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Stem volume by height classes of immature, mature and overmature stands of the main forest-forming species of Ukraine

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Abstract. Generally, it is impossible to measure diameters and heights of all trees in a forest stand. Therefore, models of relationships between heights (*h*) and diameters (*d*) of trees are commonly used in practice for stem volume estimation. This study aimed at developing models of tree height-diameter (*h-d*) relationships as well as corresponding models of the tree stem volume for immature, mature and overmature stands of the main forest-forming species of Ukraine. This paper is a aggregation of long-term studies of the stem volume, which are based on the results of measuring about 10 thousand sample trees. Modelling of the tree height-diameter relationships was performed using relative height values. The methodology used in this study allowed generalising the measurements of sample trees collected in stands of various forest site types, productivity levels, and age categories. The average height of trees with a diameter of 24 cm was taken as the reference during modelling relative heights, while the diameter of 40 cm was chosen as the reference for overmature Scots pine stands. As a result, the parameters of a unified mathematical model of relative heights for immature, mature, and overmature stands of the main forest-forming tree species of Ukraine were established. Based on these models, height-diameter relationships in forest stands of different height classes were predicted. The authors demonstrated that the developed mathematical models substantially simplify the methodology of field work during timber surveys. The paper also presents models of the tree stem volume. These models predict the stem volume outside the bark based on diameters and heights of trees or using the developed models of *h-d* relationships. In this study, a unified system of mathematical models of stem volume by height classes were created for immature, mature, and overmature stands of the main forest-forming species of Ukraine. The results of the study are introduced to the National Forest Inventory of Ukraine for growing stock volume calculation at sample plot level using measurements of individual trees. The developed models can be used both by operation forestry (estimation of the timber volume during harvesting), and forest management (forecasting the future structure of forests and estimating the growing stock volume), as well as in the forest ecology

Keywords: volume tables, relative height, form factor, mathematical model

Introduction

Accurate assessment of individual tree stem and growing stock volume of forest stands is essential for sustainable forest resource management. For this purpose, volume models based on diameter (*d*) and height (*h*) of individual trees are used. Since measuring the height of all trees is impractical for financial reasons and often involves significant errors, the growing stock volume in practice is calculated based on sample trees measurements. The heights of trees out-of-sample are calculated based on tree height-diameter (*h-d*) relationships models.

Modelling the *h-d* relationships has important scientific and practical significance. From the standpoint of forest ecology, this issue starts a discussion about the tree competition in forest stands during their growth [1], namely the estimation of competition indices [2]. Temesgen *et al*. [3] showed that larger trees (with a higher rank by diameter) reach a higher height in the forest stand. The *h-d* relationships can be used in predictive models of stand development [4], e.g., to simulate the future structure of forest stands in a result of thinning. In practical terms, the *h-d* relationship is more widely used to find the volume of individual trees and the growing stock volume of forest stands [5; 6]. Methods used absolute values of height to predict the *h-d* relationships of trees are quite common in the literature [7]. They use some stand parameters (average diameter, basal area, etc.) as factors in corresponding models.

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Results of the earlier studies [3; 8] indicate that the parameters of nonlinear models that characterise the *h-d* relationship in forest stands of a certain tree species are variable. They depend primarily on age of trees. In remove younger stands, height curves are characterised by greater steepness than in older stands. Therefore, parameters of height curves are estimated independently for different age groups (competition levels) of forest stands [1]. The *h-d* relationship in even- and uneven-aged forest stands is also important issue [9]. Some recent publications indicate that *h-d* relationships of trees depend on the origin of forest stands [10] and are closely related to their density [11]. Site conditions directly impact the *h-d* relationships of trees [12]. In general, characteristics of individual forest stand (e.g., site index, density, relative stocking, etc.) are usually considered as factors that introduce random variations in the *h-d* relationships in forest stands of the same age. While fixed-effect models characterise the most typical relationship for a wide group of forest stands, mixed-effect models explain the random component of covariance of these characteristics for a particular forest stand [11]. Such models, apart from fixed-effect terms of the equation (the typical stand), also contain random-effect terms that describes remove the differences between each individual forest stand in relation to the typical one, thus revealing specific patterns of heights and diameters depending on random factors.

There are several methodological approaches used in forest mensuration to modelling stem volume (*V*) of trees, i.e., the development of multidimensional volume equations (*V*=ψ *(d, h,...)),* the derivation of stem volumes based on the stem profile equations, and the use of specific coefficients, namely, the form factor [2]. Multidimensional mathematical models of the stem volume based on diameter and height of trees are often used in different countries: Germany, Austria, Finland, Sweden, Romania, Norway, etc. [15]. Estimating coefficients of such equations using modern computer technologies is a simple task, while accuracy of the models meets the needs of practice. Stem profile equations are used when in addition to the total stem volume, it is necessary to characterise its taper or estimate the volume of stem zones with certain qualitative characteristics (e.g., commercial timber) [16]. In Ukraine, this approach has been used relatively recently [18]. Much more often, the stem volume is considered as the product of three factors: the basal area (*g*), height, and form factor (*f*), where *f* is a conversion coefficient between the volume of cylinder (*gh*) and stem volume.

Mathematical models of the tree stem form factors for major species of Ukraine were published in earlier studies [19]. However, during the preparation of a new edition of the forest inventory handbook [20], some mathematical models have been improved.

Materials and Methods

The data for modelling stem volumes by height classes were collected during 1950-2020 on test areas distributed over the territory of Ukraine. In total, measurements about 10 thousand sample and tally trees on more than 700 temporary and permanent experimental plots for 13 main forest-forming tree species in Ukraine were used. Experimental plots characterise immature, mature, and overmature forest stands of such natural and climatic zones of Ukraine as Polissia, Forest-Steppe, Carpathians [21]. At experimental plots, the diameters of all trees were measured by 4-cm diameter classes. Then, heights of 9-20 trees of the dominant species (selected from different diameter classes) were measured to plot the height curve for the corresponding forest stand. Based on the distribution of diameters and heights (according to height curves), 5-20 sample trees were selected and cut down on each site. The diameters were measured at the midpoint of 2-m sections, while the stem volume was calculated using Newton's sectional formula.

Modelling the tree height-diameter relationships

The study utilized an approach according to which the *h-d* relationships of stems was investigated using relative values. This allows summarising the research data from a wide age range and from different forest conditions based on a unified shape of height curve. According to this, the relative heights for each diameter classes at an individual experimental plot were calculated according to the following formula:

$$h_i^e = h_i / h_{ref}, \tag{1}$$

where h_i^e is the relative height value of the i^{th} diameter class; h_i is the absolute height of the i^{th} diameter class, m; h_{ref} is the tree height of the reference diameter class, m.

For the majority of stands, a dimeter class of 24 cm was taken as the reference, while for overmature Scots pine stands it was 40 cm.

Using Equation (1), the average values of relative heights (h_i^e) in forest stands by the diameter classes were calculated for each of the 13 main forest-forming tree species in Ukraine. A unified mathematical model of relative height depending on the stem diameter was used for all species:

$$h_i^e = a_0 + a_1 \cdot \exp(a_2 \cdot d). \tag{2}$$

The following formula was used to convert relative height into absolute height values:

$$h_i = h_i^e \cdot h_{ref}. \tag{3}$$

To unify the reference data for determining tree stem and growing stock volumes, the heights of the reference diameter classes, numbering of height classes (*R*), and the interval between them were harmonized with the volume tables developed by height classes [20] that have been legally acknowledged in forestry of Ukraine. Accordingly, a height of 31.78 m was taken as the reference height in I[a] height class for overmature Scots pine stands, and 27.40 m – for the rest of species and age categories. The reference heights in other height classes for overmature Scots pine stands (the reference diameter class of 40 cm) were calculated using the following formula:

$$h_{ref} = h_{40} = 31.78 - 2.55 \cdot I_R, \tag{4}$$

where I_R is the index of the height class of tree stands (Table 1).

In other cases (the reference diameter class of 24 cm), reference heights were calculated according to the formula:

$$h_{ref} = h_{24} = 27.4 - 2.2 \cdot I_R. \tag{5}$$

Table 1 presents the coding of height classes according to the volume tables that are legally acknowledged in forestry of Ukraine.

Table 1. Indices and numbering of tree stand height categories in Ukraine

R	I[c]	I[b]	I[a]	I	II	III	IV	V	V[a]	V[b]
I_R	-2	-1	0	1	2	3	4	5	6	7

Modelling the stem volume

In the stem volume modelling, the form factors were predicted using their relationship with the diameter and height of the trees. Then, the stem volume was calculated based on the following equation:

$$V = g \cdot h \cdot f. \qquad (6)$$

A mathematical model of a form factors as a function of diameters and heights $f = \psi\ (d, h, \dots)$ was used for such species as pine and spruce of the middle and upper mountain belts of the Carpathians. Dependence of the form factors of tree trunks exclusively on diameters $f = \psi\ (d, \dots)$ was studied for spruce (on the plain), silver-fir, and maple. For the rest of the tree species, the form factor models depending on the stem heights $f = \psi\ (h, \dots)$ were used.

A direct regression of the stem volume against diameter and height was applied for birch and aspen using the allometric equation:

$$V = a_0 \cdot d^{a_1} \cdot h^{a_2}. \qquad (7)$$

To characterize the relationship between the form factors of different tree species with diameter, height, or both, the optimal set of regression coefficients in the model (6) was found based on a multivariate examination of multiple candidate equations. In general, such a variety of methodological approaches is explained by the fact that mathematical models were developed in different periods, trying to achieve maximum accuracy of models while maintaining their simplicity.

The parameters of mathematical models were calculated based on regression analysis using the nonlinear least squares method (NLS) [22].

Results and Discussion

Based on the results of the research, the parameters of a unified mathematical model of relative height for immature, mature, and overmature stands of the main forest-forming tree species of Ukraine were established (Table 2).

Table 2. Parameters of the mathematical model of relative height as a function of stem diameter

No.	Tree species	Latin name of a tree species	Parameter of Equation (2)		
			a_0	a_1	a_2
1	Scots pine	*Pinus sylvestris* L.	1.247	-1.183	-0.06527
2	Scots pine (overmature stands)		1.202	-0.9769	-0.03933
3	Norway spruce (on the plain)	*Picea abies* L.	1.391	-1.486	-0.05563
4	Norway spruce (middle mountain belt of the Carpathians)		1.501	-1.459	-0.04454
5	Norway spruce (upper mountain belt of the Carpathians)		1.711	-1.739	-0.03727
6	Silver fir	*Abies alba* (L.)	1.397	-1.374	-0.05173
7	Common oak	*Querqus robur* L.	1.295	-1.320	-0.06243
8	European beech	*Fagus sylvatica* (L.)	1.212	-0.9445	-0.06226
9	Common ash	*Fraxinus excelsior* L.	1.340	-1.343	-0.05725
10	Norway maple	*Acer platanoides* L.	1.348	-1.228	-0.05254
11	Common hornbeam	*Carpinus betulus* L.	1.144	-0.9224	-0.07738
12	Common aspen	*Populus tremula* L.	1.290	-1.199	-0.05914
13	Silver birch	*Betula pendula* Roth.	1.302	-1.080	-0.05310
14	Black alder	*Alnus glutinosa* (L.) Gaerth	1.186	-1.209	-0.07799
15	Small-leaved linden	*Tilia cordata* Mill.	1.229	-1.252	-0.07069
16	Black locust	*Robinia pseudoacacia* L.	1.210	-0.923	-0.06170

The developed tree *h-d* relationships were published in a tabular form in the new Forest inventory handbook (Tables 2.11-2.26) [20]. Stem volume models for immature, mature, and overmature stands of the main forest-forming tree species in Ukraine can be utilized using direct measurements of the diameter and height of individual trees (Tables 1.18-1.31) [20] or in combination with *h-d* models (Table 3). Finally, based on the developed models of relative height (2) and mathematical models of the stem volume presented in Table 3, volume tables by height classes were developed (Table 2.27-2.41) [20].

Table 3. Mathematical models of stem volumes outside bark

No.	Tree species	Mathematical model of stem volume in bark
1	Scots pine	$V = \exp(7.767 - 0.04235 \cdot \ln(d+8) - 0.6374 \cdot \ln(h+2) + 0.02158 \cdot (h+2)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-8}$
2	Scots pine (overmature stands)	$V = (0.3521 + 0.5343 \cdot d^{-0.4546}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
3	Norway spruce (on the plain)	$V = (0.4217 + 1.023/(h - 0.723)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$

Table 3, Continued

No.	Tree species	Mathematical model of stem volume in bark
4	Norway spruce (middle mountain belt of the Carpathians)	$V = (438 - 2.3 \cdot \mathrm{h} + 0.0934 \cdot h^2 - (d - 40)/(0.163 + 0.00874 \cdot d)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-8}$
5	Norway spruce (upper mountain belt of the Carpathians)	$V = (402.5 - 1.601 \cdot h + 0.0572 \cdot h^2 - (d - 42)/(0.142 + 0.00545 \cdot d)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-8}$
6	Silver fir	$V = (0.4118 + 1.176/(h - 0.289)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
7	Common oak	$V = (0.3812 + 0.4955 \cdot d^{-0.4811}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
8	European beech	$V = (0.5007 - 0.001507 \cdot d + 2.106/d^2) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
9	Common ash	$V = (-0.1634 + 0.8110 \cdot d^{-0.07708}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
10	Norway maple	$V = (0.3948 + 1.246 \ / \ (h + 0.966)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
11	Common hornbeam	$V = (0.103 + 0.5889 \cdot \ d^{-0.1702}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
12	Common aspen	$V = 0.3081 \cdot d^{1.8708} \cdot h^{1.1932} \cdot 10^{-4}$
13	Silver birch	$V = 0.5631 \cdot \ d^{1.755} \cdot h^{1.073} \cdot 10^{-4}$
14	Black alder	$V = (0.4105 + 1.285/(d + 1.084)) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
15	Small-leaved linden	$V = (-4.166 + 4.849 \cdot d^{-0.01390}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$
16	Black locust	$V = (0.4024 + 1.170 \cdot h^{-1.036}) \cdot d^2 \cdot h \cdot 7.854 \cdot 10^{-5}$

The use of stem volume models by height classes substantially simplifies the method of forest inventory, since there is no need to measure the height of all tally trees. Therewith, in the stem volume models (Table 3), the value of the variable *h* is obtained based on the equations (2-3).

In the literature, there are various approaches to modelling the stem volumes. In most cases, direct regression of the volume of stems against the diameter and height is used [15]. It is worth noting, the attitude towards this approach is ambiguous. Although it is possible to obtain a high value of the determination coefficient, the parameters of the equation are very sensitive to the data set of experimental information (e.g., incorrect maximum values can substantially increase/decrease the volume forecast for extreme tree diameters). The high determination coefficient is also explained by the presence of functional dependencies between the volume of solids and their size. In this regard, another approach based on the analysis of random variations in the stem volume of trees of the same size (*d* and *h*) using form factors has considerable practical advantages. For example, the stem volume has a fixed component, i.e., the volume of the cylinder (can be directly obtained based on *d* and *h*), and a variable correction factor (form factor). The accuracy of modelling the stem volume depends exclusively on the adequacy of the description of the variation in their shape depending on the diameter and height, i.e., the variability of the form factors which is lower than for the corresponding stem volumes.

In general, the stem volume of trees of the same size (*d* and *h*) is determined by the stem form. In this regard, there are forest tree species in Ukraine that reach a larger volume, i.e., they have a smaller stem taper. Based on the models presented in Table 3, it was found that for the same diameter and height, the stems of spruce, fir, and oak have the largest volumes (Fig. 1a). At the same time, the stems of birch trees have a substantially smaller volume.

The altitudial zonation of the Ukrainian Carpathians impacts the productivity, morphology, and wood quality characteristics of spruce stands. Optimal conditions for spruce growth in mountains are observed at altitudes from 700 to 1100 m above sea level. At higher altitudes, significant changes in the morphology and productivity of stands are observed, namely more sparse forest stands are mainly formed here, the trunks of which have larger taper [23]. Considering these features, the decision to develop mathematical models of the volume for the flat part, the middle (up to 1100 m) and the upper mountain (over 1100 m) belt of the Carpathians allowed more accurately characterising the volume of spruce trunks in typical growth conditions (Fig. 1b). According to our data, spruce trunks growing in the high-altitude belt of the Carpathian Mountains have the greatest stem taper (i.e., the smallest volume at constant values of diameter and height).

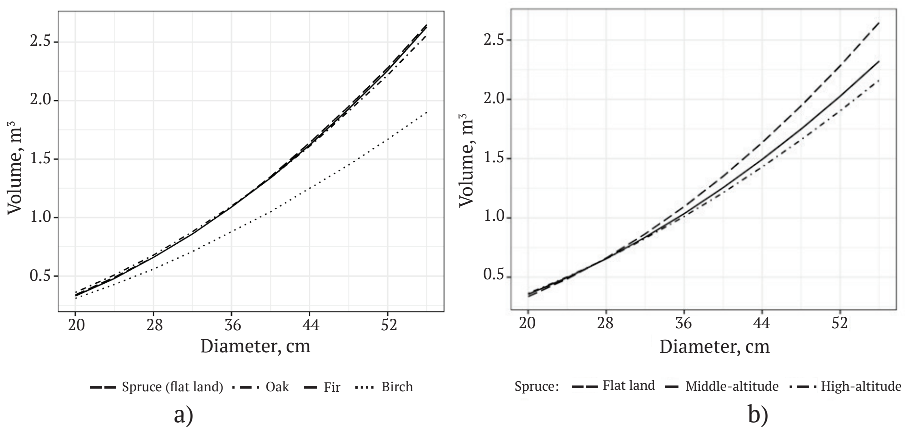

Figure 1. Comparison of the stem volumes as a function of diameter at a constant height (*h = 23 m*): a) typical examples of tree species of Ukraine that have different stem taper; b) the volume of spruce stems in different growth conditions

Similar to spruce, the study reported two groups of models for Scots pine stands (Table 2, Table 3). This can be explained by the specific *h-d* relationship in overmature stands, i.e., described by shallow curves at an older age. Furthermore, in overmature pine stands (over 130 years old), the yield of merchantable timber substantially decreases. This is explained by the specific features of the dimensional and qualitative characteristics of trunks and the structure of stands approaching the age of natural maturity. Thus, if the goal is to develop tables for the distribution of stem volume by size and quality categories, the availability of different models for the specified age groups of forest stands is critical.

The developed system of mathematical models is integrated into the system of the National Forest Inventory of Ukraine for growing stock volume calculation at sample plot level. The use of mathematical models of the *d-h* relationships simplifies the methodology of field work, since there is no need to measure the height of all tally trees on the sample plot.

Conclusions

The methods used to calculate the stem and growing stock volume of forest stands should be accurate and financially efficient to use in forest resource management over large areas. Since measuring diameters and heights of all trees in a stand is impractical or unfeasible, mathematical models of the *h-d* relationships are used in the forest inventory. This paper provides the system of mathematical models of the stem volume and the tree *h-d* relationship of the main forest-forming species of Ukraine. The presented models can be used in operational forestry (estimation the timber volume during harvesting), forest management (forecasting the future structure of forests and estimating the growing stock volume of stem wood), as well as in forest ecology, forest ecosystem services studies, etc. The developed set of mathematical models creates the basis for harmonising methods of forests assessment in Ukraine at various phases of forest management. In addition to the total stem volume calculation, developed volume equations have been integrated into tables that provide an estimate of the distribution of timber volume by thickness classes.

The results of this study promote further investigation of the distribution of the stem volume by quality classes, developing reference data, and software for improved forest recourse assessment.

References

[1] Zhang, B., Sajjad, S., Chen, K., Zhou, L., Zhang, Y., Yong, K.K., & Sun, Y. (2020). Predicting tree height-diameter relationship from relative competition levels using quantile regression models for chinese fir (*Cunninghamia lanceolata*) in Fujian Province, China. *Forests*, 11(2), article number 183. https://doi.org/10.3390/f11020183.

[2] Burkhart, H.E., & Tomé, M. (2012). *Modeling forest trees and stands*. Dordrecht: Springer. https://doi.org/10.1007/978-90-481-3170-9.

[3] Temesgen, H., Hann, D.W., & Monleon, V.J. (2007). Regional height–diameter equations for major tree species of Southwest Oregon. *Western Journal of Applied Forestry*, 22(3), 213-219. https://doi.org/10.1093/wjaf/22.3.213.

[4] Tian, X., Sun, S., Mola-Yudego, B., & Cao, T. (2020). Predicting individual tree growth using stand-level simulation, diameter distribution, and Bayesian calibration. *Annals of Forest Science*, 77(2), article number 57. https://doi.org/10.1007/s13595-020-00970-0.

[5] Briseño-Reyes, J., Corral-Rivas, J.J., Solis-Moreno, R., Padilla-Martínez, J.R., Vega-Nieva, D.J., López-Serrano, P.M., Vargas-Larreta, B., Diéguez-Aranda, U., Quiñonez-Barraza, G., & López-Sánchez, C.A. (2020). Individual tree diameter and height growth models for 30 tree species in mixed-species and uneven-aged forests of Mexico. *Forests*, 11(4), article number 429. https://doi.org/10.3390/f11040429.

[6] Santiago-García, W., Jacinto-Salinas, A.H., Rodríguez-Ortiz, G., Nava-Nava, A., Santiago-García, E., Ángeles-Pérez, G., & Enríquez-del Valle, J.R. (2020). Generalized height-diameter models for five pine species at Southern Mexico. *Forest Science and Technology*, 16(2), 49-55. https://doi.org/10.1080/21580103.2020.1746696.

[7] Temesgen, H., & Gadow, K.V. (2004). Generalized height—diameter models—an application for major tree species in complex stands of interior British Columbia. *European Journal of Forest Research*, 123(1), 45-51. https://doi.org/10.1007/s10342-004-0020-z.

[8] Peng, C., Zhang, L., & Liu, J. (2001). Developing and validating nonlinear height–diameter models for major tree species of Ontario's Boreal forests. *Northern Journal of Applied Forestry*, 18(3), 87-94. https://doi.org/10.1093/njaf/18.3.87.

[9] de-Miguel, S., Pukkala, T., Assaf, N., & Bonet, J.A. (2012). Even-aged or uneven-aged modelling approach? A case for *Pinus brutia*. *Annals of Forest Science*, 69(4), 455-465. https://doi.org/10.1007/s13595-011-0171-2.

[10] Sharma, M. (2016). Comparing height-diameter relationships of boreal tree species grown in plantations and natural stands. *Forest Science*, 62(1), 70-77. https://doi.org/10.5849/forsci.14-232.

[11] Zhang, X., Fu, L., Sharma, R.P., He, X., Zhang, H., Feng, L., & Zhou, Z. (2021). A nonlinear mixed-effects height-diameter model with interaction effects of stand density and site index for larix olgensis in Northeast China. *Forests*, 12(11), article number 1460. https://doi.org/10.3390/f12111460.

[12] Duan, G., Gao, Z., Wang, Q., & Fu, L. (2018). Comparison of different height–diameter modelling techniques for prediction of site productivity in natural uneven-aged pure stands. *Forests*, 9(2), article number 63. https://doi.org/10.3390/f9020063.

[13] Bronisz, K., & Mehtätalo, L. (2020). Mixed-effects generalized height–diameter model for young silver birch stands on post-agricultural lands. *Forest Ecology and Management*, 460, article number 117901. https://doi.org/10.1016/j.foreco.2020.117901.

[14] Temesgen, H., Zhang, C.H., & Zhao, X.H. (2014). Modelling tree height–diameter relationships in multi-species and multi-layered forests: A large observational study from Northeast China. *Forest Ecology and Management*, 316, 78-89. https://doi.org/10.1016/j.foreco.2013.07.035.

