies the need to allocate pure stands as those with 10 units (100 %) of the respective tree species. Summing up, it can be argued that for all the studied species the most substantial differences are observed when considering the index of average diameter since the "9" group can be attributed both to group "10" and to group "38" for different tree species. When analyzing average height, for all tree species, except for oak, the group "9" belongs to the same cluster as the group "38". By growing stock, this tendency is observed for all the investigated tree species. Taking into

account that the share of tree species in growing stock of a stand is used for determining its composition, it is possible to conclude that pure stands are those that feature 10 units (100 %) of the main tree species, the others should be considered as mixed.

The next stage of the research is linked with the verification of the null hypothesis about the significance of the difference between the mean values of the main biometric indices for stands of hardwood broadleaved species in the groups of pure and mixed ones, of artificial and natural origin, and of seed and vegetative origin. To do this, we have separated the stand-level database of IA "Ukrderzhlisproekt" into the groups by composition and origin and calculated Student's *t*-criterion (Student, 1908) and Fischer's *F*-criterion (Abramowitz, Milton, Stegun & Irene, 1965). The first one is calculated based on the mean values of the studied groups and their main errors, the second one – on the basis of calculation of the variances of the two samples by comparing them with the corresponding critical values (Nikitin & Shvidenko, 1978). We have used the four main biometric indices, namely average age, average height, average diameter and growing stock per hectare. The calculated statistical indices for oak stands are presented in Table 1.

1. Statistical indices of comparison of the studied groups of oak stands

Biometric indices	Statistical indices								
	mean value		t-criterion	number of degrees of freedom		p-level of significance	standard deviation		Fisher's F-criterion
	A	B		A	B		A	B	
Pure (A) and mixed (B) stands									
Age, years	73	63	92,607	82196	352420	0,000	25,368	27,577	1,182
Average height, m	19,9	18,6	56,192	82196	352420	0,000	5,341	6,400	1,436
Average diameter, cm	26,3	23,6	70,011	82142	352340	0,000	8,927	9,988	1,252
Growing stock, $m^3 \cdot ha^{-1}$	214	200	38,198	82196	352420	0,000	85,540	93,593	1,197
Stands of seed (A) and vegetative (B) origin									
Age, years	61	80	185,773	352999	81617	0,000	27,361	21,831	1,571
Average height, m	18,2	21,6	143,281	352999	81617	0,000	6,4438	4,2621	2,286
Average diameter, cm	22,8	30,0	196,511	352876	81606	0,000	9,8049	7,6671	1,635
Growing stock, $m^3 \cdot ha^{-1}$	198	222	67,825	352999	81617	0,000	95,467	73,836	1,672
Stands of artificial (A) and natural (B) origin									
Age, years	53	84	417,703	269783	164833	0,000	21,401	25,826	1,456
Average height, m	16,8	22,2	306,023	269783	164833	0,000	6,2946	4,4180	2,030
Average diameter, cm	20,0	30,8	415,845	269663	164819	0,000	8,0170	8,8220	1,211
Growing stock, $m^3 \cdot ha^{-1}$	185	232	167,507	269783	164833	0,000	96,719	76,027	1,618

The data in Table 1 shows that the actual values of the Fisher's *F*-criterion for all the compared groups of stands and for all biometric indicators exceed the critical ones, which for our number of degrees of freedom are equal to 1000. This indicates the absence of similarity between the studied groups of stands. According to the Student's *t*-criterion, the sample should be considered similar if the *t*-value does not exceed the critical one, which is equal to 2 at the probability of 0,95. According to this criterion, the biggest difference is between the groups of stands of artificial and natural origin, the smallest – between pure and mixed oak stands. Taking into account that stands of vegetative origin have a share of about 26 % all the oak stands, of natural seed origin – over 20 %, and of artificial origin – about 52 %, it is decided that in future yield tables for modal stands should be developed for the following groups:

– seed natural pure stands;
– seed natural mixed stands;
– seed artificial pure stands;
– seed artificial mixed stands;
– vegetative natural pure stands;
– vegetative natural mixed stands.

Similar calculations of statistical indices of the compared groups were made for beech stands and are shown in Table 2.