[15] Zianis, D. (2005). *Biomass and stem volume equations for tree species in Europe*. Tampere: Tammer-Paino Oy.
[16] Fonweban, J., Gardiner, B., & Auty, D. (2012). Variable-top merchantable volume equations for Scots pine (*Pinus sylvestris*) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Northern Britain. *Forestry*, 85(2), 237-253. https://doi.org/10.1093/forestry/cpr069.
[17] Fonweban, J., Gardiner, B., Macdonald, E., & Auty, D. (2011). Taper functions for Scots pine (*Pinus sylvestris* L.) and Sitka spruce (*Picea sitchensis* (Bong.) Carr.) in Northern Britain. *Forestry*, 84(1), 49-60. https://doi.org/10.1093/forestry/cpq043.
[18] Bilous, A., Myroniuk, V., Svynchuk, V., Soshenskyi, O., Lesnik, O., & Kovbasa, Y. (2021). Semi-empirical estimation of log taper using stem profile equations. *Journal of Forest Science*, 67(7), 318-327. doi: 10.17221/209/2020-JFS.
[19] Svynchuk, V., Kashpor, S., & Myroniuk, V. (2014). Model of round wood volumes based on top diameter and length of logs. *Scientific Bulletin of the National University of Life and Environmental Sciences of Ukraine*, 1, 58-64.
[20] Bilous, A., Kashpor, S, Myroniuk, V., Svynchyk, V., & Lesnik, O. (2021). *Forest inventory handbook*. Kyiv: Vinichenko.
[21] Gensiruk, S.A (1992). *Forests of Ukraine*. Kyiv: Naukova dumka.
[22] Draper, N.R., & Smith, H. (1998). *Applied regression analysis*. Hoboken: Wiley.
[23] Shvidenko, A.Z. (1981) *Theoretical and experimental backgrounds of a system of inventory of mountain forests of the zone of intensive forest management* (Doctoral thesis, Ukrainian Agricultural Academy, Kiev, Ukraine).

Об'єм стовбурів за розрядами висот пристиглих, стиглих і перестійних деревостанів основних лісоутворювальних видів України

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Анотація. У більшості випадків забезпечити вимірювання діаметра та висот усіх дерев неможливе, тому на практиці під час визначення об'єму стовбурів прийнято застосовувати моделі співвідношення висоти та діаметра дерев у насадженні. Мета роботи полягає в розробці моделей співвідношення висоти та діаметра дерев для пристиглих, стиглих і перестійних деревостанів основних лісоутворювальних видів України, а також відповідних моделей об'єму стовбурів дерев зазначених категорій лісових насаджень. Дослідження базується на узагальненні багаторічних досліджень об'єму стовбурів, в основу яких покладено результати обміру близько 10 тис. модельних дерев. Моделювання співвідношення висоти і діаметра дерев у деревостанах виконувалося за допомогою відносних значень висоти. Використаний методичний підхід дозволив узагальнювати матеріали обміру модельних дерев у деревостанах різних лісорослинних умов, рівнів продуктивності та вікових категорій. За базове значення висоти під час моделювання приймалася середня висота дерев діаметром 24 см, для перестійних соснових деревостанів як базовий обирався діаметр 40 см. Встановлено параметри єдиної математичної моделі відносної висоти для пристиглих, стиглих і перестиглих деревостанів основних лісотвірних деревних видів України. На основі неї спрогнозовано можливі співвідношення висоти і діаметрів у насадженнях за різними розрядами висот. Обґрунтована можливість використання розроблених математичних моделей, що значно спрощує методику польових робіт. У роботі також представлено моделі об'єму стовбурів дерев. Зазначені моделі дозволяють спрогнозувати об'єми стовбурів у корі залежно від діаметра та висоти дерев, або, використовуючи розроблені співвідношення висот і діаметрів дерев. На основі проведеного дослідження було створено єдину систему математичних моделей об'єму стовбурів за розрядами висот для пристиглих, стиглих і перестиглих деревостанів основних лісоутворювальних видів України. Результати дослідження запропоновано використовувати під час національної інвентаризації лісів України для визначення запасу лісових насаджень на рівні пробних площ, використовуючи обміри окремих дерев. Розроблені моделі можуть використовуватися як для вирішення практичних задач лісового господарства (визначення об'єму деревини під час рубок), лісоуправління (прогнозування майбутньої структури лісів і оцінки запасів стовбурової деревини), так і під час дослідження екології лісових екосистем

Ключові слова: таблиці об'єму стовбурів, відносна висота, видове число, математична модель

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Morphogenesis of cell lines of plants *Lysimachia nummularia* L. at *in vitro* culture promising for the content of biologically active substances

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Abstract. *Lysimachia nummularia* L. is a plant belonging to the *Primulaceae* family, which is particularly valuable as a medicinal raw material used in folk medicine in many countries. It has excellent antibacterial and antioxidant capacity of metabolites. That is why the microclonal propagation of *Lysimachia nummularia* L. is a relevant issue. The purpose of this paper is to develop approaches to microclonal propagation of L. *nummularia*. For microclonal reproduction of *L. nummularia*, the method of activation of isolated tissues and organs already present in the plant meristem and induction of direct regeneration directly by explant tissues was used. To select highly productive cell lines of representatives of the genus *Lysimachia*, callus culture was obtained by indirect morphogenesis from stem and leaf explants. It was found that the formation of tissues and organs of *L. nummularia* into *in vitro* culture depended on the composition of the nutrient medium and the quantitative and qualitative ratio of growth regulators in it. Active proliferation of *L. nummularia* microshoots into *in vitro* culture was noted on the variants of Murashige and Skoog, and Driver and Kuniyuki nutrient medium with 6-benzylaminopurine 4.0 $mg \cdot l^{-1}$, indolyl butyric acid 0.03 $mg \cdot l^{-1}$, gibberellic acid 0.1 $mg \cdot l^{-1}$. It was established that for microclonal reproduction, induction, and proliferation of the root system and obtaining regenerating plants of *L. nummularia*, the most effective is the use of nutrient media according to Murashige and Skoog with the addition of thidiazuron 0.5 $mg \cdot l^{-1}$ and 0.25 $mg \cdot l^{-1}$ kinetin. The optimal conditions for the induction of callusogenesis and obtaining the culture of cells and callus tissues of *L. nummularia* and its passage *in vitro* were selected. It has been shown that the modified nutrient medium of Murashige and Skoog, with 2.4-dichlorophenacetic acid 1.5 $mg \cdot l^{-1}$ and indole-3-acetic acid 0.2 $mg \cdot l^{-1}$, is optimal for the accumulation of callus tissue biomass of *L. nummularia*, which ensured the frequency of callusogenesis for the first and second passages up to 98.0 ± 0.2%. 5 cell lines that actively synthesize stilbenoids and the highly productive LN-EE 02/19 cell line, which is capable of synthesizing and accumulating in callus tissues up to 10-12 $mg \cdot g^{-1}$ of myricetrin, were selectively isolated. As a result of the analysis, the callus culture cell line LN-EE 02/19 was obtained, which allows obtaining myricetrin in amounts up to 10.0-12.0 $mg \cdot l^{-1}$ of raw biomass. The developed protocol can be used both for *L. nummularia* plants and other representatives of the *Primulaceae* family

Keywords: tissue and organ cell culture *in vitro*, nutrient medium, explant, microclonal reproduction, callusogenesis

Introduction

Lysimachia nummularia L. is a perennial herbaceous plant which is especially valuable as a medicinal raw material used in conventional medicine in many countries. Among the herbaceous plants of the *Primulaceae* family, the genus *Lysimachia* has about 165 species. *L. nummularia* plants contain bioactive components that are actively used in medicine. Thanks to biotechnology, it is possible to grow cells, tissues, or plant organs *in vitro* on specially selected artificial nutrient media to obtain target products on an industrial scale. Therefore, developing of microclonal propagation

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protocols is of primary importance for obtaining many aseptic, genetically homogeneous regenerating plants of *L. nummularia*.

There is little information on the cultivation of various decorative and medicinal forms of *L. nummularia* in the scientific literature [1; 2]. Available publications cover the investigation of the theoretical foundations of induced morphogenesis, the role of trophic, hormonal, and physical factors in regeneration processes, and the problem of mass production of planting material of this group of plants [3; 4].

The presence of a wide range of biologically active substances, many phenolic acids, allows for obtaining analgesic, antiseptic, anti-inflammatory herbal preparations, and medicines for wound healing. Most phenolic compounds (secondary metabolites) are obtained from various parts of the plant [5-7].

In 2013, a new saponin (glycoside triterpene – 1) was discovered, isolated from the underground part of the plant, which counteracts active prostate cancer cells without affecting normal cells [8]. This compound affects damaged (affected) glioblastoma cells and exhibits moderate activity against melanoma cells [9-11].

Uniform spread growth, high decorative qualities have preconditioned the significant use of these plants in decorative gardening, as ground cover plants and in aquaculture [12; 13].

Lately, considerable attention has been paid to the adaptive potential of plants of the genus *Lysimachia*, the selection of the most promising species, and their cultivation using modern biotechnological methods for various purposes (pharmacology and ornamental horticulture, etc.) [3; 14].

The method of microclonal reproduction allows obtaining virus-free, healthy plant material, in significant quantities, genetically identical, which is relevant both for decorative horticulture and for industry [15-17].

Currently, there are few studies on tissue culture of *Lysimachia* L. plants. The works of scientists [2-4] report on attempts to reproduce representatives of this genus – *L. christinae, L. rubrinervis*, *L. nummularia* 'Aurea' *in vitro*.

A genetic collection of the genus *Lysimachia* L. was created on the territory of the Feofaniya park in Kyiv, which is a state park. A comprehensive assessment of the pharmacological value of vegetable oils of species of this genus common in Ukraine has also been developed. Such species as *L. nummularia, L. vulgaris, L. nemorum, L. punctata* were involved [18; 19].

Distinctive features of the growth and development of this herbaceous plant were investigated, especially the formation of the generative part of plants as the main source of valuable flower oils [11, 20; 21].

Lysimachia nummularia L. is found in synanthropic communities of Feofaniya Park (on the shores of ponds and certain parts of the park). The reproductive part of plants of this species is the main source of potentially valuable flower oils, so it is vital to pay attention to the most favourable environment for its formation [21; 22].

Research on the accumulation of polysaccharides in cells of the secretory epithelium is considered as a basis for creating a polymer film with bactericidal and fungicidal components, for this it is relevant to use microclonal reproduction [23].

Earlier studies were aimed at investigating the features of introducing into the culture, obtaining aseptic plants of *L. nummularia*, and identifying the inducing effect of various cultivation factors on the processes of direct and indirect morphogenesis [21; 24].

The purpose is to develop a protocol for microclonal propagation of *L. nummularia* plants to obtain cell lines producing biologically active compounds.

The main task is to determine the features of direct regeneration of *L. nummularia* plants at the initial stage of reproduction and indirect morphogenesis to identify promising cell lines.

Specifically, the originality of the conducted research lies in the specific features of de-differentiation, the use of cell selection methods to isolate cell lines producing biologically active compounds and the detection of patterns of accumulation of flavonoids, namely myricetrin and stilbenoid with high antioxidant activity in cultivated *in vitro* cell lines of *L. nummularia*.

Materials and Methods

For conducting experimental work, samples of *L. nummularia* were used, which were selected from the population of the garden art park monument (GAPM) "Feofaniya" at the beginning of the flowering of plants and during the period of mass vegetation.

Aseptic cultures were obtained from fragments of plant shoots of 3-5 cm, using stepwise sterilization, first washing in a soapy solution for 5-10 minutes (intensely stirring). Then washed under running water for 5 minutes. In a laminar box, explants were immersed in a 25% H_2O_2 hydrogen peroxide solution for 7 min and washed once in sterile distilled water for 10 min, which ensured the least contamination and the highest percentage of viable explants with a sterilization efficiency of 93% [21].

At the initial stage of cultivation of aseptic explants *in vitro*, basic nutrient media (NM) were used according to the prescription of Murashige and Skoog (MS) [25] and Driver and Kuniyuki (DKW) [26]. For the induction of morphogenesis by plant tissues *in vitro*, the NM composition was modified by adding to its composition plant growth regulators (PGR), both individually and in combination.

For microclonal reproduction of *L. nummularia*, the authors used the method of activation of isolated tissues and organs already present in the plant meristem and induction of direct regeneration directly by explant tissues. Activated carbon as an adsorbing element in the amount of 1 $g \cdot l^{-1}$, sucrose (30 $g \cdot l^{-1}$) – as a hydrocarbon source, meso-inositol 100 $mg \cdot l^{-1}$, agar-agar – 0.7% and two chelated forms of iron: ethylenediamine-di-2-hydroxy-phenylacetic acid (Fe-EDDHA) and ethylenediaminetetraacetic acid (Fe-EDTA), medium pH 5.6-5.7 [27; 28; 29].

Explants were grown in special rooms at 25 ± 2°C, with a 16-hour photoperiod and illumination intensity of 2000-3000 lux. With the proven methodology and effective sterilization, the beginning of the growth of primary microshoots was noted in 80% of the obtained viable explants on the Days 5-7 of cultivation (Fig. 1).

To obtain a high reproduction coefficient, it is necessary to activate the regenerative capacity of totipotent plant cells [27; 28; 30].

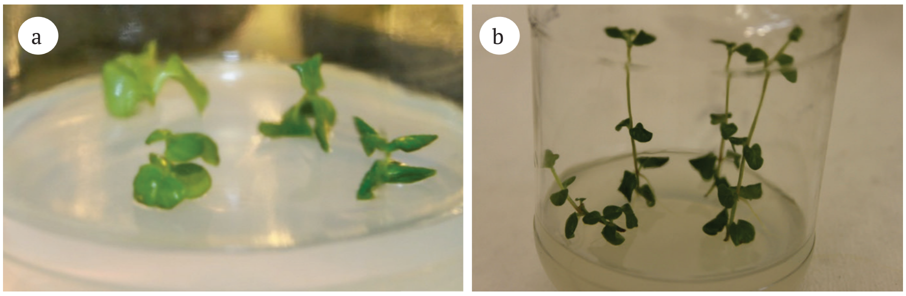

Figure 1. Formation of aseptic microshoots of *L. nummularia* on Days 7-10 of *in vitro* cultivation: a – explants on Days 1-2; b – on Days 14-21 of cultivation

Therefore, the primary regenerated plants were subcultivated on fresh NM with different compositions and quantitative ratio of PGR and used as explants for obtaining callus culture and mass microclonal reproduction.

Results and Discussion

During microclonal reproduction, the main factor is the genotypic and species characteristics of cultivated cells, tissues, and organs, but the mineral composition of NM and the ratio of vitamins and growth regulators have a direct effect on the formation of plant cells, tissues, and organs [21; 27].

For most cultures, the synthetic analogue of cytokinin, thidiazuron (TDZ) can stimulate plant growth through its biological (cytokinin) activity. For this, it is best to use low concentrations. Compared to the effectiveness of traditional purines, growth is stimulated and the ability of tissues to intensify the synthesis and accumulation of endogenous cytokinins increases [15; 25].

Thus, in the propagation of *L. nummularia*, M. Dogan uses both solid and liquid NM, but the best results regarding the number of shoots and percentage of regeneration were found in solid NM according to the values of *in vitro* propagation. On the other hand, results regarding the best shoot length formation were noted in liquid NM [20].

M. Dogan also uses TDZ in different concentrations of 0.05-0.4 mg·l^{-1} with the addition of indolylacetic acid (IAA) to stimulate tissues of *L. nummularia* explants. It is noted that high concentrations of TDZ negatively affect the explants, inhibit their growth and development [20; 26; 31]. In turn, the authors of the paper [27] use NM supplemented with 6-benzaminopurine (BA) 0.05-1.6 mg·l^{-1} for explants of *L. nummularia*, thereby stimulating the formation of added buds directly by explant tissues. Mass microclonal propagation is stimulated by adding MS BA with α-Naphthaleneacetic acid (NAA) to the NM.

Considering previous studies [20; 26; 27], experiments were conducted to establish the efficiency of regeneration of *L. nummularia* and the course of organogenesis depending on the concentration of growth regulators of the cytokinin and fuchsin type of action in NM and the type of explant [21]. For this, the authors of this study used the method of activation of isolated tissues and organs of *L. nummularia* already present in the plant meristem and induction of direct regeneration directly by explant tissues (Table 1). The authors also modified the composition of NM, specifically by adding Ethylenediamine-N,N'-bis(2-hydroxyphenylacetic acid (Fe-EDDHA), gibberellic acid and kinetin.

Table 1. Effect of NM composition on shoot formation of *L. nummularia* explants

NM	NM composition, mg·l^{-1}	Number of explants with regenerants, pcs.	Regenerative ability, %	Number of regenerants per explant, pcs.
MS1	0.5 TDZ	10.0	100.0	5.4
MS2	1.0 TDZ	4.0	53.3	1.1
MS3	0.5 KIN	8.0	80.0	3.4
MS4	0.25 KIN	9.0	86.7	3.5
MS5	0.5 BA	3	33.3	2.2
DKW 1*	4.0 BAP, IBA 0.003, GA 0.1 benzoic acid 0.025	10	100.0	8.7
DKW 2*	Basic	3.0	30.3	1.4
DKW 3*	5.0 BA, 0.01 IBA	0	0	0
DKW 4	0.5 BA	5.0	49.6	1.0
DKW 5	1.0 BA	3.0	20.5	1.0
DKW 6	2.0 BA	0	0	0

*NM with the a ddition of Fe-EDDHA 4.8%

For this, MS and DKW NM were used with the addition of distinct groups of cytokinins and auxins to their composition: 6-benzaminopurine (BA), thidiazuron (TDZ) and kinetin (KIN), indolebutyric acid (IBA), gibberellic acid (GA), etc., both separately and in combination with each other.

As a result of the experiment, shoot genesis was observed on stem explants. Explants cultured on NM with 0.5 mg·l^{-1} KIN formed a small number of shoots and were characterized by slow development. But when adding 0.25 mg·l^{-1} KIN and 1 g·l^{-1} of activated carbon to the composition of NM, it helped induce flowering of regenerating plants of *L. nummularia* already in 2-3 passages.

Cultivation of explants on a medium with 0.5 mg·l^{-1} kinetin caused the development of a small number of microshoots with bud meristems. Added buds formed in 60% of explants were characterized by slow development. The addition of KIN to the composition of NM at a concentration of 0.25 mg·l^{-1} and 1 g·l^{-1} of activated carbon induced the flowering effect of *L. nummularia* regenerating plants in 2-3 passages (Fig. 2).

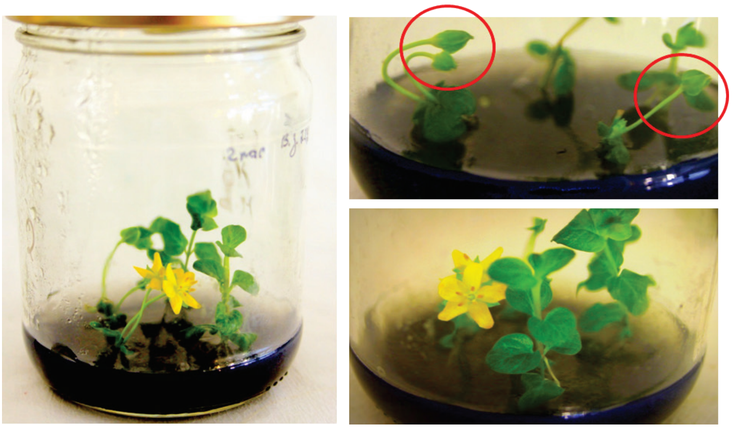

Figure 2. Flowering of regenerating plants of *L. nummularia* in *in vitro* culture

The regenerating plants of *L. nummularia*, cultivated on the nutrient media of MS and DKW with the addition of 1.0-1.5 mg·l^{-1} TDZ to its composition, had a negative effect on the explants. In some plants, reddening of leaves and their falling were noted. The formation of added microshoots was not observed. This phenomenon is characteristic when using thidiazuron [5]. High morphogenic ability and formation of the root system were noted on NM supplemented with 0.5 mg·l^{-1} TDZ. Under such conditions, the regenerative capacity and maximum growth of regenerating plants were activated, reaching almost 100% (Fig. 3a, b). The use of DKW and MS nutrient media supplemented with BA ensured little shoot formation. With the addition of 0.5 mg·l^{-1} of BA, 33.3% for MS and 49.6% for DKW were obtained for explant tissues to form microshoots.

High results were obtained on nutrient medium DKW 1*, DKW 2* with the addition of Fe-EDDHA 4.8%. Regenerating plants formed the maximum number of microshoots by activating meristems already present in the plant, but the growth rate was lower (Fig. 3c, 3d).

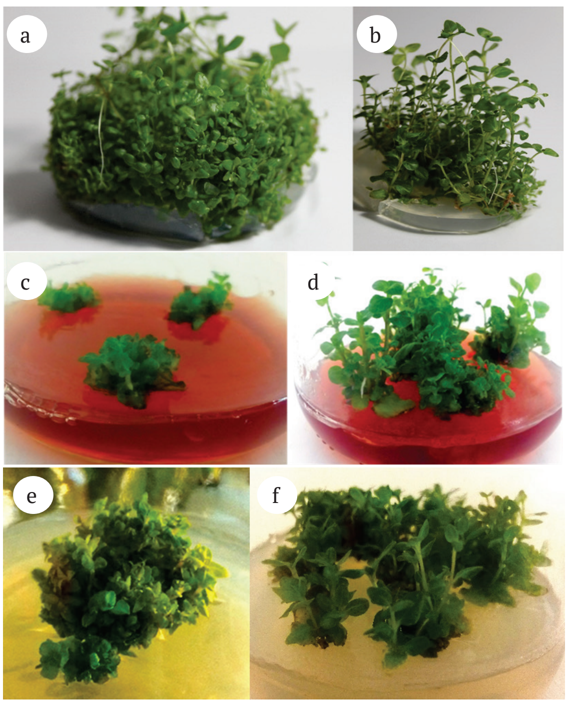

Figure 3. Morphogenesis of *L. nummularia* (a, b – direct morphogenesis on MS NM with the addition of 0.25 mg·l^{-1} kinetin; c, d – mass microclonal propagation of *L. nummularia* on NM using Fe-EDDHA 4.8% (NM DKW 1*, DKW 2*); e, f – multiplications on NM supplemented with 0.5 mg·l^{-1} TDZ)

The use of NM of this composition is best for propagation by direct morphogenesis and preservation of plants into *in vitro* culture conditions for a long time with a minimum amount of passaging.

Subsequently, the formed microshoots from distinct types of explants were passaged on fresh NM supplemented with 0.5 $mg \cdot l^{-1}$ TDZ (Figs. 3e, 3f) for a long time, such cultivation is effective only for 3-4 passages, then plant growth is inhibited and decreases regeneration coefficient. Taking this into account, further passages were carried out on NM according to the prescription of MS, or with the addition of 0.25 $mg \cdot l^{-1}$ kinetin, where the stimulation of growth factors and the induction of the morphogenic potential of explant tissues, with a high regeneration coefficient, were noted.

For the selection of highly productive cell lines of representatives of the *Lysimachia* genus, specially balanced NM was selected according to the MS prescription (Table 2).

Table 2. The influence of different concentrations of plant growth regulators on the formation of callus culture from distinct types of *L. nummularia* explants

Variant, cell lines	Growth regulators				Explant type					
					Leaf plate part			Stem part		
	2,4-D, $mg \cdot l^{-1}$	BA, $mg \cdot l^{-1}$	TDZ, $mg \cdot l^{-1}$	NAA, $mg \cdot l^{-1}$	Frequency of callus formation, %	Intensity of callus formation*	Growth index	Frequency of callus formation, %	Intensity of callus formation*	Growth index
K	0	–	–	–	–	–	–	–	–	–
1	1.0	–	–	0.1	24.3	++	1.3	13.3	+	1.2
2	1.5	–	–	0.1	85.7	++	1.4	20.0	+	1.5
3	2.0	–	–	–	56.7	++	3.6	50.0	+ +	3.2
4	2.5	–	–	–	84.7	++	1.8	30.0	+	1.7
5	3.0	–	–	–	96.2	+ + +	–	–	–	–
6	–	–	1.0	–	–	–	–	–	–	–
7	–	–	1.5	–	–	–	–	–	–	–
8	–	–	–	–	–	–	–	–	–	
9	–	1.0	–	–	–	–	–	–	–	–
10	–	2.0	–	–	–	–	–	–	–	–
11	–	2.5	–	–	16.1	+	–	–	–	–
12	–	3.0	–	–	23.4	+	–	–	–	–
13	–	1.0	–	0.1	67.6	+ + +	–	–	–	–
14	–	1.5	–	0.1	100	+ + +	1.4	83.3	+ +	3.0
15	–	2.0	–	0.2	100	+ + +	4.8	98.3	+ + +	7.2

Note: (–) – absence of callus formation, (+) – low, (++) – medium, (+++) – active

As a result, a callus culture was obtained from segments of young stems and leaf plates, which were grown on selective MS media with different ratios of hormones of cytokinin – TDZ, BA, and auxin – NAA, 2.4-D type of action.

According to the data of the experiment on NM with TDZ of different concentrations, the formation of callus culture did not occur, only 30% of the explants showed activation of axillary buds, the rest were twisted or did not undergo changes. The addition of high concentrations of BA to NM led to the intensive formation of accessory buds directly on the explant, without the stage of callus formation. Callus was formed only in some variants, not in significant quantities.

As a result of adding 2.0 $mg \cdot l^{-1}$ BA and 0.2 $mg \cdot l^{-1}$ NOK to NM and cultivation in the dark under controlled conditions for 3-4 weeks, callus cultures with a predominantly dense structure with a coarsely bumpy surface were obtained, of light green and yellow colors, which grew intensively in the depth of NM.

To investigate the possibilities of growth and accumulation of phenolic compounds, studies on the cultivation of raw callus biomass, as well as strains obtained from cultivated cells of *L. nummularia*, were continued on six variants of NM with the addition of plant growth regulators, namely: 1.5-2.0 $mg \cdot l^{-1}$ BA and 0.1-0.2 $mg \cdot l^{-1}$ NOK, 1.5-3.0 $mg \cdot l^{-1}$ 2.4-D (Table 3).

Table 3. Obtaining cell lines of *L. nummularia* with the content of specific metabolites

Variant, cell lines	Growth regulators				Visual observations, after 3 weeks in a thermostat
	2.4-D, $mg \cdot l^{-1}$	BA, $mg \cdot l^{-1}$	TDZ, $mg \cdot l^{-1}$	NAA, $mg \cdot l^{-1}$	
K	0	–	–	–	–
LN-EE 01/19	2.0	–	–	–	Slight formation of callus, loose yellow-white structure

Table 3, Continued

Variant, cell lines	Growth regulators				Visual observations, after 3 weeks in a thermostat
	2.4-D, mg·l⁻¹	BA, mg·l⁻¹	TDZ, mg·l⁻¹	NAA, mg·l⁻¹	
LN-EE 02/19	–	2.0	–	0.2	Active formation of biomass with a dense tumour structure, light green and white
LN-EE 03/19	1.5	–	–	0.1	Inactive formation of yellow callus mass
LN-EE 04/19	3.0	–	–	–	Active formation of callus biomass of non-morphogenic nature, light yellow with brown zones
LN-EE 05/19	–	–	0.5	–	Insignificant formation of a dense light green callus culture, with the ability to morphogenesis.
LN-EE 06/19	2.5				Slight formation of callus, loose yellow-white structure

As a result of three-week cultivation in the dark, strains of callus cultures were obtained, which were analysed for the presence of promising biologically active substances and their concentrations.

All cultured cell lines were characterized by sufficiently high production of callus biomass, but they differed in structure and colour. Three major phenolic components were isolated from six cell lines' biomass. As a result of the analysis, the most significant accumulation of active substances was the LN-EE 02/19 cell line (Fig. 4).

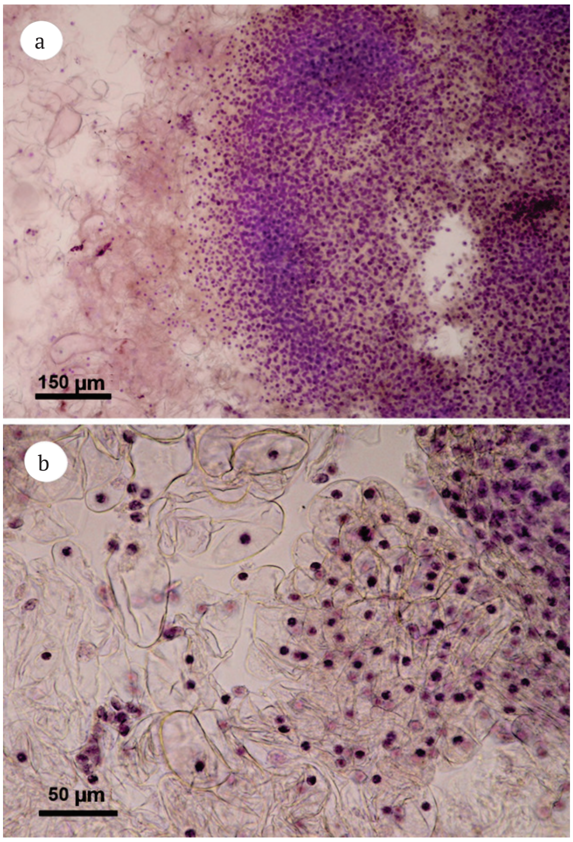

Figure 4. Cells of non-morphogenic callus of *L. nummularia* line LN-EE 02/19 – an active producer of myricetrin; DNA staining with Schiff's reagent after cold hydrolysis for 40 min with 1N HCl at 25°C

It was established that on MS nutrient media with 2.0 mg·l^{-1} BAP and 0.2 mg·l^{-1} NAA in callus and suspension culture biomass, the accumulation of the flavanol myricetrin occurs, where its amount was the largest and amounted to 9.8 mg·l^{-1} raw weight.

Cells of non-morphogenic callus had high proliferative activity and the nuclei sizewas 7-8 µm. The cells of the peripheral zone are elongated, much larger and mostly anucleate. The active zone of division is represented by small cells with an insignificant index of the ratio of the nucleus to the cytoplasm.

The ability of callus cultures to synthesize target substances under the conditions of serial passage was preserved. Among the isolated groups of secondary metabolites in the LN-EE 02/19 line, myricetrin (flavonol) was isolated (Fig. 5). The ability of the obtained *L. nummularia* cell lines to synthesize this group of compounds actively can be considered in the perspective of its use as an antiseptic agent.

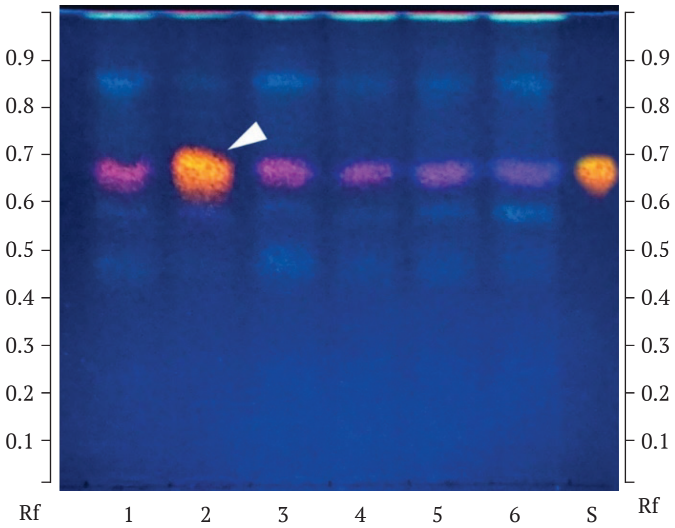

Figure 5. Chromatography of methanolic extracts of callus tissues of the investigated *L. nummularia* cell lines: 1 – LN-EE 01/19, 2 – LN-EE 02/19, 3 – LN-EE 03/19, 4 – LN-EE 04/19, 5 – LN-EE 05/19, 6 – LN-EE 06/19

As a result of the analysis, the obtained callus culture cell line LN-EE 02/19 allows obtaining myricetrin in amounts up to 10.0-12.0 mg·l^{-1} of raw biomass.

This suggests that for cultivation and obtaining the isolated cell lines, it is necessary to use NM with 2.0 BAP and 0.2 NAA in the dark for 3 weeks, and after that continue cultivation on the same medium, but under lighting conditions for 7 days The change in NM composition to lower concentrations of hormones during subsequent passages and their effect on the synthesis and accumulation of target products have not yet been studied.

The established experiments indicated that the most effective callus formationoccurs on stem segments without access to light, for 3-4 weeks, followed by their cultivation on specially selected media.

Cell lines LN-EE 01/19, LN-EE 05/191, LN-EE 06/19 were characterized by low productivity. For Days 21-28 of growth on the nutrient medium according to the MS prescription, the callus biomass yield was on average 1.7 mg per explant. In contrast to this, line 2 accumulated significantly more callus biomass under the same cultivation conditions and biologically active substances, respectively, which is promising for growing the culture in industrial conditions. The high ability of the obtained lines to morphogenesis under lighting conditions was also noted. This was in contrast to cell lines LN-EE 01/19, LN-EE 03/19, LN-EE 05/19, which were characterized by a low ability for morphogenesis, slowed growth and accumulation of a small numberof flavonoid substances.

Conclusions

It was found that organogenesis in the culture of *L. nummularia* depended on the size of the donor plant, the phenological phase of plant vegetation, the composition of NM and the amount of PGR.

The need to develop methods of microclonal reproduction lies in optimizing the composition of the nutrient medium for cultivating various explants and using methods of direct and indirect morphogenesis.

It was established that on nutrient media with 0.25 mg·l^{-1} kinetin and 0.5 mg·l^{-1} TDZ g·l^{-1}, the full realization of the morphogenetic potential of explant tissues, induction, and proliferation of the root system took place, and regenerative plants capable of adaptation were obtained.

For long-term cultivation of *L. nummularia* plants in *in vitro* culture, the hormone-free MS nutrient medium is optimal. For the active proliferation of microshoots from different types of explants of *L. nummularia* in isolated conditions, the best results were obtained using NM with Fe-EDDHA complex 4.8%, DKW NM with 4.0 mg·l^{-1} BA, 0.003 mg·l^{-1} IBA, 0.1 mg·l^{-1} GA, 0.025 mg·l^{-1} BA.

The optimal conditions for the induction of callus formation and obtaining the culture of cells and callus tissues of *L. nummularia* and its passage *in vitro* were selected. It has been shown that the modified nutrient medium of Murashige and Skoog, with 2.4-D (1.5 mg·l^{-1}) and NAA (0.2 mg·l^{-1}) is optimal for the accumulation of callus tissue biomass of *L. nummularia*, which provided the callus formation frequency for the first and second passages up to 98.0 ± 0.2%.

5 cell lines that actively synthesize stilbenoids and the highly productive LN-EE 02/19 cell line, which is capable of synthesizing and accumulating in callus tissues up to 10-12 mg/g of myricetrin, were selectively isolated.

It was established that for the intensive synthesis of myricetrin by the LN-EE 02/19 cell line, the nutrient medium of MS with 2.0 mg·l^{-1} BA and 0.2 mg·l^{-1} NAA is optimal.

The prospect of further research lies in the implementation of the developed protocols and the verification of the effectiveness of the technology on an industrial scale.

References

[1] Belmain, S. (2014). Herbivore defence compounds occur in pollen and reduce bumblebee colony fitness. *Journal of Chemical Ecology*, 40, 878-881.

[2] Zhang, H.Z., Jie, J.Q., & Lv, D. (2005).Tissue culture of *Lysimachia christinae*. *Agricultural Science and Practice,* 3, 83-85.

[3] Xu, G.F. (2007). Physiological process of drough tresistance of two *Lysimachias* pecies. *Journal of Northwest Forestry University*, 22, 12-14.

[4] Gupta, S., Kaliamoorthy, S., Jayashankar, D., Mao, A., & Soneswar, S. (2012). Micropropagation of *Lysimachia laxabaudo*. *Asian Journal of Science and Technology*, 4(12), 024-027.

[5] Grodzinsky, A.M. (Ed.). (1989). *Medicinal plants*. Kyiv: Main Editorial Office of the Ukrainian Soviet Encyclopedia.

[6] Goncharenko, I.V., Ignatyuk, O.A., & Shelyag-Sosonko, Yu.R. (2013). Forest vegetation of the Feofania tract and its anthropogenic transformation. *Ecology and Noospherology,* 24(3-4), 51-63.

[7] Johannsson, M., Winsor, J., & Stephenson, A. (1994). Genetic and environmental effects on *in vitro* pollen tube growth in Cucurbita. Pollen-pistil interactions and pollen tube growth. *An American Society of Plant Physiologists*, 12, 307-309.

[8] Simpson, S., & Raubenheimer, D. (2012). *The nature of nutrition: A unifying framework from animal adaptation to human obesity.* Princeton: Princeton University Press.

[9] Havens, K. (1995). Secondary nitrogen limitation in a subtropical lake impacted by non-point source agricultural pollution. *Environmental Pollution*, 89, 241-246.

[10] Jakobsen, H., & Martens, H. (1994). Influence of temperature and aging of ovules and pollen on reproductive success in *Trifolium repens* L. *Annals of Botany*, 74, 493-501.

[11] Podolak, I., Koczurkiewicz, P., Michalik, M., Galanty, A., Zajdelm, P., & Janeczko, Z. (2013). A new cytotoxic triterpene saponin from *Lysimachia nummularia* L. *Carbohydrate Research*, 375, 1-20.

[12] Tsukanova, G.O., Andrienko, T.L., & Pryadko, O.I. (2002). Vegetation cover of the Dnipro islands within the city of Kyiv. *Ukrainian Botanical Journal*, 59(2), 135-140.

[13] Tsukanova, G.O. (2003). Sozological characteristics of the flora of the Dnipro islands and the adjacent part of the floodplain within the city of Kyiv. *Ukrainian Botanical Journal,* 60(4), 397-404.

[14] Stowe, L. (1979). Allelopathy and its influence on the distribution of plants in an Illinois old-field. *Journal of Ecology*, 67, 1065-1085.

[15] Svetla, D.Y., Sara, G., Ervin, F., Simcha, L.Y., & Moshe, A.F. (2003). Auxin type and timing of application determine the activation of the developmental program during *in vitro* organogenesis in apple. *Plant Science,* 165, 299-309.

[16] Richards, L.A., Dyer, L.A., Forister, M.L., Smilanich, A.M., Dodson, C.D., Leonard, M D., & Jeffrey, C.S. (2015). Phytochemical diversity drives diversity of tropical plant-insect communities. *Proceedings of the National Academy of Sciences*, 112, 10973-10978.

[17] Ruedenauer, F., Spaethe, J., & Leonhardt, S. (2016). Hungry for quality individual bumblebees forage flexibly to collect high-quality pollen. *Behavioral Ecology and Sociobiology*, 70, 1209-1217.

[18] Vanderplank, S., Rebman, J., & Ezcurra, E. (2017). Where to conserve? Plant biodiversity and endemism in mediterranean Mexico. *Biodiversity and Conservation*, 27, 109-122.

[19] Didukh, Y.P., & Didukh, Ya.P. (2011). *The ecological scales for the species of Ukrainian flora and their use in synphytoindication*. Kyiv: Phytosociocenter.

[20] Dogan, M. (2022). *In vitro* shoot regeneration of *Lysimachia nummularia* L. in solid and liquid culture medium. *CUPMAP*, 6, 875-881.

[21] Radchenko, V.H., Bilous, S.Yu., & Matiashuk, R.K. (2016). Peculiarities of obtaining aseptic culture of stem explants of *Lysimachia nummularia* L. in *in vitro* conditions. In *Actual problems of the forestry sector and horticulture* (p. 102). Kyiv: National University of Life and Environmental Sciences of Ukraine.

[22] Radchenko, V., Likhanov, A., & Matyashuk, R. (2017). Histochemical heterogeneity of secretory structures in the flowers of *Lysimachia nummularia* L. *Agrobiodiversity for Improving Nutrition, Health and Life Quality*, 1, 383-387.

[23] Ruedenaue, F., Leonhard, S., Lunau, K., & Spaethe, J. (2019). Bumblebees are able to perceive amino acids via chemotactile antennal stimulation. *Journal of Comparative Physiology*, 205, 321-331.

[24] Konvaliuk, I.I., Kravets, N.B., Drobyk, N.M., Melnyk, V.M., & Kunakh, V.A. (2010). Direct organogenesis *in vitro* of yellow tirlych (*Gentiana lutea* L.). *Biotekhnolohiia*, 3(5), 66-73.

[25] Murashige, T., & Scoog, F. (1962). Arevised medium for rapid, grow than bioassays with tobacco tissue cultures. *Physiologia Plantarum*, 15, 473-497.

[26] Driver, J.A., & Kuniyuki, J.H. (1984). *In vitro* propagatio of Paradox walnu troot stock. *HortScience*, 19, 507-509.

[27] Dogan, M., (2018). *In vitro* micropropagation from nodal explants of the medicinal plant *Lysimachia nummularia* L. *Journal of Agriculture and Nature*, 21(6), 875-881.

[28] Chornobrov, O., & Bilous, S. (2021). In vitro plant regeneration of Christmas cactus (Schlumbergera truncata (Haw.) Moran) by indirect morphogenesis. *Folia Forestalia Polonica, Series A – Forestry*, 63(1), 68-73.

[29] Mitrofanova, I.V. (2011). *Somatic embryogenesis and organogenesis as the basis of biotechnology for the production and preservation of perennial garden crops*. Kyiv: Agricultural Science.

[30] Butenko, R.G. (1975). *Experimental morphogenesis and differentiation in plant cell culture*. Moscow: Nauka.

[31] Hussain, S.A., Ahmad, N., & Anis, M. (2018). Synergetic effect of TDZ and BA on minimizing the post-exposure effects on axillary shoot proliferation and assessment of genetic fidelity in *Rauvolfia tetraphylla* (L.). *Rendiconti Lincei. Scienze Fisiche e Naturali*, 29(1), 109-115.

Морфогенез в культурі *in vitro* клітинних ліній рослин *Lysimachia nummularia* L. перспективних за вмістом біологічно активних речовин

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Анотація. *Lysimachia nummularia* L. – це рослини, що належать до родини *Primulaceae*, є особливо цінними як лікарська сировина, що використовується в народній медицині багатьох країн. Має чудову антибактеріальну та антиоксидантну здатність метаболітів. Саме тому мікроклональне розмноження *Lysimachia nummularia* L є актуальним питанням. Мета статті – розробити підходи до мікроклонального розмноження L. *nummularia*. Для мікроклонального розмноження L. *nummularia* використовували метод активації вже існуючих у рослині меристем ізольованих тканин і органів та індукція прямої регенерації безпосередньо тканинами експланту. Для добору високопродуктивних клітинних ліній представників роду *Lysimachia* калюсну культуру отримували шляхом непрямого морфогенезу із стеблових та листкових експлантів. З'ясовано, що формування тканин та органів L. *nummularia* у культурі *in vitro* залежало від складу живильного середовища й кількісного та якісного співвідношення регуляторів росту в ньому. Активну проліферацію мікропагонів L. *nummularia* в культурі *in vitro* відмічено на варіантах живильного середовища Мурасіге і Скуга та Драйвера Куньюки з додаванням 6-бензиламінопурину 4,0 мг·л$^{-1}$, індоліл масляної кислоти 0,03 мг·л$^{-1}$, гиберелової кислоти 0,1 мг·л$^{-1}$. Встановлено, що для мікроклонального розмноження, індукування й проліферації кореневої системи та отримання рослин-регенерантів L. *nummularia* найефективнішим є використання живильних середовищ за прописом Мурасіге і Скуга з додаванням тідіазурону 0,5 мг·л$^{-1}$ та 0,25 кінетину. Підібрано оптимальні умови для індукції калюсогенезу і отримання культури клітин і калюсних тканин L. *nummularia* та її пасажування в умовах *in vitro*. Показано, що оптимальним для накопичення біомаси калюсних тканин L. *nummularia* є модифіковане живильне середовище Мурасіге і Скуга, з 2,4-дихлорфеноцтовою кислотою 1,5 мг·л$^{-1}$ та індол-3-оцтовою кислотою 0,2 мг·л$^{-1}$, що забезпечували частоту калюсогенезу для першого й другого пасажу до 98,0 ± 0,2 %. Селективним шляхом виділено 5 клітинних ліній, які активно синтезують стильбеноїди та високопродуктивну клітинну лінію LN-EE 02/19, яка здатна синтезувати і накопичувати в калюсних тканинах до 10-12 мг/г мирицетрину. У результаті аналізу отримано клітинну лінію калюсної культури LN-EE 02/19, що дозволяє отримувати мирицетрин у кількостях до 10,0-12,0 мг·л$^{-1}$ сирої біомаси. Розроблений протокол може використовуватись як для рослин L. *nummularia* так і інших представників родини *Primulaceae*

Ключові слова: культура клітин, тканин та органів *in vitro*, живильне середовище, експлантат, мікроклональне розмноження, калюсогенез

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Mobile technology of thermal modification of wood

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Abstract. Wood as a structural material has some disadvantages, which include a short service life, relatively low form resistance, considerable volumetric deformations under moisture, pronounced anisotropy, and water absorption. Thermal modification slightly improves the physical and mechanical properties. However, a problem of changing surface characteristics occurs, specifically adhesion. To determine the technological characteristics of thermally modified wood and develop possible measures to improve the technology of applying protective coatings, the surface energy and compressive strength along the fibres were determined. A comprehensive approach was applied to analyse the surface state of thermally modified wood through the investigation of surface energy characteristics based on the Fowkes method, which considers dispersion, hydrogen, and dipole-dipole interactions at the solid-liquid interfacial boundary. According to the marginal angle of wetting, it was found that the thermal modification of wood helps increase the resistance of its surface to wetting by reducing the polarity by 1.68 times with an increase in the duration of modification to 30 min. Therewith, the surface free energy for samples modified at 300°C for 5 min is 64.5 mJ/m^2, for 30 min – 24.1 mJ/m^2. Regarding compressive strength, thermal modification reduces the strength limit by 1.46 times. Thus, at 300°C and a time of 5 min and 15 min, the indicator stays at the level of ordinary wood – 42 MPa. Processing for 30 minutes reduces the strength limit to 29 MPa, the wood loses its plasticity. The obtained results allow effectively choosing stable coatings for such wood for high-quality surface treatment with paint and varnish materials. Knowing the moment of time from which the reduction of the strength limit begins, thermal modification becomes more controlled and allows predicting the characteristics of the future material

Keywords: wood material, technological parameters, thermal modification process, wetting angle, surface free energy, compression along the fibres, strength limit, brittleness

Introduction

Wood is widely used in construction due to its mechanical and operational properties. However, it tends to collapse under atmospheric factors. Still, it is possible to increase the level of operation of building structures made of wood by thermal modification. The essence of this modification method is to give wood new improved properties – to resist the influence of moisture, biological factors, and prevent wood destruction.