2. Statistical indices of comparison of the studied groups of beech stands

Biometric indices	Statistical indices								
	mean value		t-criterion	number of degrees of freedom		p-level of significance	standard deviation		Fisher's F-criterion
	A	B		A	B		A	B	
Pure (A) and mixed (B) stands									
Age, years	87	75	43,811	27990	113785	0,000	37,292	41,818	1,257
Average height, m	24,8	21,8	59,839	27990	113785	0,000	5,766	7,685	1,776
Average diameter, cm	31,4	27,5	48,788	27987	113718	0,000	10,498	12,372	1,389
Growing stock, $m^3 \cdot ha^{-1}$	317	276	48,544	27990	113783	0,000	107,01	128,11	1,433
Stands of seed (A) and vegetative (B) origin									
Age, years	77	78	0,956	136328	5447	0,000	41,437	35,989	1,326
Average height, m	22,5	20,8	16,556	136328	5447	0,000	7,493	5,656	1,755
Average diameter, cm	28,3	26,5	10,761	136259	5446	0,000	12,202	9,866	1,530
Growing stock, $m^3 \cdot ha^{-1}$	286	254	18,196	136327	5447	0,000	125,64	111,08	1,279
Stands of artificial (A) and natural (B) origin									
Age, years	36	83	150,899	17172	124603	0,000	22,104	40,001	3,275
Average height, m	13,5	23,7	187,869	17172	124603	0,000	8,156	6,421	1,613
Average diameter, cm	15,1	30,1	166,347	17160	124545	0,000	9,773	11,261	1,328
Growing stock, $m^3 \cdot ha^{-1}$	176	299	127,399	17172	124601	0,000	139,49	115,48	1,459

The results in Table 2 show that the actual values of the Fisher's *F*-criterion for all the compared groups of stands and for all biometric indicators exceed the critical ones, so the groups are not similar. According to the Student's *t*-criterion, the biggest difference is between the groups of stands of artificial and natural origin, the smallest – between beech stands of seed and vegetative origin. Taking into account that stands of vegetative origin have a share of about 3,7 % all the beech stands, of artificial origin – about 8,8 %, it is decided that in future yield tables for modal stands should be developed for the following groups:

– seed natural pure stands;
– seed natural mixed stands.

Calculations of the statistical indices for the compared groups of hornbeam stands are presented in Table 3.

Statistical indices of comparison of the studied groups of hornbeam stands (Table 3) show that there is almost no difference between artificial and natural hornbeam stands. The least similar are the stands of seed and vegetative origin. Pure and mixed stands have a significant difference by average growing stock per hectare. Considering that vegetative stands occupy 67,2 % of all the stands with hornbeam in their composition, and those of artificial origin – only 0,6 %, it is decided that in future yield tables for modal stands should be developed for the following groups:

3. Statistical indices of comparison of the studied groups of hornbeam stands

Biometric indices	Statistical indices								
	mean value		t-criterion	number of degrees of freedom		p-level of significance	standard deviation		Fisher's F-criterion
	A	B		A	B		A	B	
Pure (A) and mixed (B) stands									
Age, years	58	57	1,402	7130	109249	0,000	21,966	23,629	1,157
Average height, m	17,5	17,1	6,195	7130	109249	0,000	4,644	5,170	1,239
Average diameter, cm	19,6	18,4	15,900	7129	109238	0,000	5,807	6,246	1,157
Growing stock, $m^3 \cdot ha^{-1}$	162	192	29,543	7130	109249	0,000	72,241	84,192	1,358
Stands of seed (A) and vegetative (B) origin									
Age, years	59	57	18,930	37222	79157	0,000	23,661	23,416	1,021
Average height, m	17,8	16,8	30,689	37222	79157	0,000	5,403	4,980	1,177
Average diameter, cm	19,2	18,1	29,198	37218	79149	0,000	6,540	6,040	1,172
Growing stock, $m^3 \cdot ha^{-1}$	205	183	41,477	37222	79157	0,000	89,570	80,044	1,252
Stands of artificial (A) and natural (B) origin									
Age, years	55	57	3,099	1078	115301	0,000	20,150	23,559	1,367
Average height, m	17,3	17,1	1,293	1078	115301	0,000	5,037	5,141	1,042
Average diameter, cm	19,0	18,4	2,925	1078	115289	0,000	6,022	6,229	1,070
Growing stock, $m^3 \cdot ha^{-1}$	184	190	2,401	1078	115301	0,000	80,453	83,851	1,086

– vegetative natural pure stands;
– vegetative natural mixed stands;
– seed natural mixed stands.

Calculations of statistical indices for the compared groups of ash stands are given in Table 4.

The data presented in Table 4 enables to trace the fact that by the Fisher's F-criterion all the compared groups of stands and for all biometric indicators are different from one another. According to the Student's t-criterion, the biggest difference is between the groups of stands of artificial and natural origin, the smallest – between pure and mixed ash stands. Given that stands of vegetative origin have a share of about 39,2 % of all the ash stands, of seed natural origin – 24,2 %, of artificial origin – 36,6 %, and pure stands – only 4,6 %, it is decided that in future yield tables for modal ash stands should be developed for the following groups:

– seed natural mixed stands;
– seed artificial mixed stands;
– vegetative natural mixed stands.