But during thermal modification of wood, there are certain difficulties associated with technological parameters, specifically time and temperature. This is because in effective thermal modification of wood, it is necessary to season it for several days at temperatures above 200°C. Therewith, there may be a difference in the structure of wood and modification is not always achieved. Knowledge of the physical and mechanical properties of thermally modified wood and quality indicators allows choosing a technology considering economic indicators and the safety of technology application, environmental aspects.

Therefore, the development of the mode of mobile technology of thermal modification of wood, the study of thermophysical transformations for this process is an unresolved component of the production of sustainable building materials from wood. This determines the need

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to establish the technological parameters of such thermal modification.

The purpose of this study is to investigate the technological characteristics of thermally modified wood to determine the surface energy and justify the compressive strength along the fibres.

To fulfil the purpose of this study, the tasks were set as follows:

– to establish the features of changing the surface energy of wood depending on the time of thermal modification of wood.

– to find the limits of strength during compression along the fibres, depending on the time of thermal modification of wood.

The scientific originality lies in the creation of a mobile technology for thermal modification of wood, characterized by a decrease in the time of thermal modification at elevated temperatures.

Literature Review

A review [1] summarizes recent advances and provides a perspective on the choice of wood modification method, i.e., the currently commercialized methods (acetylation, furfurylation, and thermal modification). An ancient practice (charring) has been rediscovered, certain types of polymerization modifications have now reached pilot scale, and samples of new functional wood-based materials are being explored at laboratory scale. And in paper [2] it is stated that wood modification is an excellent and increasingly popular method of expanding the use of wood materials. Conventional methods, such as chemical or thermal, have been developed to purposefully improve some selected wood properties, unfortunately usually at the expense of other parameters. These methods, as a rule, change the composition of wood, and therefore its mechanical properties, increase dimensional stability, water resistance, or reduce its sensitivity to microorganisms. Although conventional methods achieve the desired properties, they require the use of a lot of energy or chemicals. Therefore, research is more often shifting towards the development of more ecological processes. The advantage of modern methods is that in most cases they only modify the surface and do not affect the structure and mechanical properties of wood, while the use of chemicals is minimized. Cold plasma surface treatment is one of the cheapest and simplest technologies with limited environmental impact.

Compared to other building materials, wood has many advantages [3], such as thermal insulation, high strength-to-weight ratio, easy to process and has an attractive aesthetic appearance. But, as a valuable building and industrial material, it needs protection from biodegradation, especially when structures are exposed to harsh environmental conditions during operation. The durability of wood can be increased with wood preservatives and modification systems. Wood protection must be safe to use, reliable and long-lasting, cost-effective, and must not corrode metal or damage wood components. Presently, the scientific literature holds numerous reports on wood protection, but so far, the combination of wood preservation and modification has not been considered. Notably, the latest wood protection research projects in academia do not always reflect the most current developments in the field due to exclusive rights. The obtained results and conclusions, which are reported in scientific publications, contribute to the safe use of preservatives, the improvement of wood modification methods, as well as the processing and disposal of treated material. Thus, this paper discusses the latest research and advances in wood protection, including a general summary of the latest developments in wood preservatives, several types of preservatives, natural preservatives, and modification technologies. Therefore, it is desirable to use natural materials in the future.

Wood used outdoors is exposed to several biotic and abiotic factors, and for this reason, it needs protection to extend its life [4]. Some wood protection technologies are already being used commercially. One such technology is thermal modification, which refers to the structural, mechanical, and chemical transformations that occur in lignocellulosic material when gradually heated to certain temperature ranges. Over the past few years, researchers have evaluated weather resistance for distinct types of wood. Some experiments looked at natural radiation in different countries with distinct climatic conditions, while others focused on artificial radiation during UV and xenon tests. Most of the studies evaluated the effect of weathering on chemical, mechanical, and physical and anatomical changes compared to the initial characteristics of the material. A review of the scientific literature revealed a significant lack of research focused on abiotic impact factors, such as industrial and marine environments, or even individual climate factors, such as salt spray (simulated marine environment) or polluting gases (simulated industrial environment). This lack of information may be an opportunity for future work. This can provide understanding whether thermally modified wood is sensitive to pollutant gases or salinity, or a combination of the two. Knowing the mechanisms of degradation caused by these factors, it will be possible to investigate other forms of protection.

The greatest interest of researchers is caused by heat treatment of wood occurring in an airless environment at 180-250°C, since heat treatment of wood can increase its moisture resistance, reduce hygroscopicity and increase resistance to rot [5]. However, a decrease in the hygroscopicity of wood adversely affects the process of obtaining glued materials due to a decrease in surface wettability of thermally modified wood and, as a result, a decrease in adhesive characteristics. This paper investigates the effect of ozone on the surface of thermally modified wood to improve the adhesive properties during bonding. It was established that ozonation contributes to an increase in the surface wettability of thermally modified wood by over 15% due to the reactivity of ozone to oxidize and degrade lignin-containing wood products. It was found that the modification of wood, which includes preliminary volume heat treatment followed by surface treatment with ozone, causes an increase in the strength of the adhesive layer during operation in conditions of elevated humidity. In connection with the obtained results, an improved technology to produce glued support structures for wooden house construction is proposed.

The study [6] examines the results of hygroscopic and dimensional behaviour of thermally modified wood, modified in dry (the cell wall has almost zero moisture content) and wet (the cell wall contains moisture) conditions.

The literature on the thermal degradation of polysaccharide and lignin components of the cell wall, as well as the role of extractives, is also examined. Properties of wood modified in wet and dry conditions are compared, including mass loss, hygroscopic behaviour, and dimensional stability. The role of hydroxyl groups in determining hygroscopicity is discussed, as well as the importance of considering the mobility of cell wall polymers and crosslinking when interpreting sorption behaviour. The behaviour of thermally modified wood produced under wet conditions changes when the wood is further treated with water leaching, which includes further weight loss, changes in sorption behaviour and dimensional stability, but without any further adjustments in available hydroxyl (OH) content. This raises fundamental questions about the role played by OH groups in the sorption behaviour.

The paper [7] reviews systems that combine established wood modification procedures with secondary techniques or modifications to develop innovative technologies with multiple functionalities. These include UV stabilization, fire resistance or increased suitability for the application of paints and protective coatings. Thus, wood can become a multifunctional material through a series of modifications, treatments, or reactions to create a high-performance material with previously impossible properties. New applications targeting this extra functionality are diverse and range from enhancing electrical conductivity, creating sensors or responsive materials, improving well-being in the architectural environment, and improving fire and flame protection. Two parallel and related topics are identified: the functionality of modified wood and the modification of wood for multifunctionality. The new generation of wood modifications and wood processing uses a wide range of nanotechnology concepts. As this industry is expanding rapidly, current research trends are also included in the review to estimate the current status, but the likely direction of the industry is unknown.

Alternative and environmentally friendly technologies, such as thermal modification, can improve the durability and dimensional stability of wood, as reported in [8]. The effect of thermal modification on increasing the resistance of *Corymbia citriodora* and *Pinus taeda* wood against brown and white rot fungi in laboratory conditions was evaluated. Wood samples were exposed to temperatures of 160°C, 180°C, 200°C, 220°C, and 240°C in a laboratory electric furnace in a dynamic nitrogen atmosphere. For *P. taeda*, a processing temperature of 260°C was additionally used. Seven boards with dimensions of 6 cm×16 cm×56 cm (thickness × width × length) were used for each temperature. The thermally modified boards were transformed into prismatic test specimens with dimensions of 1.9 cm×1.9 cm×1.9 cm. Bottles of inoculated cultures containing test blocks were stored in the incubation room for 12 weeks. It was found that temperatures of thermal modification at the level of 160°C and 180°C reduced the biological stability of *C. citriodora* wood. Treatment temperatures of 200°C, 220°C and 240°C showed a satisfactory increase in rot resistance for both breeds.

In the study [9], pine (*Pinus massoniana* Lamb.) samples were thermally treated at different temperatures (150°C, 170°C, and 190°C), and the nanomechanical properties of the cell wall of the wood, which was coated with a water-based polyacrylic lacquer product, were determined and compared. The modulus and cell wall hardness of the wood and coating were measured and characterized by nanoindentation, and the factors influencing the mechanical properties during thermal modification were investigated by chemical composition analysis, contact angle analysis, and colorimetric analysis. The results showed that as the heat treatment temperature increased, the contact angle of water with the wood surface and the colorimetric difference increased, while the content of cellulose and hemicellulose decreased. After thermal modification at 190°C, the modulus of elasticity and hardness of the wood cell wall increased by 13.9% and 17.6%, respectively, and the modulus of elasticity and hardness of the polyacrylic coating applied to the wood decreased by 12.1% and 22.2%. The modulus of elasticity and hardness of the interface between the coating and the wood were lower than near the surface of the coating. The modulus of elasticity and the hardness of the cell wall at the interface between the coating and the wood were lower than those at a distance from the coating. The necessity and improvement of wood materials processing technology after thermal modification is not shown.

Due to environmental problems, the use of wood materials is becoming increasingly widespread and causes a shortage of wood [10], so the use of *Populus* wood as a fast-maturing wood is vital. *Populus* wood has several disadvantages: it is not durable, has a low density and is hygroscopic. Thermal modification is a technology that can be used to improve the situation. Therefore, in the study, aspen (*Populus tremula* L.) was thermally treated for 50 minutes at 160°C, and poplar (*Populus* x *canadensis* Moench) was processed in a vacuum environment for 120 min at 204°C, 120 min at 214°C, 180 min at 217°C, and 30 min at 218°C. Mass loss, colour change, density, tensile strength along the fibres, moisture removal efficiency and weight loss after the action of the brown rot fungus *Coniophora puteana* were determined, and light microscopy images were taken. The aspen veneer lost 5.3% weight between the 120-214 (6.2%) and 30-218 (4.6%) treatments in vacuum, which was consistent with the results in the scientific literature. The highest rate of mass loss was 8.7% in samples of wood modified with parameters of 180 min at 217°C in a vacuum, while the lowest – 2.9% – was obtained at 204°C for 120 min. The total colour change ΔE was 44 c.u., with the lightness parameter L providing the largest effect, which was halved after modification. Tensile strength decreased by 47% after modification for 50 min at 160°C and had a decrease of 29% during vacuum treatment. The weight loss of wood after exposure to the fungus *C. puteana* was 33% for 50 min at 160°C. After vacuum modification – 0-2.4%. The most suitable to produce plywood was poplar veneer thermally modified with the following operating parameters – 120 min at 214°C and 180 min at 217°C, vacuum environment.

Mozambique's abundance of tropical hardwoods is hindered by the predominance of low-grade wood species, as well as the lack of cost-effective treatment technologies to improve wood properties. *Brachystegia spiciformis* and *Julbernadia globiflora* are the most common wood species in terms of volume in the country, but with limited use due to poor wood quality. Therefore, in [11] thermal modification of wood of both species at three different temperatures (215°C, 230°C, and 245°C) for 2 hours was investigated with subsequent measurement of physical and mechanical properties of the material. The results indicate that the initially light sapwood of both types of wood gradually darkened with increasing intensity of thermal modification. Furthermore, from untreated samples to the highest level of heat treatment, *B. spiciformis* wood experienced a maximum weight loss of 27%, while the dry wood density decreased from 0.65 to 0.56 g/cm^3 and the equilibrium moisture content changed from 7 to 3%. *J. globiflora* wood had a 23% mass loss after the highest treatment level, a decrease in density from 0.81 to 0.74 g/cm^3 and a decrease in equilibrium moisture content from 8 to 3%. The changes in mechanical properties from the control samples to the highest level of heat treatment were also significant. For *B. spiciformis*, the modulus of elasticity decreased by 10.2%, the tensile strength – by 50.8%, the compressive strength along the fibre – by 29.2%, and the Brinell hardness – by 23.5%. The wood of *J. globiflora* follows the same trend of decreasing parameters – 6.9%, 53.2%. and 21.9%, respectively. All tested wood properties showed a considerable response to thermal modification after applying the most intensive treatment level. Despite the deterioration of the mechanical properties of both species, it is possible to achieve an optimal combination of temperature and processing time. The registered changes in the examined properties of wood of both species can expand the range of applications. Furthermore, the acquired colour resembled the colour of deciduous tropical species, which is very much in demand.

The research presented in [12] investigates the effect of thermal modification on the physical and mechanical properties of wood. To this aim, the experimental part was focused on the selected influencing parameters, namely temperature, residence time and density, while the four-point flexural strength was obtained as an output parameter. The obtained experimental data are stochastically modelled and compared with the model created by the method of genetic programming. Classical mathematical analysis provided processing parameters for the maximum bending strength – T = 187°C, t = 125 min, ρ = 0.780 g/cm^3) and compared with the results obtained by the genetic algorithm – T = 208°C, t = 122 min, ρ = 0.728 g/cm^3). Using stochastic modelling and evolutionary algorithms, it is possible to obtain models that aptly describe the experimental results. But the weatherproof properties of the material are not known.

Thermal modification of wood in a nitrogen atmosphere [13] allows increasing its suitability for use. Black poplar was thermally modified in a nitrogen atmosphere in the temperature within 160-220°C, duration of exposure from 2 to 8 hours. Wood colour parameters were measured according to the CIE L*a*b* colour space model. The changes in a* and b * had a non-linear profile. The maximum value of a* for black poplar wood was achieved after modification at 200°C, while the maximum value of b* was achieved after modification at 190°C. Changes in colour ΔE of black poplar after modification at 160°C and 170°C were similar, and the dynamics of changes increased after modification at 180°C. The highest value of ΔE, about 40 conditional units, was observed after modification at 220°C and over 8 hours. There were no statistically significant differences between ΔE for the radial and tangential cross-sections. Statistical analysis indicated that the modification temperature has a more significant influence on the variability of the L* value by 90%, and for changes in parameters a* and b* – about 70%. The effect of modification time on colour parameters was insignificant – less than 4%. The effect of the combined interaction between modification temperature and time on colour parameters was less than 10%. As a result, in case of ΔE of black poplar wood, the influence of temperature was at the level of about 80%. On the other hand, the effect of time and the interaction between temperature and modification time were below 3%.

In the study [14], wood was modified by a combined pre-compression treatment and post-vacuum thermal modification to simultaneously improve its mechanical strength and dimensional stability. The law of changes in the mechanical properties of wood with the degree of compression was investigated, as well as the effect of improving the dimensional stability of wood treated in this way. The results indicate that the optimal temperature and time of vacuum-thermal modification were 190°C and 10 h, respectively. Under these conditions, the structure of pre-pressed and post-vacuum thermally modified wood is gradually densified with an increase in the compression degree, which leads to a constant improvement in mechanical properties. Meanwhile, the anti-swelling performance after water absorption is correspondingly better than that of pressed wood before thermal modification. This indicates that the dimensional stability of compressed wood was improved by thermal modification. When the compression ratio was 70%, the modulus of rupture and impact toughness of the wood were 176 MPa and 63 kJ/m^2, which were 125% and 59% higher than those of untreated wood. The swelling index was also 26% higher than that of wood after compression. Thus, this method improves the mechanical strength and dimensional stability of the wood at the same time. This fact provides a scientific basis for optimizing the reinforcement modification of fast-growing wood. But the issue related to the resistance of the material to leaching stays unresolved.

The paper [15] analysed the change in colour, morphology, and wetting of beech wood thermally modified at 200°C during three periods of heating – 1, 3, and 5 h. The results show that with increasing heating time, the lightness parameter L* decreased significantly, while the a* and b* coordinates increased during three hours. Subsequently, there was a moderate decline. Immediately after the one-hour thermal modification, the total colour difference ΔE was much higher than 12. This means that as a result of heat treatment, which lasted only one hour, an entirely new colour was obtained. Further modification caused a further increase in ΔE, but more moderate. Increased surface roughness was detected during the examination of changes in the surface morphology of beech wood. But this fact was not confirmed unambiguously in all three processing periods. The results indicate that the heat treatment of beech wood led to a considerable improvement in the wetting resistance of the beech wood surface. It is confirmed by the values of the wetting contact angle – θ > 90°. Furthermore, the time required for complete absorption of the drop by the material increased by one or two orders of magnitude. The wettability changed mainly due to the change in the processing temperature. The importance of the duration of the modification has not been unequivocally confirmed. A decrease in the wetting of the wood surface substantially affected the decrease in the free energy of the wood surface, which was mainly caused by a decrease in the polar component of this energy. This can adversely affect the process and the quality of the surface treatment, if coating materials are applied to wood modified in this way.

Thus, it has been established from literary sources that thermal modification of wood can provide it with the ability to resist decay. However, the high schedule parameters of thermal modification, namely temperature and time, encourage the search for more effective technologies. Therefore, research in this area is an unresolved component of thermal modification of wood and necessitated more in-depth research.

Materials and Methods

To investigate the technological characteristics of thermally modified wood to determine the surface energy and substantiate the compressive strength along the fibres, samples of pine wood with dimensions of about 50×50×50 mm were used (Fig. 1).

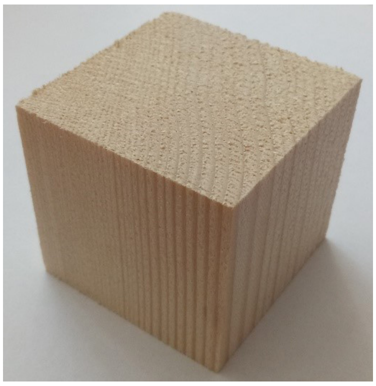

Figure 1. Samples of research materials: pine wood

Thermal modification of pine wood samples was carried out in a convective chamber. In general, the material was seasoned at 300°C for 5, 10, 15, 20, 25, and 30 min (Fig. 2). To analyse the surface energy characteristics of wood, the marginal angle of wetting on samples of thermal pine wood was determined (Fig. 3). Testing: a drop of coating was applied to the sample using a pipette [16]. After the drop reached an equilibrium state, its height and diameter were determined using a microscope with a certain degree of magnification.

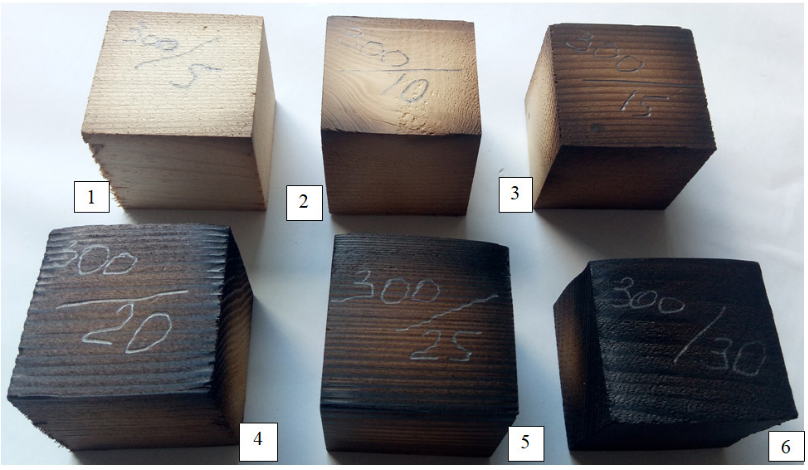

Figure 2. Pine wood samples after thermal modification at 300°C for contrasting times: 1 – 5 min, 2 – 10 min, 3 – 15 min, 4 – 20 min, 5 – 25 min, 6 – 30 min.

The marginal wetting angle θ was determined through the tangent of the angle θ, which was calculated according to the formula:

$$tg\theta = \frac{4dh}{d^2 - 4h^2}, \quad (1)$$

where *d*, *h* are the diameter and height of the drop, mm.

Figure 3. Determination of the edge wetting angle of the coating

To estimate the surface energy of thermally modified wood, the Fowkes method was used [17], which allows considering dispersion, hydrogen, and dipole-dipole interactions at the solid-liquid interface:

$$(1 + cos\theta)\sigma_l = 2(\sigma_s^d \cdot \sigma_l^d)^{0,5} + 2(\sigma_s^p \cdot \sigma_l^p)^{0.5}, \quad (2)$$

where θ is the marginal wetting angle; σ_s, σ_l are the surface energy of solid and liquid, respectively; index *p* is the component of the total surface energy due to hydrogen and dipole-dipole interactions; index *d* is due to dispersion interactions.

This equation has two unknown values σ_s^d and σ_s^p, and for practical use, contact angle data for two different liquids with known surface tensions σ_l^d and σ_l^p are required (Table 1).

Table 1. Surface tension and dispersed and polar components for test liquids

Liquid	σ_l^d	σ_l^p	σ_l
water	21.8	50.8	72.6
ethylene glycol	29.3	19.0	48.3

The compressive strength along the fibres of pine wood was determined according to ISO 13061-3:2014 [18].

Results and Discussion

Conducting the test: a drop of coating was applied to the sample using a pipette (Fig. 4). After the drop reached an equilibrium state, its height and diameter were determined using a microscope.

As Figure 4 shows, water creates an almost straight angle of the drop during wetting, which increases along with the level of modification, while ethylene glycol creates a sharp angle, which in turn decreases.

The results of determining the marginal angle of wetting by test liquids and determining the corresponding components of the free energy of the plywood surface are presented in Table 2.

Table 2. Marginal angle of wetting and free energy component of the wood surface

Thermally modified pine wood	Marginal angle of wetting, θ, º		Surface free energy, mJ/m²			Polarity
	Water	Ethylene glycol	General	Polar	Dispersed	
at 300°C and for 5 min	78.1	40.1	64.5	37.3	27.2	57.9
at 300°C and for 10 min	81.1	38.8	54.2	27.7	26.5	51.1
at 300°C and for 15 min	84.0	33.3	43.3	20.6	22.7	47.6
at 300°C and for 20 min	86.1	29.2	38.1	17.2	20.4	45.1
at 300°C and for 25 min	87.4	26.4	32.2	13.6	18.6	42.2
at 300°C and for 30 min	88.3	20.1	24.1	8.3	15.8	34.4

As a result (Table 2), it was established that thermal modification of wood led to an increase in resistance to wetting and a decrease in the surface free energy of wood.

Thus, an increase in the active component in the modifier leads to a decrease in the surface free energy and the polarity of the wood surface. As a result of a complex approach to the study of wettability, polarity, interphase tension, it is possible to choose stable coatings for wood. The results of determining the compressive strength of wood along the fibres are presented in Figure 5.

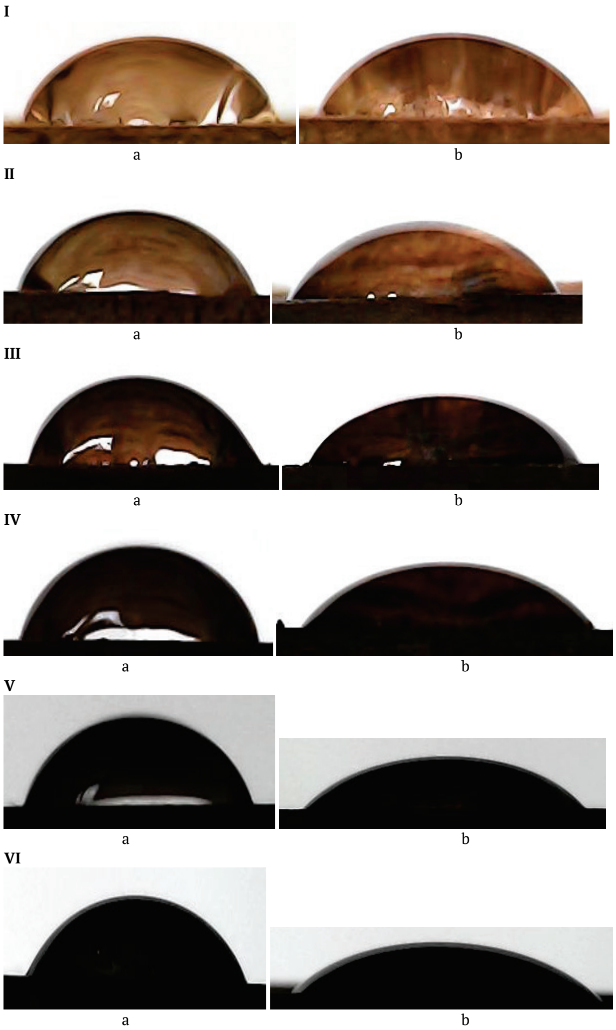

Figure 4. A drop of liquid on pine wood after thermal modification during: I – 5 min, II – 10 min, III – 15 min, IV – 20 min, V – 25 min, VI – 30 min, a – water, b – ethylene glycol

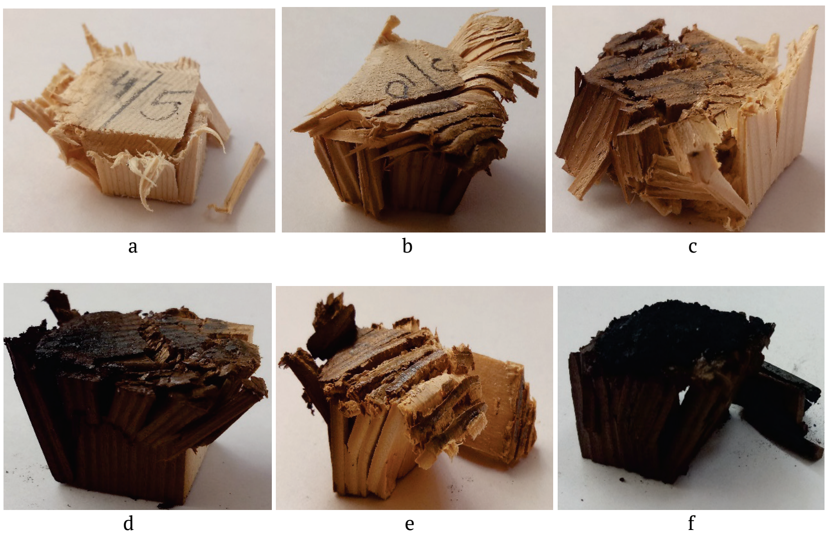

Figure 5. Determination of the compressive strength of thermally modified wood for contrasting times: a – 5 min, b – 10 min, c – 15 min, d – 20 min, e – 25 min, f – 30 min

For wood samples with a modification time of up to 20 minutes, crumpling of the fibres at the load point with minor chipping is characteristic (Fig. 5). In the samples with a modification time of 25 and 30 min, complete destruction under load is observed. The results of determining the resistance of pine wood to compression depending on the level of thermal modification are presented in Table 3.

Table 3. Compressive strength of wood samples

Thermally modified pine wood	Sample dimensions, mm			Maximum pressure, N	Compressive strength, MPa
	width	thickness	length		
at 300°C and for 5 min	20.00	19.90	30.50	16,828.9	42.3
at 300°C and for 10 min	20.00	20.00	30.00	16,448.2	41.1
at 300°C and for 15 min	20.20	20.10	29.90	17,064.8	42.2
at 300°C and for 20 min	20.00	19.70	30.20	15,275.6	38.9
at 300°C and for 25 min	19.80	19.80	30.10	20,507.2	52.3
at 300°C and for 30 min	20.90	19.80	30.40	12,009.2	29.0

As a result of research, it was established that during thermal modification for 10 minutes, pine wood withstands compression at 41.1 MPa. With an increase in the time of thermal modification to 25 min, the compressive strength increases to 52.3 MPa. Over time, the wood becomes brittle, less plastic, while the compressive strength decreases by 1.46 times.

During the thermal modification of wood, as evidenced by the research results, the chemical transformations of pine wood is natural. This is manifested in a change in colour under temperature and, accordingly, in a change in structure, which can lead to a change in certain properties, e.g., water absorption. Thermal modification of wood leads to an increase in resistance to wetting [19], which is characterized by an increase in the water wetting angle. Therewith, the calculated components of the free energy of the wood surface showed a decrease in both polar and dispersive components. Thermally modified wood is obtained at the same exposure temperature, but for a longer time, characterized by a larger wetting angle with water and a decrease in surface energy (Fig. 4, Table 2). Obviously, such a mechanism of thermal modification of wood is a factor in regulating the degree of formation of weather-resistant material. This agrees with data known from studies [8; 15], the authors of which also link the effectiveness of protection against the influence of water during thermal modification of wood. Unlike the results of studies [4; 7], the obtained results regarding the change in compression of thermally modified wood and changes in its surface properties suggest the following:

– the main regulator of resistance to wetting is not only the formation of the surface, but also the chemical transformations of wood components, which provide resistance to moisture penetration.

– a substantial impact on reducing the wettability of the surface of thermal wood is carried out towards the formation of water-resistant capillary porous elements, as a result, the reduction of the adhesive characteristics of the material.

Such conclusions can be considered appropriate from a practical standpoint because they allow a reasonable approach to the definition of the necessary technology of thermal modification of wood. From a theoretical standpoint, they allow stating the determination of the mechanism of wood thermal transformation processes [20], which constitute certain advantages of this study. The results of determining the compressive strength after thermal modification of wood (Table 3) indicate an ambiguous effect of the nature of the change in strength on the compression of thermally modified wood. This assumes the availability of data sufficient for qualitatively performing thermal modification and identifying, on its basis, the time at which the drop in strength begins. Such detection allows investigating the transformation of wood moving towards reduced resistance to destruction and to determine those variables that substantially affect the beginning of the transformation of this process.

Conclusions

The results of determining the strength on the compression of pine wood show that the compressive strength decreases depending on the degree of thermal modification. Specifically, at 300°C and for 5 min and 15 min of thermal modification, the compressive strength is equal to ordinary wood, at 300°C and a time of 10÷20 min, the compressive strength is reduced to 1.1 times. At a modification temperature of 300°C and a time of 25÷30 min, the wood becomes brittle, less plastic, while the compressive strength decreases by 1.46 times. Therewith, for samples of pine wood thermally modified for up to 20 min, crumpling of fibres at the point of pressure with minor splitting is characteristic, and for samples of pine wood thermally modified for more than 20 min, complete destruction under the pressure with discolouration of the outer layers is observed.

Thermal modification of wood leads to an increase in resistance to wetting, which is characterized by an increase in the angle of wetting. Therewith, the calculated components of the free energy of the wood surface showed a decrease in both the polar and dispersive components. A decrease in the free surface energy of wood can adversely impact the effectiveness of surface treatment of the material with paint and varnish coatings.

In the future, it is planned to develop equipment and work out this technology of thermal modification of wood and to investigate the technological properties of the obtained materials.

References

[1] Zelinka, S.L., Altgen, M., Emmerich, L., & Guigo, N. (2022). Review of wood modification and wood functionalization technologies. *Forests,* 13(7), article number 1004. https://doi.org/10.3390/f13071004.

[2] Klébert, S., Mohai, M., & Csiszár, E. (2022). Can plasma surface treatment replace traditional wood modification methods? *Coatings*, 12(4), article number 487. https://doi.org/10.3390/coatings12040487.

[3] Khademibami, L., & Bobadilha, G.S. (2022). Recent developments studies on wood protection research in academia: A review. *Frontiers in Forests and Global Change,* 5, article number 793177. https://doi.org/10.3389/ffgc.2022.793177.
[4] Godinho, D., Araújo, S.O., Quilhó, T., Diamantino, T., & Gominho, J. (2021). Thermally modified wood exposed to different weathering conditions: A review. *Forests*, 12(10), article number 1400. https://doi.org/10.3390/f12101400.
[5] Mukhametzyanov, S., Khasanshin, R., Safin, R., Shaikhutdinova, A., & Safiullina, A. (2021). Modification of the surface of thermally modified wood with ozone when creating glued structures. *E3S Web of Conferences,* 274, article number 04014. https://doi.org/10.1051/e3sconf/202127404014.
[6] Hill, C., Altgen, M., & Rautkari, L. (2021). Thermal modification of wood – a review: Chemical changes and hygroscopicity. *Journal of Materials Science,* 56(11), 6581-6614. https://doi.org/10.1007/s10853-020-05722-z.
[7] Spear, M.J., Curling, S.F., Dimitriou, A., & Ormondroyd, G.A. (2021). Review of functional treatments for modified wood. *Coatings,* 11, article number 327. https://doi.org/10.3390/coatings11030327.
[8] Paes, J.B., Brocco, V.F., Loiola, P.L., Silva, M.R., & Juizo, C.G.F. (2021). Effect of thermal modification on decay resistance of *Corymbia Citriodora* and *Pinus Taeda* wood. *Journal of Tropical Forest Science,* 33(2), 185-190. https://doi.org/10.26525/jtfs2021.33.2.185.
[9] Wu, Y., Wu, X., Yang, F., Feng, X., & Zhang, J. (2020). Effect of thermal modification on the nano-mechanical properties of the wood cell wall and waterborne polyacrylic coating. *Forests,* 11(12), article number 1247. https://doi.org/10.3390/f11121247.
[10] Meija, A., Irbe, I., Morozovs, A., & Spulle, U. (2020). Properties of *Populus* genus veneers thermally modified by two modification methods: Wood treatment technology and vacuum-thermal treatment. *Agronomy Research*, 18(3), 2138-2147. https://doi.org/10.15159/AR.20.184.
[11] Nhacila, F., Sitoe, E., Uetimane Jr. E., Manhica, A., Egas, A., & Möttönen, V. (2020). Effects of thermal modification on physical and mechanical properties of Mozambican *Brachystegia spiciformis* and *Julbernardia globiflora* wood. *European Journal of Wood and Wood Products,* 78(2), 871-878. https://doi.org/10.1007/s00107-020-01576-z.
[12] Chu, D., Hasanagić, R., Hodžić, A., Kržišnik, D., Hodžić, D., Bahmani, M., Petrič, M., & Humar, M. (2022). Application of temperature and process duration as a method for predicting the mechanical properties of thermally modified timber. *Forests,* 13(2), article number 217. https://doi.org/10.3390/f13020217.
[13] Bytner, O., Drożdżek, M., Laskowska, A., & Zawadzki, J. (2022). Temperature, time, and interactions between them in relation to colour parameters of black poplar (*Populus nigra* L.) thermally modified in nitrogen atmosphere. *Materials,* 15(3), article number 824. doi: 10.3390/ma15030824.
[14] He, Z., Qi, Ya., Zhang, G., Zhao, Yu., Dai, Yo., Liu, B., Lian, Ch., Dong, X., & Li, Yo. (2022). Mechanical properties and dimensional stability of poplar wood modified by pre-compression and post-vacuum-thermo treatments. *Polymers,* 14(8), article number 1571. https://doi.org/10.3390/polym14081571.
[15] Kúdela, J., Lagaňa, R., Andor, T., & Csiha, C. (2020). Variations in beech wood surface performance associated with prolonged heat treatment at 200 °C. *Acta Facultatis Xylologiae Zvolen,* 62(1), 5-17. doi: 10.17423/afx.2020.62.1.01.
[16] Rekiel, E., Zdziennicka, A., & Jańczuk, B. (2021). Mutual influence of ethanol and surfactin on their wetting and adhesion properties. *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* 627, article number 127161.
[17] Traciak, J., Fal, J., & Żyła, G. (2021). 3D printed measuring device for the determination the surface tension of nanofluids. *Applied Surface Science,* 561, article number 149878.
[18] ISO 13061-3:2014 Physical and mechanical properties of wood. Test methods for small clear wood specimens. Part 3: Determination of ultimate strength in static bending. (2014). Retrieved from https://www.iso.org/standard/60065.html.
[19] Tsapko, Yu., Horbachova, O., Mazurchuk, S., & Bondarenko, O. (2022). Specific aspects of the study of the surface properties of plywood. *Materials Science Forum,* 1066, 175-182. https://doi.org/10.4028/p-b15jpx.
[20] Tsapko, Yu., Horbachova, O., Tsapko, A., Mazurchuk, S., Zavialov, D., & Buiskykh, N. (2021). Establishing regularities in the propagation of phase transformation front during timber thermal modification. *Eastern-European Journal of Enterprise Technologies*, 1/10(109), 30-36. https://doi.org/10.15587/1729-4061.2021. 2253104.

Мобільна технологія термічного модифікування деревини

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Анотація. Деревина як конструкційний матеріал має ряд недоліків, до яких відносяться малий термін служби, відносно низька формостійкість, значні об’ємні деформації під впливом вологи, виражена анізотропія та водопоглинання. Термомодифікування дещо покращує фізико-механічні властивості, але постає проблема зміни поверхневих характеристик, зокрема адгезії. З метою визначення технологічних характеристик термічно модифікованої деревини та розроблення можливих заходів покращення технології нанесення захисних покриттів визначено поверхневу енергію та межу міцності на стиск вздовж волокон. Застосовано комплексний підхід для аналізу стану поверхні термічно модифікованої деревини через вивчення поверхневих енергетичних характеристик на основі методу Фоукса, який враховує дисперсійні, водневі та диполь-дипольні взаємодії на міжфазній границі «тверде тіло-рідина». За крайовим кутом змочування встановлено, що процес термічного модифікування деревини сприяє збільшенню стійкості її поверхні до змочування за рахунок зменшення полярності в 1,68 рази із збільшенням тривалості модифікування до 30 хв. При цьому вільна енергія поверхні для зразків модифікованих за 300 °С упродовж 5 хв. становить 64,5 мДж/м^2, упродовж 30 хв. – 24,1 мДж/м^2. Щодо стійкості на стиск – термічне модифікування знижує межу міцності у 1,46 рази. Так, за температури 300 °С і часу 5 хв. та 15 хв. показник залишається на рівні звичайної деревини – 42 МПа. Оброблення упродовж 30 хв. зменшує межу міцності до 29 МПа, деревина втрачає пластичність. Отримані результати дають можливість ефективно підібрати стабільні покриття для такої деревини для якісної обробки поверхні лакофарбовими матеріалами. Знаючи момент часу, з якого починається зменшення межі міцності, ведення процесу термічного модифікування стає більш контрольованим і дає можливість передбачити характеристики майбутнього матеріалу

Ключові слова: деревинний матеріал, технологічні параметри, процес термічного модифікування, кут змочування, вільна поверхнева енергія, стиск вздовж волокон, межа міцності, крихкість

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Bioproductivity of the forests of the Cheremsky Nature Reserve

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Abstract. Climate change undermines the stability of natural ecosystems and adversely affects human life. Forest biocenoses can regulate the gas exchange of the atmosphere, accumulate and sequester carbon dioxide emissions, which are dangerous for the environment, in the phytomass components for a long time. The purpose of this study is to investigate the dynamics of bioproductivity of stands of the main forest-forming species of the Cheremsky Nature Reserve by components of phytomass and the carbon deposited in them. To solve the tasks of the study, the method of P.I. Lakyda was used. Experimental data of temporary trial plots, which fully characterize the forest massifs of the object under study, were used for modelling. The ratio coefficients R_v were calculated for stem wood ($R_{v(sw)}$); stem bark ($R_{v(sb)}$); branches ($R_{v(b)}$); leaves (needles) ($R_{v(l)}$). It was established that all above-ground components of Scots pine phytomass are described by regression equations. The coefficients of determination turned out to be insignificant, for the wood and bark of the stems of silver birch and common alder. In the structure of the phytomass of the forest stands of the reserve, the largest share (72.0%) falls on coniferous stands, a much smaller share – on soft-wood stands (26.0%) and the smallest – on hard-wood stands (2.0%). Over 13 years, the density of phytomass of stands and the carbon sequestered in it increased 1.4 times. Every year, forest biocenoses of the reserve release 6,989 tonnes of oxygen (4.2 $t \cdot ha^{-1}$) into the atmosphere. The main volume of oxygen (91.8%) is produced by coniferous stands. Based on the collected research material for stands of the main forest-forming species of the Cheremsky Nature Reserve, the following were calculated: ratios of above-ground phytomass components to their stock in the bark; mathematical models for evaluating the dynamics of phytomass components; standards for calculating oxygen productivity. The results of the study of the bio- and oxygen productivity of the forests of the Cheremsky Nature Reserve will be a significant contribution to effective management of the forest reserves, as well as to solving problems related to climate change at the regional and global levels

Keywords: mathematical models, conversion coefficients, phytomass of tree stands, sequestered carbon, oxygen productivity

Introduction

The growth of the Earth's population, the lack of food and drinking water supplies, the limitation of fossil energy resources and global climate change are the main challenges and threats facing humanity and require sound solutions aimed at reducing adverse consequences. In this sense, the forests of the planet "feel" the negative degrading effect of these phenomena and, therewith, are an effective tool in stabilizing the environment, solving trophic, and energy problems [1, 2].

Recently, the attention of humanity has been increasingly focused on one of the critical issues – global climate change, which is closely related to the so-called "greenhouse effect", upon which there is an increase in the concentration of greenhouse gases in the atmosphere. This process occurs due to the constant growth of anthropogenic load on the environment, as a result of which the volume of emissions of these gases, of which 80-90% is CO_2, exceeds their flow. The authors of the paper [3] believe that the concentration of carbon dioxide in the atmosphere can be reduced as a result of reducing emissions or by removing it from the atmosphere and sequestering it in terrestrial and aquatic biocenoses.

The phytomass of tree stands principally determines the course of processes in forest biocenoses. While carbon dioxide emissions are hazardous and poisonous for the environment and humanity, it is the phytomass components

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that can accumulate and sequester those emissions for a long time. That is why studies of the carbon potential in forest ecosystems are aimed primarily at estimating the phytomass of tree stands. Furthermore, this indicator is also used for ecological monitoring of sustainable forest management, modelling of forest productivity and assessment of their carbon sequestration capacity[2].

The estimation of the phytomass of tree stands is substantially different from the conventional estimation of stem wood reserves. Today, data on stocks and productivity of phytomass are few compared to data on forest taxing, where massive banks of data on stem wood stocks have been accumulated. There are numerous indicators of list taxing of temporary and permanent trial areas. Numerous regional stand development tables (SDT) have been compiled for stands with different wood species [4].

At the first stages of research, the phytomass of the tree stand was estimated by spreading the results of the calculated phytomass on separate trial areas to significant forest regions. Therewith, the final results were inflated [2]. Gradually, the estimation methods were improved. Currently, methods are used that combine data from the State Forestry Fund Accounting (SFFA) on stem wood stocks and standards with data on forest phytomass based on multivariate regression models, which estimate the phytomass or its conversion coefficients based on the main indicators included in SFFA and SDT [1-3].

The purpose of this study is to investigate the dynamics of bioproductivity of stands of the main forest-forming species of the Cheremsky Nature Reserve by components of phytomass and the carbon deposited in them. To fulfil the purpose of this study, it was necessary to solve the following tasks: develop mathematical models for estimating the components of the above-ground phytomass of trees and stands of the main forest-forming species of the Cheremsky Nature Reserve according to their inventory indicators; to investigate the dynamics of phytomass and carbon in the tree stands of the reserve and to estimate the oxygen productivity of the forests of the object under study.

This study is the first to calculate conversion coefficients of ratios of phytomass components of tree stands to their stock in the bark for the Cheremsky Nature Reserve. Dependences have also been established and a system of mathematical models has been developed to estimate the phytomass components of tree stands and the carbon sequestered in them by the main forest-forming species. The dynamics of total phytomass and sequestered carbon in tree stands were modelled and evaluated. The main trends in oxygen productivity of forests were covered and their potential was estimated.

Theoretical Overview

Climate change and environmental pollution undermine the stability of natural ecosystems and adversely affect human life. Stocks of phytomass and primary products are the main features that characterize the bioproductivity of forests and show their capability to regulate atmospheric gas exchange and the global carbon cycle [5-7]. Management of the carbon balance of forest phytocenoses both within the country and at the regional level is possible if there is a representative information base of forest ecosystem functions [8].

Forest ecosystems can support the natural balance of the planet's ecosystem, as they are capable of accumulating and long-term retention of dangerous and poisonous substances for humans and the environment [7]. That is why the biosphere role of forests as a natural absorber of greenhouse gases is gaining priority. Proceeding from this, a comprehensive study of the ecological role of the forest is relevant, which is closely interconnected with studies of their bioproductivity, the main components of which are phytomass and the carbon sequestered in it [1].

Today, a network of protected areas has been created in Ukraine, whose activities are aimed at investigating the state of natural complexes, restoring and preserving the natural state of the environment. Research on the bioproductivity of tree stands in such territories to preserve unique biodiversity, as well as to solve certain environmental issues, is quite promising. The problems of transformation of natural ecosystems and their preservation are also inherent in the Cheremsky Nature Reserve.

Considering the fact that the Cheremsky Nature Reserve was created on December 19, 2001, few scientific studies have been covering its forest ecosystems. However, the ecosystem services of the forests of other objects of the nature reserve fund have been evaluated by researchers for a long time [9-11].

The forest ecosystem is a sophisticated dynamic diffuse system, in which it is impossible to accurately distinguish the effect of various individual factors that are in close interaction with each other [12]. Forest ecosystems are characterized by constant variability in space. The economic activity of people largely determines the variability of the features of the microenvironment within its boundaries, which makes the research quite difficult [5]. Although a considerable amount of research on bioproduction processes in forest biocenoses has already been carried out, the mechanisms of anthropogenic influence on the state and productivity of tree stands are still understudied. It is necessary to investigate forest biogeocenoses comprehensively, considering all the diversity of connections between their parts and the processes occurring within them. Therefore, modern ideas of the system approach are used for its analysis and solution [13-15].

Modelling of forest biogeocenoses allows predicting the results of the selected scenario, giving preference to a safer and more useful scenario for the system under study. The use of models allows quickly predicting the consequences of directed actions decades and even centuries in advance without harmful consequences of experimentation for the natural environment [13; 15].

Forests perform important ecological functions, including climate regulation, soil protection, water protection, sanitary and hygienic, recreational, etc. It is based on the analysis of these functions that their ecological potential is estimated. Among the main criteria for estimating the ecological potential of forest phytocenoses are their carbon-sequestering and oxygen-producing functions [3].

Assessment of the carbon balance of forests has gained great popularity among researchers. Today, there are several methods of calculating the carbon sequestering function of forests. These include [3; 6]:

1. Weight method – a calculation method based on the available reserves of phytomass, which ensures carbon accounting in statics and dynamics.

2. Chlorophyll method – the content of chlorophyll in all organs of arboreal plants per unit area of forest plots covered with forest vegetation is calculated.

3. The method of determining the mass of photosynthetically bound and sequestered carbon in tree stands (the above-mentioned indicators and phytomass growth are determined synchronously by a direct indicator of the arrival of solar radiation).

4. Use of remote sensing methods.

5. Methodology of M.I. Chesnokov and V.M. Dolgosheev, the essence of which is to use the amount of oxygen that is released as a result of the formation of one tonne of completely dry matter and phytomass in a completely dry state (it is the most practical) [3; 10; 11].

Presently, there is a considerable number of studies that differ in research methodology [3], but all of them are aimed at predicting the carbon and oxygen balance to keep the stability of the planet's climate system.