Conclusions and opportunities. As a result of the statistical processing (cluster analysis) of the database of IA "Ukrderzhlisproekt" for hardwood broadleaved tree species of Ukraine, namely for stands with the participation of oak, beech, ash and hornbeam, we have justified that those stands that have 10 units of the main tree species in their compositions should be

4. Statistical indices of comparison of the studied groups of ash stands

Biometric indices	Statistical indices								
	mean value		t-criterion	number of degrees of freedom		p-level of significance	standard deviation		Fisher's F-criterion
	A	B		A	B		A	B	
Pure (A) and mixed (B) stands									
Age, years	54	59	20,177	9479	95567	0,000	20,309	24,636	1,471
Average height, m	17,5	19,1	23,661	9479	95567	0,000	6,564	6,603	1,012
Average diameter, cm	21,2	23,2	21,573	9454	95556	0,000	7,942	8,934	1,266
Growing stock, $m^3 \cdot ha^{-1}$	182	197	14,511	9479	95567	0,000	103,79	99,027	1,099
Stands of seed (A) and vegetative (B) origin									
Age, years	56	63	42,961	73602	31444	0,000	22,082	28,304	1,643
Average height, m	18,6	20,0	32,458	73602	31444	0,000	6,635	6,464	1,053
Average diameter, cm	22,3	24,7	39,963	73589	31421	0,000	8,587	9,288	1,170
Growing stock, $m^3 \cdot ha^{-1}$	191	208	25,313	73602	31444	0,000	99,832	97,921	1,039
Stands of artificial (A) and natural (B) origin									
Age, years	52	65	87,830	52881	52165	0,000	18,381	27,703	2,271
Average height, m	17,3	20,7	87,978	52881	52165	0,000	6,262	6,510	1,081
Average diameter, cm	20,6	25,5	93,741	52869	52141	0,000	7,599	9,361	1,517
Growing stock, $m^3 \cdot ha^{-1}$	173	218	75,185	52881	52165	0,000	94,322	99,623	1,116

considered as pure stands. The analysis of variance was carried out for the following biometric indices: age, average height, average diameter and growing stock per hectare. The statistical toolbox applied included Fisher's *F*-criterion and Student's *t*-criterion. As a result of the analysis of calculated indices and the distribution patterns of the studied stands by composition and origin, we have established homogeneous groups of stands for the tree species in question. From there, 6 groups of oak stands, 2 groups of beech stands, 3 groups of hornbeam stands, and 3 groups of ash stands were allocated. In the future, in the context of the received groups, it is expedient to produce yield tables for modal stands as well as other forest mensuration reference materials and information support.

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Розробка нормативів для оцінки динаміки таксаційних показників модальних деревостанів є однією з важливих складових досліджень продуктивності лісів. Одним із найважливіших етапів у процесі розробки нормативів прогнозу росту для модальних деревостанів є аналіз, оцінка та моделювання динамічних процесів росту, які в них відбуваються. На основі повидільної бази даних ВО «Укрдержліспроект» проведено статистичне обґрунтування виділення чистих та мішаних деревостанів для твердолистяних деревних видів за допомогою кластерного аналізу та графічного порівняння дендрограм кластерних об'єктів за основними таксаційними показниками (середня висота, середній діаметр, запас на 1 га). З отриманих результатів було встановлено, що за переважною більшістю показників насадження з участю 9 одиниць у складі відносяться до одного кластера з деревостанами з участю від 3 до 8 одиниць, що дало можливість стверджувати про виділення деревостанів з участю 10 одиниць у складі в якості чистих. Наступним етапом була перевірка нульової гіпотези значущості різниці між середніми величинами основних таксаційних показників в розрізі груп деревостанів повидільної бази з поділом на чисті та мішані за складом, штучного та природнього, а також насіннєвого та вегетативного походження з використанням t-критерію Ст'юдента та F-критерію Фішера. В результаті аналізу розрахованих показників та переважання зростання досліджуваних деревних видів за складом та походженням було виділено 6 груп деревостанів для дубових, 2 – для букових, 3 – для грабових та 3 – для ясеневих насаджень. В подальшому складання таблиць ходу росту для модальних деревостанів твердолистяних деревних видів буде здійснюватися в розрізі отриманих груп деревостанів та динамічних класів бонітету.

Ключові слова: *склад деревостану, походження насадження, кластерний аналіз, біометричні показники, критерій Ст'юдента, критерій Фішера.*

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