Materials and Methods

The phytomass components of the tree stands of the main forest-forming tree species of the Cheremsky Nature Reserve (NR) were modelled by establishing single- and multifactorial dependences of the phytomass components on the inventory indicators of the tree stands, which are presented in the materials of the forest cadastre. Aggregated experimental material of temporary experimental plots, which fully characterize the current state of the forest areas of the research object, was used as initial data for modelling. A total of 64 temporary experimental plots (TEP) were used, of which 45 were established in natural stands and 19 – in artificial stands. The number of TEPs by main tree species and origin is distributed as follows: Scots pine – 39 TEPs (20 in natural stands and 19 in artificial stands), common alder – 14 TEPs and silver birch – 11 TEPs in natural stands. To solve the problems of the study, the method of P.I. Lakyda was used [2]. The collected experimental material allows developing identical mathematical models to estimate the phytomass components of model tree stands in statics and dynamics and, based on them, to characterize the total volumes of phytomass (by fractions) and the amount of accumulated carbon in the forest stands of the object under study.

The mathematical dependencies of the change of coefficients within each tree species were determined according to the method of multiple regression using the package of statistical software *STATISTICA*.

To obtain the combined characteristics of the inventory structure of the forest stands of the Cheremsky NR, data from three periods of forest management in 2005, 2011, and 2018, carried out by the production association "Ukrderzhlisproekt", were selected, aggregated, and processed. To analyse the nature of changes in the productivity of tree stands, data consisting of the characteristics of individual parameters of the forest fund were used:

1. Distribution of areas and stocks of forest plots covered with forest vegetation by groups of main forest-forming tree species.

2. Distribution of tree stands by age groups (young, middle-aged, maturing, mature, and over-mature) within the group of tree species.

3. Average quality of tree stands (according to M.M. Orlov [16]) within a group of tree species.

The total amount of phytomass in the forests of the Cheremsky NR and the carbon budget in them were calculated on a personal computer in the *Microsoft Office Excel* program.

The intensity of oxygen production by the tree stands of the Cheremsky NR were calculated according to the method of I.Ya. Liepa [17].

When modelling the dependence of the phytomass of stands on their inventory indicators, conversion coefficients were used [4]:

$$R_v = \frac{M_f}{M},$$

where R_v is the conversion factor of the taxation index; M_f – mass of phytomass fraction, thous. t; M – stem stock in the bark, thous. m^3.

A general working array of experimental data of TEPs was prepared, which includes the following inventory indicators: average age *(A, years)*; average diameter *(D, cm)*; average height *(H, m)*; site index class *(I)*; relative stocking *(S)*; stock *(M, m^3·ha^{-1})*.

The ratio coefficients R_v were calculated for the following phytomass components of the plantation: stem wood ($R_{v(sw)}$); stem bark ($R_{v(sb)}$); branches (wood and bark of crown branches) ($R_{v(b)}$); leaves (needle) ($R_{v(l)}$).

The average diameters *(D)*, average heights *(H)* and relative stocking *(S)* of the stands of the main forest-forming species of the Cheremsky NR were used as arguments for the regression equations.

The mathematical models of the relationship between the conversion coefficients of the stands of the Cheremsky NR with their total phytomass were searched using a dependency with the following general form:

$$R_v = f(D, H, S),$$

where R_v are the corresponding conversion factors (wood, bark, leaves (needles), etc.); *f(D, H, S)* are functions of inventory indicators of the tree stand (diameter, height, relative stocking).

The following type of allometric dependence was used to model the change in R_v coefficients [4]:

$$R_v = a_o \cdot D^{a1} \cdot H^{a2} \cdot S^{a3},$$

where D is the average diameter of the tree stand, cm; H is the average height of the tree stand, m; S is the relative stocking of the tree stand; a_0, a_1, a_2, a_3 are regression coefficients.

The complete characteristics of the equation parameters of the ratio coefficients R_v of the phytomass fractions of the stands of the main forest-forming species of the Cheremsky NR are presented in Table 1.

Table 1. Multiple regression equations of conversion coefficients R_v of estimation of phytomass components of stands of the main forest-forming species of the Cheremsky NR

Regression model	R^2	Regression model	R^2
Scots pine, artificial			
$R_{v(sw)}=0.349 \cdot D^{0.028} \cdot H^{0.064} \cdot S^{0.028}$	0.70	$R_{v(b)}=1.353 \cdot D^{-0.395} \cdot H^{-0.511} \cdot S^{-0.787}$	0.61
$R_{v(sb)}=0.296 \cdot D^{-0.445} \cdot H^{-0.095} \cdot S^{-0.132}$	0.72	$R_{v(l)}=2.271 \cdot D^{-0.295} \cdot H^{-1.550} \cdot S^{-0.203}$	0.78
Scots pine, natural			
$R_{v(sw)}=0.336 \cdot D^{-0.003} \cdot H^{0.101} \cdot S^{-0.038}$	0.79	$R_{v(b)}=0.124 \cdot D^{2.115} \cdot H^{-2.436} \cdot S^{0.129}$	0.13
$R_{v(sb)}=0.535 \cdot D^{0.091} \cdot H^{-0.802} \cdot S^{0.296}$	0.78	$R_{v(l)}=0.054 \cdot D^{-0.124} \cdot H^{-0.386} \cdot S^{-0.002}$	0.17
Silver birch			
$R_{v(sw)}$= *Dependency not established (average value – 0.437)*	–	$R_{v(sb)}$= *Dependency not established (average value – 0.082)*	–
$R_{v(l)}=20.498 \cdot D^{0.117} \cdot H^{-2.591} \cdot S^{0.167}$	0.96	$R_{v(b)}=0.976 \cdot D^{-0.153} \cdot H^{-0.430} \cdot S^{-0.810}$	0.85
Common alder			
$R_{v(sw)}$= *Dependency not established (average – 0.419)*	–	$R_{v(sb)}$= *Dependency not established (average value – 0.101)*	–
$R_{v(b)}=8.428 \cdot D^{0.017} \cdot H^{-1.591} \cdot S^{-1.241}$	0.98	$R_{v(l)}=0.185 \cdot D^{-1.081} \cdot H^{0.070} \cdot S^{-0.708}$	0.86

Notes: *sw* – stem wood, *sb* – stem bark, *b* – branches, *l* – leaves (needles)

The significance of the influence of the factors on the phytomass components under study was estimated by the confidence intervals of the regression coefficients at the 5% level.

Results and Discussion

As a result, it was established that all above-ground components of Scots pine phytomass of natural and artificial origin are described by regression equations. The determination coefficients for stem wood and stem bark of silver birch and common alder turned out to be insignificant. Considering that the phytomass conversion coefficients of tree stems are the conditional density of stem wood, the model essentially describes the parametric and geographical variability of the conditional density. Given certain biological features of tree species, this variability cannot be high [17]. Therefore, their average values were used in future calculations.

Since in the study of the biotic productivity of the Cheremsky NR forests the phytomass of understorey vegetation ($R_{v(uv)}$) and the underground phytomass of tree stands ($R_{v(up)}$) of the main forest-forming tree species were not investigated, multiple regression equations of conversion coefficients obtained by P.I. Lakyda were used [18].

Considering the level of data aggregation for the conversion of completely dry phytomass into sequestered carbon and based on the results of the analysis of literary sources [7; 18] average transfer coefficients were adopted: 0.50 – for wood and bark, 0.45 – for leaves and the understorey.

Based on the developed models (Table 1) and data from the forest cadastre, the total amounts of phytomass and carbon in the forest stands of the Cheremsky NR were obtained (Table 2).

According to the indicators presented in Table 2, during 2005-2018, the area of forest areas covered with forest vegetation stayed unchanged. Therewith, the supply of stem wood increased from 244.9 thous. m^3 in 2005 to 336.2 thous. m^3 in 2018 (by 91.3 thous. m^3, or by 37.3%). Accordingly, the volume of the total phytomass of stands increased by 57.2 thous. t (36.5%) and the carbon accumulated in it by 28.4 thous. t (36.5%).

Table 2. Total amounts of phytomass and carbon in the forests of Cheremsk NR

Accounting year	Area of forest areas covered with forest vegetation, ha	Stem wood stock, thous. m^3	Phytomass		Carbon	
			thous. tonnes	density, $kg \cdot (m^2)^{-1}$	thous. tonnes	density, $kg \cdot (m^2)^{-1}$
2005	1,809.3	244.90	156.6	8.7	77.8	4.3
2011	1,809.3	281.64	179.5	9.9	89.2	4.9
2018	1,809.3	336.20	213.8	11.8	106.2	5.9

Figure 1 shows the dynamics of changes in the average density of phytomass and carbon in the tree stands of the Cheremsky NR. According to this figure, over the course of 13 years, these indicators gradually acquired higher values (from 8.7 $kg \cdot (m^2)^{-1}$ to 11.8 $kg \cdot (m^2)^{-1}$ for phytomass and from 4.3 $kg \cdot (m^2)^{-1}$ up to 5.9 $kg \cdot (m^2)^{-1}$ for carbon).

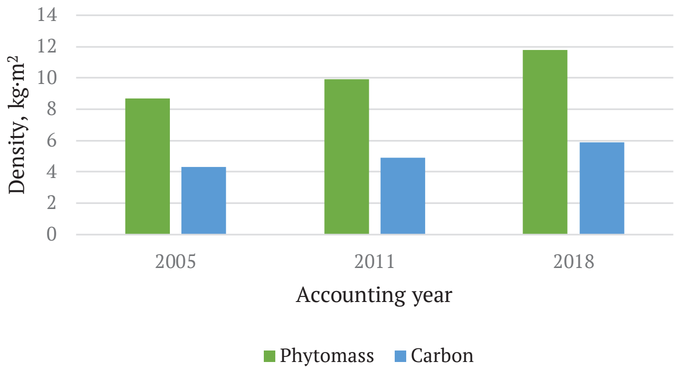

Figure 1. The dynamics of changes in the average density of phytomass and carbon in the forests of the Cheremsky NR

As of 2018, the carbon density in the forest stands of the Cheremsky NR for forest areas covered with forest vegetation reaches 5.9 kg·$(m^2)^{-1}$ on average. Moreover, in coniferous stands, the carbon density (6.1 kg·$(m^2)^{-1}$) is the closest to the average carbon density for the forest areas covered with forest vegetation in the Cheremsky NR. This indicator was the lowest in soft-wood stands (5.2 kg·$(m^2)^{-1}$), while it was the highest in hard-wood stands (7.6 kg·$(m^2)^{-1}$). Moreover, carbon density increases most intensively in hard-wood tree species (from 5.1 kg·$(m^2)^{-1}$ in 2005 to 7.6 kg·$(m^2)^{-1}$ in 2018), less intensively – in needles (from 4.5 kg·$(m^2)^{-1}$ in 2005 to 6.1 kg·$(m^2)^{-1}$ in 2018), and in soft-wood species – only by 0.6 $(m^2)^{-1}$.

Figure 2 shows the dynamics of changes in the density of phytomass by groups of forest-forming tree species in the forests of the Cheremsky NR. During the 13 experimental years, the density of phytomass in the tree stands of all groups of forest-forming tree species gradually increased (from 8.7 kg·$(m^2)^{-1}$ to 11.8 kg·$(m^2)^{-1}$), and, therefore, their bioproductivity increased. The most intensive growth of this indicator is observed in hard-wood stands (by 1.5 times) – from 10.3 kg·$(m^2)^{-1}$ to 15.1 kg·$(m^2)^{-1}$. It is somewhat smaller (1.4 times) in needless (from 9.1 kg·$(m^2)^{-1}$ to 12.4 kg·$(m^2)^{-1}$) and from 7.63 kg·$(m^2)^{-1}$ to 10.4 kg $(m^2)^{-1}$ in soft-wood stands.

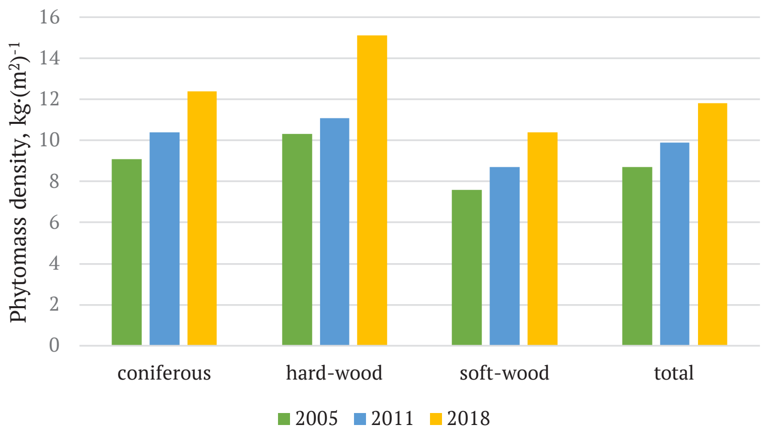

Figure 2. Dynamics of changes in phytomass density by groups of forest-forming tree species in the forests of Cheremsky NR

In general, in the tree stands of the reserve for 2005-2018, as a result of the change in the age class composition of stands and the growth of the average stock, the density of phytomass and sequestered carbon increased by 1.4 times.

According to Figure 3, wood and bark of tree stems comprise the largest share of the total phytomass of the forests of the Cheremsky NR. A much smaller, but solid share falls on the roots and a small amount – on the wood and bark of branches, understorey vegetation and leaves (needless).

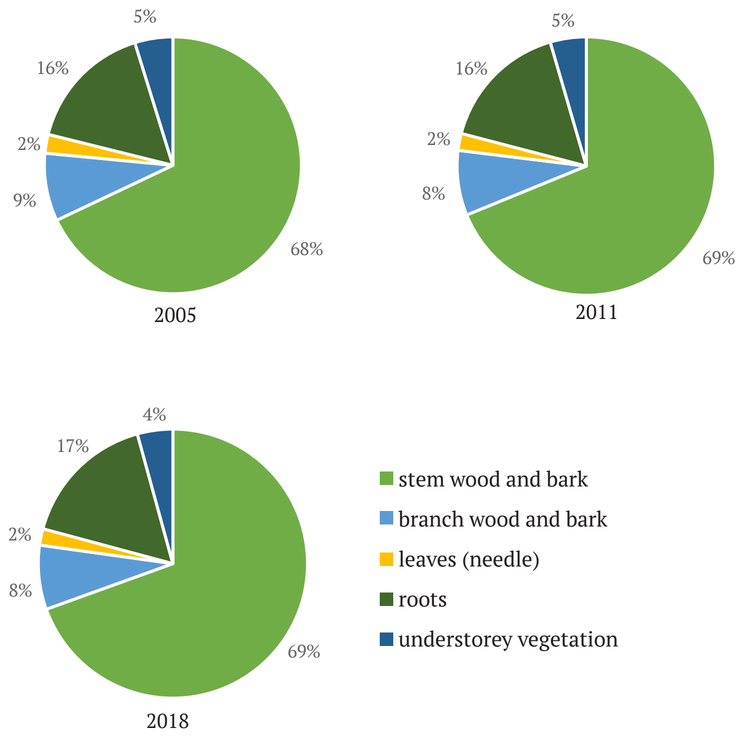

Figure 3. Dynamics structure of phytomass components of Cheremsky NR stands

Along with the increase in the total stock of stem wood during the period under study (see Table 2), the share of stem phytomass in 2005-2018 increased in the total structure of tree stands by only 1.0% (from 68.0% in 2005 to 69.0% in 2018). These indicators are somewhat higher compared to the average in Ukraine (in the forests of Ukraine, the phytomass of stems is 66.0% of the total phytomass of forests [19]). This is quite natural, since the forests of the Cheremsky NR are dominated by middle-aged tree stands, which grow intensively and quickly accumulate stem stock. Therewith, there are mature and maturing tree stands, the supply of stem wood of which is the largest.

According to Figure 4, a much smaller share in the structure of the phytomass components of the forests of the Cheremsky NR comprises root systems, wood and bark of branches, understorey vegetation, and leaves (needles) – to a minimal extent. Notably, in the overall structure of phytomass components of NR tree stands, the share of wood and bark of branches is half as much as the share of root systems (8% and 16%, respectively) (Fig. 3). Examination of the structure of phytomass components by groups of the main forest-forming tree species of this experimental object (Fig. 4) suggests that in hard-wood species, the share of wood and bark of branches is greater than the share of root systems. The distribution of phytomass of tree stands of the Cheremsky NR by groups of forest-forming tree species as of 2018 is presented in Fig. 5.

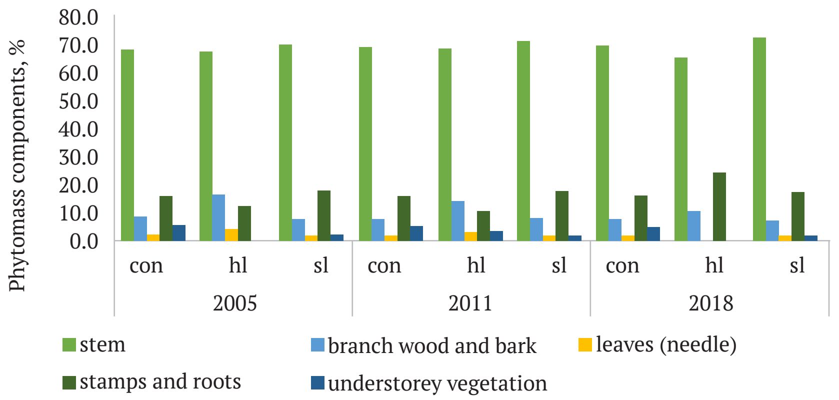

Figure 4. The structure of phytomass components by groups of the main forest-forming species of Cheremsky NR

Note: con – needles, hw – hard-wood, sw – soft-wood

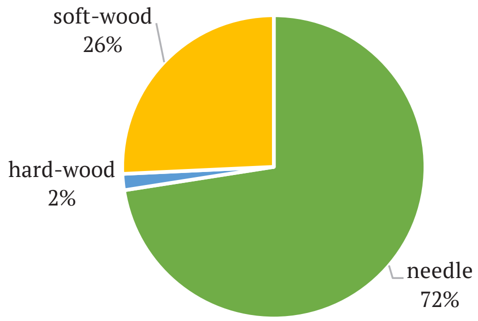

Figure 5. Phytomass distribution of tree stands of the Cheremsky NR by groups of forest-forming species as of 2018

According to this figure, the largest share in the phytomass structure of the nature reserve's forests is accounted for by coniferous stands (72.0%), a smaller share fell on soft-wood stands (26.0%) and the smallest – on hard-wood stands (2.0%).

Calculations of the intensity of oxygen production by tree stands of the Cheremsky NR were made according to the method of I.Ya. Liepa. The method is that based on the data on the composition of the total phytomass of the tree stands of the object under study for all components in a completely dry state, which is formed per unit of time, the volume of oxygen that released into the atmosphere due to photosynthesis is determined [17]. Admittedly, it is impossible to accurately determine the amount of oxygen produced, since part of it is spent on the decomposition of precipitation. But it is insignificant, so it is ignored.

According to N.I. Chesnokova and V.M. Dolgosheev, oxygen productivity per 1 t of completely dry matter of various species is approximately the same and is 1.393 t for pine, 1.413 t for spruce, 1.393 t for birch, and 1.423 t for aspen [11]. Therefore, this indicator was taken as 1.4 on average. Based on the results of calculations of the total phytomass of the tree stands of the Cheremsky NR, the annual change of the total phytomass per 1 ha was determined separately for 2005-2011 and 2011-2018. By multiplying the annual change in phytomass per 1 ha by the accepted oxygen productivity coefficient of 1 t of absolutely dry matter (1.4), the weight of oxygen released from each hectare in 1 year was obtained. Next, the obtained indicator was multiplied by the area of the experimental forest plots covered with forest vegetation and the total amount of oxygen produced by the tree stands of the Cheremsky NR in 1 year was found (Table 3).

Table 3. The volume of oxygen released by the Cheremsky NR tree stands

Forest management period	Area covered with forest vegetation, ha	Stem wood stock, thous. m^3	Phytomass		Annual change in phytomass, $t \cdot ha^{-1}$	The volume of oxygen released per year by 1 ha of forest, $t \cdot ha^{-1}$	The total amount of oxygen produced by the forest in 1 year, t
			total, thous. t	per 1 ha, $t \cdot ha^{-1}$			
2005	1809.3	244.90	156.6	86.6	2.1	2.9	5247
2011	1809.3	281.64	179.5	99.2			
2018	1809.3	336.20	213.7	118.1	2.7	3.8	6875

As evidenced by the data in Table 3, along with the increase in the productivity of forests, greater amounts of oxygen are released into the atmosphere.

According to the calculations, the forest biocenoses of the Cheremsky NR produce 6,875 t of oxygen every year (3.8 $t \cdot ha^{-1}$ on average). The distribution of oxygen production by the tree stands of the Cheremsky NR within groups of tree species as of January 1, 2018 is clearly shown in Figure 6. It indicates that the main volume of oxygen is produced by needles (69.8%), and 2.6 times less – by soft-wood stands (27.2%). Hard-wood tree stands, albeit with the highest phytomass and carbon density indicators, produce a meagre amount of oxygen (3.0%) in the Cheremsky NR, as they grow on a small area (24.4 ha) compared to other groups of tree species.

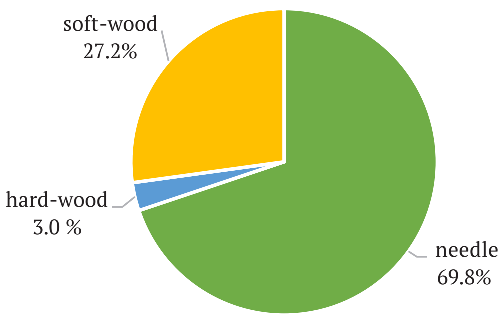

Figure 6. Oxygen productivity of stands of the Cheremsky NR within groups of forest-forming species as of January 1, 2018

This is explained by the fact that coniferous forests grow here on the largest territory (1,099.9 ha) and have the highest wood stock (218.42 thous. m^3). The share of softwood and hard-wood stands in the total stock of forest areas of the reserve is insignificant (66.53 and 4.65 thousand m^3). Therefore, they produce significantly less oxygen (6.1% and 2.1%, respectively). Coniferous tree stands emit more oxygen per unit area (6.2 $t \cdot ha^{-1}$), hard-wood stands – slightly less (5.3 $t \cdot ha^{-1}$), while soft-wood stands produce only 0.8 $t \cdot ha^{-1}$ oxygen.

Therefore, the most valuable from the perspective of oxygen production in the Cheremsky NR are coniferous forests, which emit 6,775 t of oxygen (6.2 $t \cdot ha^{-1}$) into the atmosphere every year, while soft-wood stands produce only 449 t and hard-wood stands – 156 t of oxygen.

To date, the oxygen-producing function of forests has been investigated in other regions of Ukraine. Thus, H.A. Saharuk established that the oxygen productivity of the forests of the Shatskyi National Nature Park is 3.2 $t \cdot ha^{-1}$ per 1 year. I.P. Lakyda studied the urban forests of Kyiv, Yu.S. Miklush – forests of the green zone of Lviv, O.M. Melnyk – forest phytocenoses of the Pripyat-Stokhid National Nature Park. According to their data, the indicators of oxygen productivity in these objects are within 4.6-4.8 $t \cdot ha^{-1} \cdot year^{-1}$. However, the most productive are the forests of the Ukrainian Carpathians, which release 7.5 $t \cdot ha^{-1}$ of oxygen into the air every year [3].

For the forest vegetation zone of Polissia, the results of the oxygen-producing function of the forests of the Cheremsky NR (4.2 $t \cdot ha^{-1}$) are average compared to the same indicators in other regions and can be used in the estimation of forest resources along with other indicators of ecological and economic areas. At the same time as releasing oxygen into the atmosphere, forests absorb carbon dioxide. Therefore, the estimation of the oxygen-producing function of the forests of the Cheremsky NR is a clear confirmation of their importance in improving the state of the air basin in the region under study.

Conclusions

The dependence of the phytomass components of tree stands of the main forest-forming tree species of the Cheremsky Nature Reserve on their main morphometric features was modeled using multiple regression analysis by establishing single- and multifactorial dependences of the phytomass components on the inventory indicators of the tree stands filed in the forest cadastre.

All above-ground components of Scots pine phytomass of natural and artificial origin are statistically significant. The coefficients of determination and other statistical indicators were found to be insignificant for the wood and bark of the stem of the silver birch and common alder. Therefore, their average values were used in further calculations.

During 2005-2018, the supply of stem wood increased from 244.9 thous. m^3 in 2005 to 336.2 thous. m^3 in 2018 (by 91.3 thous. m^3, or by 37.3%). Accordingly, the volume of the total phytomass of stands increased by 57.2 thous. t (36.5%) and the carbon accumulated in it by 28.4 thous. t (36.5%).

The largest share in the structure of the phytomass of the forest stands of the reserve falls on coniferous stands (72.0%), a much smaller share – on soft-wood stands (26.0%) and the smallest – on hard-wood stands (2.0%).

The average density of phytomass and carbon in the forests of Cheremsky NR during the 13 experimental years gradually increased: from 8.7 $kg \cdot (m^2)^{-1}$ to 11.1 $kg \cdot (m^2)^{-1}$ for phytomass and from 4.3 $kg \cdot (m^2)$ -1 to 5.5 $kg \cdot (m^2)^{-1}$ for carbon.

As of 2018, the carbon density in the forests of the Cheremsky NR for forest areas covered with forest vegetation reaches 5.5 $kg \cdot (m^2)^{-1}$ on average. This indicator was closest to the average value in coniferous stands (6.0 $kg \cdot (m^2)^{-1}$), the lowest – in soft-wood stands (4.4 $kg \cdot (m^2)^{-1}$) and the highest (6.3 $kg \cdot (m^2)^{-1}$) – in hard-wood stands.

Carbon density increases more intensively in needles (from 4.5 $kg \cdot (m^2)^{-1}$ in 2005 to 6.0 $kg \cdot (m^2)^{-1}$ in 2018) and hard-wood tree species (from 5.1 $kg \cdot (m^2)^{-1}$ in 2005 to 6.3 $kg \cdot (m^2)^{-1}$ in 2018), and in soft-wood plants – less intensively (only by 0.6 $(m^2)^{-1}$).

During the period under study, the density of phytomass of tree stands and the carbon deposited in it increased 1.4 times in the forests of the reserve due to redistribution in the age class composition of forest stands and, as a result, an increase in the average stock per 1 ha.

Forest biocenoses of the Cheremsky Nature Reserve produce 6,989 t of oxygen every year (4.2 $t \cdot ha^{-1}$ on average). The main volume of oxygen is produced by coniferous stands (91.8%), as they grow here on the largest territory (1,099.9 ha) and have the highest wood stock (218.42 thous. m^3). The share of soft-wood and hard-wood stands in the total stock of forest areas of the reserve is insignificant (66.53 and 4.65 thous. m^3). Therefore, they produce much less oxygen (6.1% and .1%, respectively) Coniferous stands also emit more oxygen per unit area (6.2 $t \cdot ha^{-1}$), hard-wood stands – a little less (5.3 $t \cdot ha^{-1}$), while soft-wood stands produce only 0.8 $t \cdot ha^{-1}$ of oxygen.

The conducted studies of the forests of the Cheremsky Nature Reserve demonstrate the positive dynamics of the accumulation of phytomass volumes and the carbon sequestered in it (36.5% over the 13 years under study). In the future, the research will be aimed at predicting the increase in bioproductivity of the plantations of this object to improve their ecological functions and establish the possibilities of their impact on the environment.

References

[1] Lakyda, P.I., Bala, O.P., Matushevich, L.M., Lakyda, I.P., & Ivanyuk, I.D. (2018). *Forestry and ecological potential of forests of Polissia of Ukraine*. Korsun-Shevchenkivskyi: IE I.S. Maidachenko.

[2] Lakyda, P.I. (2002). *Phytomass of forests of Ukraine*. Ternopil: Zbruch.

[3] Lakyda, P.I., Melnyk, O.M., Vasylyshyn, R.D. (2019). *Bioproductivity of forest phytocenoses of the Pripyat-Stokhid National Nature Park*. Korsun-Shevchenkivskyi: IE I.S. Maidachenko.

[4] Lakida, P., Nilsson, S., & Shvidenko, A. (1995). *Estimation of forest phitomass for selected countries of the former European USSR*. Laxenburg: IIASA.

[5] Lakyda, P., Shvidenko, A., Bilous, A., Myroniuk, V., Matsala, M., Zibtsev, S., Schepaschenko, D., Holiaka, D., Vasylyshyn, R., Lakyda, I., Diachuk, P., & Kraxner, F. (2019). Impact of disturbances on the carbon cycle of forest ecosystems in Ukrainian Polissya. *Forests*, 10, article number 337.

[6] Matthews, G. (1993). *The carbon contents of trees*. Edinburgh: Forestry Commission.
[7] Schepaschenko, D., Chave, J., Phillips, O.L. et al. (2019). The forest observation System, building a global reference dataset for remote sensing of forest biomass. *Scientific Data*, 6(1), article number 198. https://doi.org/10.1038/s41597-019-0196-1.
[8] An, X., Wen, Y., Zhang, Y., & Xu, S. (2019). Evaluation of the forestry and environmental conservation policies in Western China with multi-output regression method: Original papers. *Computers and Electronics in Agriculture*, 157, 239-246. https://doi.org/10.1016/j.compag.2018.12.035.
[9] Lakyda, P.I., & Dubrovets, B.V. (2020). *Forests of the Holosiivskyi National Nature Park: Bioproductivity and ecological functions*. Korsun-Shevchenkivskyi: IE I.S. Maidachenko.
[10] Bokoch, V.V., Lakyda, P.I., Vasylyshyn, R.D., & Terentyev, A.Yu. (2012). Modeling indicators of stands phytomass components of the Carpathian NNP. *Scientific Bulletin of the National University of Bioresources and Nature Conservation of Ukraine. Series Forestry and Ornamental Horticulture*, 171(2), 18-25.
[11] Lakyda, P.I., & Saharuk, G.A. (2013). *Bioproductivity of the forests of the Shatskyi National Natural Park*. Korsun-Shevchenkivskyi: IE V.M. Havryshenko.
[12] Myklush, S.I. (2007). Plantation growth modeling based on materials from the separate database. *Scientific Bulletin of the National Agrarian University*, 106, 191-200.
[13] Albers, A., Collet, P., Benoist, A., & Helias, A. (2019). Data and non-linear models for the estimation of biomass growth and carbon fixation in managed forests. *Data in Brief*, 23, article number 103841. https://doi.org/10.1016/j.dib.2019.103841.
[14] Dang, A.T.N., Nandy, S., Srinet, R., Luong, N.V., Ghosh, S., & Senthil Kumar, A. (2019). Forest aboveground biomass estimation using machine learning regression algorithm in Yok Don National Park, Vietnam. *Ecological Informatics*, 50, 24-32.
[15] Forrester, D.I., Tachauer, I.H., Annighoefer, P., Barbeito, I., Pretzsch, H., Peinado, R., Stark, H., Vacchiano, G., Zlatanov, T., Chakraborty, T., Saha, S., & Sileshi, G.W. (2017). Generalized biomass and leaf area allometric equations for European tree species incorporating stand structure, tree age and climate. *Forest Ecological Management*, 396, 160-175.
[16] Lakyda, P.I., & Domashovets, G.S. (2009). *Bioproductivity of Lviv Oblast forests and its dynamics*. Korsun-Shevchenkivskyi: IE I.S. Maidachenko.
[17] Melnyk, O.M. (2017). *Biotic productivity and ecological potential of the forests of the Pripyat-Stokhid National Nature Park* (Doctoral thesis, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine).
[18] Lakida, P. (1996). *Forest phytomass estimation for Ukraine*. Laxenburg: IIASA.
[19] Ministry of Environmental Protection and Nuclear Safety of Ukraine. (1996). *National report on the state of the environment in Ukraine in 1996*. Kyiv: Raevsky Publishing House.

Біопродуктивність лісів Черемського природного заповідника

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Анотація. Кліматичні зміни підривають стабільність природних екосистем і негативно впливають на життя людини. Лісові біоценози здатні регулювати газообмін атмосфери, накопичувати й утримувати протягом тривалого часу в компонентах фітомаси небезпечні для навколишнього середовища викиди діоксиду вуглецю. Метою даного дослідження є вивчення динаміки біопродуктивності деревостанів головних лісотвірних видів Черемського природного заповідника за компонентами фітомаси та депонованого в них вуглецю. Для вирішення завдань роботи застосована методика П.І. Лакиди. Для здійснення процесу моделювання використані дослідні дані тимчасових пробних площ, які у повній мірі характеризують лісові масиви досліджуваного об'єкта. Розрахунок коефіцієнтів відношень R_v здійснювали для деревини стовбура ($R_{v(st)}$); кори стовбура ($R_{v(k)}$); гілок ($R_{v(g)}$); листви (хвої) ($R_{v(l)}$). Встановлено, що всі надземні компоненти фітомаси сосни звичайної описуються регресійними рівняннями. Для деревини й кори стовбурів берези повислої та вільхи клейкої коефіцієнти детермінації виявилися незначущими. У структурі фітомаси лісостанів заповідника найвагоміша частка (72,0 %) припадає на хвойні лісостани, значно менша – на м'яколистяні (26,0 %) і найменша – на твердолистяні насадження (2,0 %). За 13 років щільність фітомаси деревостанів та депонованого в ній вуглецю зросли в 1,4 рази. Щороку лісові біоценози заповідника виділяють в атмосферу 6989 т кисню (4,2 $т \cdot га^{-1}$). Основний об'єм кисню (91,8 %) продукують хвойні насадження. На основі зібраного дослідного матеріалу для деревостанів головних лісотвірних видів Черемського природного заповідника розраховані: коефіцієнти відношень компонентів надземної фітомаси до їхнього запасу в корі; математичні моделі оцінки динаміки компонентів фітомаси; нормативи розрахунку киснепродуктивності. Результати дослідження біо- та киснепродуктивності лісів Черемського природного заповідника стануть вагомим внеском для ефективного ведення господарства в заповідних лісах, а також при вирішенні проблем, пов'язаних зі змінами клімату на регіональному та глобальному рівнях

Ключові слова: математичні моделі, конверсійні коефіцієнти, фітомаса деревостанів, депонований вуглець, киснепродуктивність

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The influence of recreational load on the anti-erosion properties of the soils of park stands

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Abstract. Changes related to urban infrastructure directly affect the ecological environment, including soil properties. The purpose of this study is to investigate the anti-erosion and flow-regulating effect of park stands in complex terrain conditions of Kyiv. Forestry and tax indicators of plantings are established according to recognized tax methods. The upper layers of the soil were studied by determining the hardness, water permeability, density, and humidity on paths and in stands. Soil hardness in plantations increases from 9.1 ± 0.76-10.8 ± 1.01 kg/cm^2 to 15.4 ± 0.25-30.8 ± 0.15 kg/cm^2, which is associated with the intensity of trampling them. Therewith, the soil changes from loose to medium loose and even dense. Determination of water permeability also showed a significant discrepancy, from 18.6 ± 0.76-20.6 ± 0.66 mm/min to 1.9 ± 0.10-5.7 ± 0.33 mm/min, respectively. Research has confirmed the inverse correlation between soil hardness and water permeability. The obtained indicators of soil density in the stands (1.12-1.20 g/cm^3) and on the paths (1.34-1.66 g/cm^3), albeit without sharp differences, in both cases indicate their criticality for further normal development of stands. Changes in soil moisture data in stands (16.9-20.6%) are decreasing in comparison with paths (11.2-12.6%), which also indicates the deterioration of growing conditions. The presence of active roots in the upper thickness of the soil on the control was 5.8-9.8 g, and on the paths, depending on the intensity of trampling, from 0.0 to 2.2 g. The territories under study were surveyed to identify characteristic erosion processes. It was established that the park spaces are in a satisfactory condition and fully perform an anti-erosion effect. The threat of erosion processes occurs on paths of intense load. The results obtained can be used for monitoring and regulating anthropogenic load

Keywords: complex terrain, test network, root system, surface runoff, erosion processes

Introduction

Scientists of the world increasingly note the dominant role of human activity in terms of adverse impact on vegetation in general and park stands in particular [1; 2]. Tourist activity affects the reduction of adaptation of vegetation to anthropogenic loads and increases its vulnerability [3]. An increase in degraded zones is observed in areas adjacent to tourist hiking tests [4]. S.V. Halla-Bobik [5] notes the negative impact of the functioning of recreational and tourist complexes on the state of water in the Syniavka River in the National Natural Park (NNP) "Zacharovanyi Krai".

The risk of soil erosion is increasing on a global scale. It is related to the type of soil, topography, slope, frequency, and intensity of extreme precipitation, the state of vegetation cover, etc. [6]. Since urban park areas in complex terrain are affected by water erosion, tree and shrub vegetation plays an extraordinary role in protecting and preventing the development of landslides and soil degradation [7; 8]. The conditions of the crossed relief are most vulnerable to the destructive action of water erosion, the development of which is influenced by the steepness, length, exposure, and shape of the slope. Specifically, soil is washed out more intensively on convex slopes than on concave ones. In turn, the water-physical properties of the soil, including density and moisture, directly determine its anti-erosion resistance. At the same time, vegetation is an essential factor that prevents the development of erosion processes or reduces them. The destruction of vegetation, including by recreational exercise, increases the danger.

Therefore, park plantations suffer from excessive trampling, damage to vegetation by burning, especially in places where spontaneous recreation areas are arranged, erosion processes, clogging, etc. This leads to a weakening of their biological stability, liquefaction, aesthetics, and

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death. Preservation and reproduction of plant cover, the main producer of organic matter for trophic chains, is the key to the normal development of the natural environment in general and parks and forest parks in particular. In this context, it is important to be aware of the recreational value of vegetation. As for green spaces, recreation should be understood as the restoration of a healthy person's strength as a result of direct communication with nature.

Studies of the recreational load on park plantings stay relevant, as they can be used to regulate and limit anthropogenic impact. They were aimed at the manifestation of erosion processes, which occur mainly on test networks, especially in conditions of complex terrain. The purpose of these studies was to find out the anti-erosion and runoff-regulating effects of urban parks. The main task included determining the condition and basic water-physical properties of the soils of the test network of the park territories. The originality of this study lies in the use of runoff sprinklers on the test network to protect against water erosion. To fulfil the purpose of the study and complete the main task, the application of a complex approach is provided.

It is equally important to identify the causes of erosion processes. Soil washout on tests occurs due to the concentration of surface runoff, which is formed in liquefied vegetation on slopes, or comes in transit from the carriageway of highways or paved roads. Asphalted roads bordered by curbs contribute to the concentration of surface runoff. The improper condition of hydrotechnical structures, e.g., high-speed channels, is the reason for the development of erosion processes [7]. In this paper, attention is focused on test networks with a soft ground surface, which are common on the slopes of parks on difficult terrain: M.T. Rylsky Holosiivskyi Park of Culture and Recreation (PCR) and NNP "Holosiivskyi". Compared to forest stands of natural and especially artificial origin, which require considerable time for the formation of the forest environment in countering the manifestation of erosion, hydraulic structures operate relatively quickly from the moment of their construction. However, stands that have an established forest environment are much more efficient than hydraulic structures. The latter require constant maintenance and repairs, and the anthropogenic factor plays a crucial role.

Literature Review

The deterioration of the ecological state of the natural environment inevitably affected people's health (burnout, stress, etc.). Recently, the need for recreational forest use in general and forest park and park use in particular has increased substantially. The known positive and comprehensive impact of forest stands on the human body encourages it to communicate more often with the natural environment. In this regard, systems of green spaces can provide architectural and planning, recreational and health and aesthetic functions.

It is important to consider the age parameters of the city parks being created. Young urban landscapes are less resistant to degradation compared to old ones [9]. Soil and vegetation are interconnected and mutually determined. During soil formation, the main role is played by green plants – creators of organic matter. At the same time, plants depend on the soil on which they grow. Consequently, soil destruction leads to degradation of plant communities [10]. There should be constant monitoring of soil and vegetation properties, as well as the number of visitors and their activity in parks [11; 12]. Grass cover reacts earlier than arboreal plants to the use of precipitation that enters the soil [13]. E.A. Fedoruk [14] notes that the living ground cover is the first link in the forest environment that suffers from an increase in anthropogenic impact on it. Trampling of the soil by recreationists manifests negative properties of the upper layers of the soil and adversely affects the plant cover [15]. The impact of trampling substantially affects the species diversity of ecosystems [16].

Together with disturbance and compaction of litter, the recreational load leads to compaction of the upper mineral part of the soil to a depth of up to 15 cm, and much deeper on the paths [17]. Typically, the indicator of recreational load per 1 ha of their area is used to assess the impact of visitors on park stands [18; 19]. Recreational load, as an indicator, was calculated by the authors in person-days/ha, which is the most common methodical approach. However, this kind of assessment does not allow establishing the causes and prevent the manifestations of erosion processes in time. These studies are dedicated to solving the issue of preventing the development of erosion processes on the test networks of park plantations with complex terrain.

Modern studies of the recreational load on the plantations of the NNP "Holosiivskyi" highlight the constantly growing urban influence, the consequences of which for the natural components of the forest are increasing degrees of degradation and a decrease in the value of forest ecosystems. The main value of Holosiivskyi forest ecosystems for urban visitors is noted, which lies in protecting soils from erosion, regulating water flow, producing oxygen, absorbing carbon dioxide, preserving biodiversity, recreational, wellness and cultural-historical functions [20]. Therewith, the pine stands of the zone of regulated recreation in the southern part of the "Holosiivskyi" NNP are characterized by a moderate recreational load of 1.2-2.5 people·days/ha, which corresponds to the second stage of recreational digression. The recreation coefficient was 0.05-0.15, i.e., the permissible load is not exceeded [21]. Considering the forecast of a multi-year steady distribution of the daily average annual flow of visitors to sites in Kyiv [22], the "Holosiivskyi" NNP has a 19% share of the city's visitors, being almost at the same level as Podol (18%) and inferior only to Pechersk (28%) and Starokyivska Hora (20%). This testifies to the rather high importance of the territory under study among the city's recreational locations, and the importance of maintaining its aesthetic and ecological potential. Therefore, it is necessary to perform monitoring and, specifically, erosion control of the anthropogenic load on park plantings in the conditions of the complex topography of Kyiv.

Materials and Methods

The recreational load on the soils of park stands was studied on temporary experimental plots (TEP) in the "Holosiivskyi" NNP (TEP No. 4-6) and the M.T. Rylskyi Holosiivskyi PCR (TEP No. 1-3), which is part of it. Monitoring of the water and physical properties of soils took place in April-August 2022, which accounts for 60% of the flow of visitors to urban park areas. The location of the experimental sites is presented in Figure 1.

The leading factor in the destruction of plant communities is trampling, which primarily affects the ground cover and herbaceous vegetation. According to the intensity of trampling [23] in the territories under study, it was found that up to 20% of the hiking tests are devoid of any vegetation cover that is, they have the stage V of complete trampling; up to 30% of the paths are in the stages III-IV of trampling with the destruction of the grass cover from 15% to 60%; 50% of the total area of the test network is classified as stages I-II of trampling, where up to 15% of the grass cover has been destroyed.

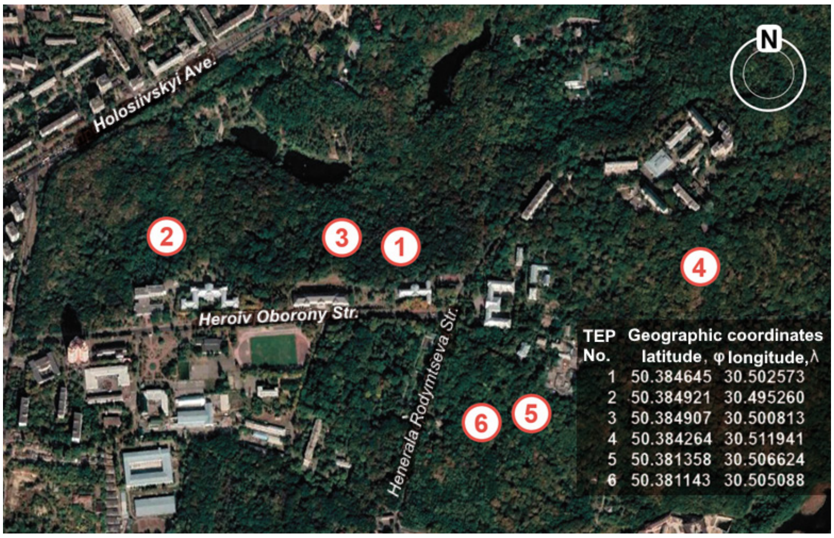

Figure 1. Geolocation of temporary test areas in park plantations
Source: developed by the authors based on a Google Earth image

Experimental plots of plantations on the TEP were chosen in the middle part of the slopes. All of them are mixed with representatives of deciduous tree species of maple (*Acer platanoides* L.), hornbeam (*Carpinus betulus* L.) and oak (*Quercus robur* L.). The steepness of the slopes is from 7 to 17 degrees of northern, eastern, and southern exposures. The difference in the thickness of the humus horizon is insignificant and ranges from 19 to 21 cm (Table 1).

Table 1. The main forestry and taxation indicators of park stands

Number TEP	Stand composition	Age, years	Average		Density	Slope		Humus horizon, cm
			height, m	diameter, cm		steepness, degree	exposition	
M.T. Rylskyi Holosiivskyi PCR								
1	6Ap4Cb	75	24.5	28.0	0.7	13	N	20
2	6Cb4Ap	80	25.0	29.0	0.6	17	N	19
3	7Cb3Ap	75	25.0	30.0	0.7	15	N	19
NNP “Holosiivskyi”								
4	7Ap3Cb	70	23.5	27.0	0.5	8	E	21
5	5Cb5Ap	80	26.0	31.0	0.6	12	E	20
6	7Ap3Qr	70	24.0	26.0	0.5	7	S	21

Note: Ap – *Acer platanoides* L.; Cb – *Carpinus betulus* L.; Qr – *Quercus robur* L.
Source: compiled by the authors based on the studies conducted

According to the determined forest inventory parameters, the researched plantations grow according to the first (I) site index class, having an age ranging from 70 to 80 years and a stocking of 0.5-0.7 (Fig. 2). According to the method of I.D. Rodichkin [17], they form landscapes of closed (TEP No. 1-3, 5) and semi-open (TEP No. 4, 6) types of spaces.

TEP No. 1 TEP No. 2 TEP No. 3 TEP No. 4 TEP No. 5 TEP No. 6

Figure 2. General view of the test network of park stands on temporary experimental plots
Source: photographs taken by the authors

Soil hardness was measured from the surface with a Golubev hardness tester. The number of measurements is 20 times in the middle of the path of different trampling intensity. Measurements in stands at 20 m from the paths were used as a control and comparison of research results. The water permeability of the soil was determined using steel cylinders with a diameter of 80 mm and a height of 100 mm by sinking them into the soil half the height and filling the above-ground part with water. The time of water penetration into the soil is measured by a stopwatch. The determined absorption time of a 50 mm layer of water corresponds to torrential precipitation. The number of measurements is 10 times. Water permeability is defined as the amount of absorbed water over the time it was absorbed in mm/min [7]. The statistics of measuring soil hardness and water permeability were obtained for ungrouped series based on a small number of observations: N is the number of repetitions, χ is the mean value, σ is the mean square deviation, m is the error of the mean value, υ is the coefficient of variation, p is the precision of the mean value. The significance of the difference between the average values was also estimated [24]. The root mass was collected from monoliths measuring 10×10×10 cm with a total volume of 1,000 cm^3. The density of the soil, as the dry mass of a unit of its volume without disturbing the natural compaction [25] was identified according to the method of a cutting steel ring with a diameter of 50 mm and a height of 30 mm. Soil moisture was determined by the drying method.

The manifestation of erosion processes was observed in 2018-2022. Research on the types of soil erosion was investigated on the test network of intensive trampling by measuring the depth and length of erosion. The washes were studied by the arrangement of trenches on the flow sprinklers before the dam day for silt retention.

Results and Discussion

The anti-erosion and runoff-regulating effect of park stands is closely related to the hardness and water permeability of the upper soil layer and the spread of root systems in it [7]. In turn, the above-mentioned depends on the state of the stands themselves and their use of living space [26]. The measured indicators of soil hardness (Table 2), in plantations and on paths, have a substantial difference, which can be explained by the trampling intensity.

Table 2. Soil hardness measurement statistics

No.TEP	Stand composition	A, years	N	χ	σ	m	υ	p
1	6Ap4Cb	75	20	9.5	0.88	0.23	4.74	1.22
1a	path	–	20	19.7	1.25	0.29	6.34	1.46
2	6Cb4Ap	80	20	10.8	1.01	0.26	5.67	1.46
2a	path	–	20	30.8	0.66	0.15	2.14	0.40
3	7Cb3Ap	75	20	9.1	0.76	0.20	4.45	1.15
3a	path	–	20	15.4	1.10	0.25	7.15	1.60
4	7Ap3Cb	70	20	9.8	0.84	0.22	4.83	1.25
4a	path	–	20	23.7	0.68	0.15	2.86	0.64
5	5Cb5Ap	80	20	10.5	0.98	0.25	5.52	1.43
5a	path	–	20	29.0	0.63	0.14	2.14	0.84
6	7Ap3Qr	70	20	10.2	0.94	0.24	5.29	1.36
6a	path	–	20	25.8	0.70	0.16	2.70	0.60

Note: in the TEP numbering, “a” indicates that the soil hardness measurements were made in the middle of the path
Source: compiled by the authors based on the studies conducted

In the tree stands, despite the difference in age and composition, the range of hardness indicators was within 9.1 ± 0.76-10.8 ± 1.01 kg/cm^2, which according to M.A. Kaczynski classifies [25] them as loose and medium loose. The assessment of the significance of the difference between the average values of the indicators (Table 3) shows that it is insignificant in the stands on TEP No. 1-3, where the Student's criterion does not exceed 4.34. On the paths, these indicators differ substantially from each other. This is related to the trampling intensity, 15.4 ± 0.25-30.8 ± 0.15 kg/cm^2, as well as the vegetation and changes from a medium loose to a dense state. They revealed a significant difference in the average values of soil properties indicators, where the Student's criterion increases from 8.82 to 13.77.

Table 3. Evaluation of the significance of the difference between the average values of hardness indicators

Difference between average values	Number of degrees of freedom	Criterion Student $t_{0.05}$	Difference between average values	Number of degrees of freedom	Criterion Student $t_{0.05}$
1-2*	36	4.34	1-4	36	1.10
2-3a*	36	13.77	6a-4a*	36	9.62
2a-5a*	36	8.82	1a-3a*	36	11.55

Note: * – significant
Source: compiled by the authors based on the studies conducted

For park stands to effectively perform anti-erosion action, it is important to know not only the indicators of soil hardness, but also their ability to absorb liquid atmospheric precipitation according to indicators of water permeability (Table 4).

Table 4. Statistics of soil water permeability measurement

No. TEP	Stand composition	A, years	N	χ	σ	m	υ	p
1	6Ap4Cb	75	10	19.9	1.42	0.45	13.7	4.32
1a	path	–	10	4.6	0.63	0.20	13.6	4.32
2	6Cb4Ap	80	10	18.6	1.77	0.76	15.3	4.80
2a	path	–	10	1.9	0.20	0.10	10.0	3.18
3	7Cb3Ap	75	10	20.6	1.58	0.66	13.8	4.17
3a	path	–	10	5.7	1.04	0.33	18.2	5.75
4	7Ap3Cb	70	10	20.0	1.45	0.53	13.4	4.39
4a	path	–	10	3.9	0.32	0.11	8.3	2.61
5	5Cb5Ap	80	10	19.0	1.63	0.54	16.1	4.83
5a	path	–	10	2.7	0.16	0.05	5.8	1.83
6	7Ap3Qr	70	10	19.5	1.75	0.53	15.5	4.73
6a	path	–	10	3.4	0.33	0.11	9.6	3.20

Note: in the TEP numbering, "a" indicates that the soil hardness measurements were made in the middle of the path
Source: compiled by the authors based on the studies conducted

The determined water permeability of the soil under the experimental stands ranged within 18.6 ± 0.76-20.6 ± 0.66 mm/min, which has no significant difference between the average values (Table 5). On the test network, the water permeability indicators had a sufficiently large discrepancy from 1.9 ± 0.10 to 5.7 ± 0.33 mm/min, which revealed significant differences between the average values of the indicators both on the tests and compared to the plantations. Therewith, the Student criterion was 2.86-19.88.

Table 5. Evaluation of the significance of the difference between the average values of soil water permeability indicators

Difference between average values	Number of degrees of freedom	Criterion Student $t_{0.05}$	Difference between average values	Number of degrees of freedom	Criterion Student $t_{0.05}$
1-2*	16	1.81	1-4	16	0.16
2-3a*	16	19.88	6a-4a*	16	3.44
2a-5a*	16	9.88	1a-3a*	16	2.86

Note: * – significant
Source: compiled by the authors based on the studies conducted

The absorptive capacity of the soil of park plantations according to the intensity of infiltration during the first hour will be from 1116 to 1236 mm/h. According to M.A. Kaczynskii [25], such results allow estimating the water permeability of the soil as failure. The obtained indicators of water permeability of the soil under the stands testify to their powerful anti-erosion capabilities. On the paths, depending on their trampling during the first hour, the intensity of infiltration can range from 114 to 342 mm/h. Therefore, the researched park plantings contribute to the rapid transfer of surface runoff to ground runoff, which makes it impossible for erosion processes to occur. However, provided the formation of liquefied stands of surface runoff on the sloping sections of the paths or the arrival of its transit part under the tent, the threat of erosion processes increases depending on the intensity of trampling.

Research has confirmed that soil hardness is clearly correlated with water permeability, having inverse correlations (Fig. 3). Both indicators substantially depend on the level of soil moisture. As the level of soil moisture increases, its hardness decreases, which allows plants to build up their root system. But excessive soil moisture also reduces water permeability.

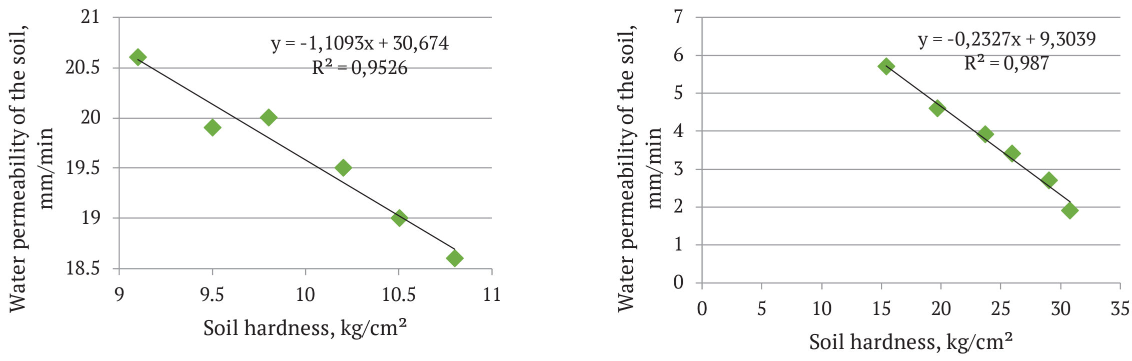

Figure 3. Dependence of soil water permeability on hardness: a – in stands; b – on the paths
Source: compiled by the authors based on the studies conducted

The density of soil composition and its hardness have a proportional relationship. As the folding density increases, the hardness increases. Investigating the physical and mechanical properties of the soil cover (Table 6), it was established that the density of the soil composition in the park stands (1.12-1.20 g/cm^3) and in the middle of the paths (1.34-1.66 g/cm^3) substantially differs due to greater anthropogenic load (trampling). Comparable results were obtained in the parks of Ivano-Frankivsk region [27; 28]. At an elevated level of recreational load, the volumetric mass of the soil increases by 1.5 or more times, and on the paths, the diversion is 2 to 10 times. A soil density level of 0.8-1.0 g/cm^3 allows tree stands to grow and develop normally, and when it increases to 1.12-1.20 g/cm^3, tree species begin to fall from the stand [17]. That is, the established density of the soil is critical for the further normal development of tree stands and can lead to its liquefaction.

Table 6. Physical and mechanical properties of the soil cover

No. TEP	Stand composition	A, years	Soil characteristics				Root weight, d
			raw weight, g	dry weight, g	density, g/cm³	humidity, %	
1	6Ap4Cb	75	83	69	1.17	20.3	9.1
1a	path	–	92	82	1.39	12.2	1.9
2	6Cb4Ap	80	82	68	1.15	20.6	6.2
2a	path	–	109	98	1.66	11.2	0.0
3	7Cb3Ap	75	78	66	1.12	18.2	9.8
3a	path	–	91	81	1.37	12.3	2.2
4	7Ap3Cb	70	85	71	1.20	19.7	7.5
4a	path	–	89	79	1.34	12.6	0.7
5	5Cb5Ap	80	83	71	1.20	16.9	8.3
5a	path	–	100	89	1.51	12.3	0.0
6	7Ap3Qr	70	81	69	1.17	17.4	5.8
6a	path	–	88	79	1.34	11.4	0.8

Source: compiled by the authors based on the studies conducted

Soil moisture in plantations (16.9-20.6%) is higher compared to paths (11.2-12.6%), this is explained by the presence of forest litter 2-3 cm thick, which acts as mulch and reduces the load. The presence of active roots (diameter < 2 mm) in a 10-centimetre layer clearly reflects the influence of soil density and moisture. In tree stands, the weight of roots in a volume of 1000 cm^3 is 5.8-9.8 g, and on paths, depending on the intensity of anthropogenic load, from 0.0 to 2.2 g. At soil hardness over 29.0 ± 0.14 kg/cm^2, active roots are absent in the upper active layer. Therefore, the possibilities of binding the soil are minimized, and the probability of its washing out under such conditions, during the passage of concentrated surface runoff, increases. The obtained data confirm earlier studies [7].

The most frequent and largest washouts occur on intensively used tests that are located on the slopes of complex landforms. This applies to the areas where concentrated surface runoff is formed under the canopy of liquefied vegetation, as well as in places where the transit part of the runoff coming from roadways reaches them (Fig. 4a).

a b c

Figure 4. Characteristic erosion processes on park paths were identified: a – linear erosion; b – scum on the drain sprayer; c – the thickness of washed soil for 2021-2022

Source: photographs taken by the authors

In 2017, runoff sprinklers were installed at TEP No. 5 to protect the path from erosion and silt retention (Fig. 4b). In 2020, the operation of drain sprinklers was studied. During the three years of operation of one of the sprinklers (2018-2020), it retained 1.5 m^3 of silt. The total thickness of the washed soil layers during this period was 20 cm, and their number was 18 pieces (Fig. 4c). Maintenance work was carried out to remove silt for uninterrupted operation of the drain sprayer. During the next period (2021-2022), the thickness of the washed soil layer was 9 cm (Fig. 4c). Such a difference is related to the number and intensity of downpours in the specified periods. Therefore, for the effective operation of a simple hydraulic structure – a drain sprinkler, it is necessary to carry out constant monitoring and maintenance, and if necessary, in cases of damage by recreationists, to carry out repairs.

The obtained data on the anthropogenic influence on the anti-erosion properties of the soils of the parks of Kyiv confirm the zones [20] where conflict and threats are identified in the areas of the territories under study: unregulated recreational load (dense laying of tourist tests, visits to the most valuable, least developed areas of the forest) and non-target use of forest areas (dumping of household waste, felling, unorganized parking lots), as a result – destruction of the age-old structure of stands.

It is impossible to immediately react to the thinning of the stands through which the test routes pass, where surface runoff is formed during intense torrential rains, or their transit part arrives in the conditions of complex relief on the slopes. However, it is possible to install runoff sprinklers, which can prevent the manifestation of erosion (soil washout or erosion) under conditions of constant monitoring, maintenance, and prompt repairs. The prospect of further research envisages the implementation of studies on the improvement of flow sprinklers.

Conclusions

Park spaces are in a satisfactory condition and fully perform an anti-erosion effect. The threat of erosion processes occurs on paths of intense load. The anti-erosion and runoff-regulating effect of park stands is closely related to the hardness, water permeability of the upper soil layer, and the spread of root systems in it. In park stands, despite the difference in age and composition, the range of hardness indicators was within 9.1 ± 0.76-10.8 ± 1.01 kg/cm^2, which refers them to the loose and medium loose state. On the paths, these indicators differ substantially between each other and between stands and vary from a medium loose to a dense state of 15.4 ± 0.25-30.8 ± 0.15 kg/cm^2, which is explained by the trampling intensity.

The water permeability of the soil under the experimental stands was determined, which ranges within 18.6 ± 0.76-20.6 ± 0.66 mm/min. On the test network, the water permeability indicators had a fairly large discrepancy from 1.9 ± 0.10 to 5.7 ± 0.33 mm/min. Research has confirmed that soil hardness is clearly correlated with water permeability, having an inverse correlation.

It was established: the density of the soil composition in the park stands (1.12-1.20 g/cm^3) and in the middle of the paths (1.34-1.66 g/cm^3); soil moisture in stands (16.9-20.6%) is higher compared to paths (11.2-12.6%); the presence of active roots of a 10-centimetre layer of stands is 5.8-9.8 g, and on paths, depending on the intensity of anthropogenic load, from 0.0 to 2.2 g. With a soil hardness over 29.0 ± 0.14 kg/cm^2, there are no active roots on the paths, which can lead to washout or erosion.

The identified partially adverse impact of the recreational load on the soils of park stands can be used for its regulation, which allows preventing the complete degradation of the investigated ecosystems under constantly growing urbanization. Further studies should continue to monitor the state of anti-erosion properties of park plantings in conditions of complex terrain, as they are valuable for their aesthetic and ecological potential.

References

[1] Amaral, Y.T., Santos, E.M., Ribeiro, M.C., & Barreto L. (2019). Landscape structural analysis of the Lençóis Maranhenses national park: Implications for conservation. *Journal for Nature Conservation*, 51, article number 125725. https://doi.org/10.1016/j.jnc.2019.125725.

[2] Wan, Z., & Gao, W. (2020). Changes in urban vegetation cover and analysis of the influencing factors: A case study of Harbin, Heilongjiang Province, China. *Arabian Journal of Geosciences*, 13, article number 1053. https://doi.org/10.1007/s12517-020-05931-5.

[3] Li, L., & Zhou, G. (2020). Response of forest vegetation to scenic activities in Wuyishan National Park. *Shengtai Xuebao*, 40, 7267-7276.

[4] Fidelus-Orzechowska, J., Gorczyca, E., Bukowski, M., & Krzemień, K. (2021). Degradation of a protected mountain area by tourist traffic: Case study of the Tatra National Park, Poland. *Journal of Mountain Science*, 18(10), 2503-2519.

[5] Halla-Bobyk, S.V. (2016). Recreation pressure in the National park "Enchanted edge". *Scientific Bulletin of the Uzhhorod University. Series "Chemistry"*, 36(2), 73-76.

[6] Peng, Q., Wang, R., Jiang, Y., Zhang, W., Liu, C., & Zhou, L. (2022). Soil erosion in Qilian Mountain National Park: Dynamics and driving mechanisms. *Journal of Hydrology: Regional Studies*, 42, article number 101144. https://doi.org/10.1016/j.ejrh.2022.101144.

[7] Minder, V.V., Maliuha, V.M., & Yukhnovskyi, V.Yu. (2019). *Meliorate properties of park stands in the conditions of complex relief*. Kyiv: "Kondor" Publishers.

[8] Chornomaz, N.M. (2016). Planting on the slopes of the Mariinsky Park, species and spatial structure, current status. *Scientific Bulletin of UNFU*, 26.3, 198-203.

[9] Bryant, C.S., John, E.L., & Jodi, L.J.-M. (2005). Distinguishing urban soils with physical, chemical, and biological properties. *Pedobiologia*, 49, 283-296.

[10] Mosaffaei, Z., Jahani, A., Chahouki, M.A.Z., Goshtasb, H., Etemad, V., & Saffariha, M. (2020). Soil texture and plant degradation predictive model (STPDPM) in national parks using artificial neural network (ANN). *Modeling Earth Systems and Environment*, 6, 715-729.

[11] Shumilova, A.V. (2014). Assessment of recreational load on landscapes NNP "Slobozhanskiy". *Man and Environment. Problems of Neoecology,* 1-2, 70-74.

[12] Sarah, P., Zhevelev, H.M., & Oz, A. (2015). Urban park soil and vegetation: Effects of natural and anthropogenic factors. *Pedosphere,* 25(3), 392-404.

[13] Marx, C., Tetzlaff, D., Hinkelmann, R., & Soulsby, C. (2022). Seasonal variations in soil – plant interactions in contrasting urban green spaces: Insights from water stable isotopes. *Journal of Hydrology*, 612, article number 127998. doi: 10.1016/j.jhydrol.2022.127998.

[14] Fedoruk, E.A. (2019). Living ground cover as an indicator of the state of forest park massives. *Scientific Bulletin of UNFU*, 29.3, 23-26.

[15] Li, Y., Chen, K., Liu, Z., & Cao, G. (2022). Short-term impacts of trampling on selected soil and vegetation properties of alpine grassland in Qilian Mountain National Park,China. *Global Ecology and Conservation*, 36, article number e02148. https://doi.org/10.1016/j.gecco.2022.e02148.

[16] Annika, K.J., & Juha, M.A. (2015). Effects of human trampling on abundance and diversity of vascular plants, bryophytes and lichens in alpine heath vegetation, Northern Swedenalo. *Jägerbrand and Alatalo Springer Plus*, 4, article number 95. https://doi.org/10.1186/s40064-015-0876-z.

[17] Yavorovskyi, P.P., Sendonin, S.Ye., & Tokareva, O.V. (2019). *Recreational forestry*. Kyiv: Naukova stolytsia.

[18] Kutya, M.M., & Girs, A.A. (2012). Description of recreational loading and recreational capacity of Kyiv forest park landscapes. *Scientific Bulletin of UNFU*, 22.12, 86-90.

[19] Kukhtar, D.V., & Kachala, T.B. (2021). Assessment of greening the urban ecosystem of the city and development of measures for its optimization based on the example of Ivano-Frankivsk. *Scientific and Technical Journal*, 23(1), 33-45.

[20] Shyshchenko, P.H., Havrylenko, O.P., & Tsyhanok, Ye.Yu. (2019). Ecosystem value of Holosiyivskyi forest as an urban protected area: Causes and consequences of degradation. *Ukrainian Geographical Journal*, 108(4), 40-49. https://doi.org/10.15407/ugz2019.04.040.

[21] Romanets, O.M., & Yukhnovskyi, V.Yu. (2021). *Phytomeliorative features and urboecological potential of green spaces in the city of Kyiv*. Kyiv: "Kondor" Publishers.

[22] Organization plan of the territory of the state historical and architectural reserve "Ancient Kyiv": Scientific and project documentation. Book 4. (2021). Kyiv: Ukrainian Institute of Cultural Heritage.

[23] Dunaievska, O.F., & Kozlovskyi, O.Iu. (2013). Studying the digression of urban park ecosystems as a result of an increase in recreational load. *Geography and Tourism*, 26, 284-294.

[24] Seno, P.S. (2007). *Probability theory and mathematical statistics*. Kyiv: Znannia.

[25] Berezhniak, M.F. (2013). *Pedology*. Kyiv: TOV "NVP "Interservis".

[26] Maliuha, V.M., & Minder, V.V. (2020). Indicator of tension in the living space of protective forest stands. *Ukrainian Journal of Forest and Wood Science*, 11(4), 47-59. https://doi.org/10.31548/forest2020.04.005.

[27] Henyk, Ya.V., & Dyda, A.P. (2013). Impact of anthropogenic loads on the state of soil cover of park and forest plantations in the cities of Carpathian region of Ukraine. *Scientific Bulletin of UNFU*, 23.13, 110-114.
[28] Henyk, Ya.V., Dyda, A.P., & Marutyak, S.B. (2014). Some changes in physicochemical properties of soils in urban woodlands and parklands as a result of recreational loadings. *Scientific Bulletin of UNFU*, 24.10, 66-71.

Вплив рекреаційного навантаження на протиерозійні властивості ґрунтів паркових насаджень

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Анотація. Зміни, пов'язані з міською інфраструктурою, безпосередньо впливають на екологічне середовище, у тому числі, на властивості ґрунту. Мета роботи – вивчення протиерозійної та стокорегулюючої дії паркових насаджень у складних умовах рельєфу міста Києва. Лісівничо-таксаційні показники насаджень встановлено за визнаними таксаційними методами. Верхні шари ґрунту вивчено шляхом визначення твердості, водопроникності, щільності та вологості на стежинах і в насадженнях. Твердість ґрунту в насадженнях із 9,1 ± 0,76-10,8 ± 1,01 кг/см^2 зростає до 15,4 ± 0,25-30,8 ± 0,15 кг/см^2, що пов'язано з інтенсивністю їх витоптування. При цьому ґрунти із пухкого стану переходять до середньопухкого та навіть щільного. Визначення водопроникності теж показало значну розбіжність відповідно від 18,6 ± 0,76-20,6 ± 0,66 мм/хв. до 1,9 ± 0,10-5,7 ± 0,33 мм/хв. Дослідженнями підтверджено обернено пропорційні зв'язки між показниками твердості та водопроникності ґрунту. Отримані показники щільності складання ґрунту в насадженнях (1,12-1,20 г/см^3) і на стежинах (1,34-1,66 г/см^3), хоч і мають не дуже різкі відмінності, але в обох випадках вказують на їх критичність для подальшого нормального розвитку насаджень. Зміни даних вологості ґрунту в насадженнях (16,9-20,6 %) мають спадний характер у порівнянні із стежинами (11,2-12,6 %), що теж свідчить про погіршення умов зростання. Наявність активного коріння у верхній товщі ґрунту на контролі виявилась 5,8-9,8 г, а на стежинах, залежно від інтенсивності витоптування, від 0,0 до 2,2 г. Здійснено обстеження досліджуваних територій на виявлення характерних ерозійних процесів. Встановлено, що паркові насадження знаходяться у задовільному стані та повністю виконують протиерозійну дію. Загроза прояву ерозійних процесів має місце на стежках інтенсивного навантаження. Отримані результати можуть використовуватись для моніторингу та регулювання антропогенного навантаження

Ключові слова: складний рельєф, стежкова мережа, коренева система, поверхневий стік, ерозійні процеси

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Peculiarities of formation of the forest litter of the water protection pine plantations in the Ukrainian interflue of the Dnipro and Desna rivers

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Abstract. The effective performance of ameliorative functions by water protection plantations is largely determined by the development of the forest litter, its structure, capacity, quality composition, and degree of mineralization. Therefore, the aim of the study was to identify the features of the formation of the forest litter of pine plantations of the Ukrainian interfluves of the Dnipro and Desna. The study of forest litter was carried out on the accounting sites in all age groups of plantations, in which 22 test plots were laid. Litter samples were taken in between rows and directly in rows of forest plantations. During the analysis of the qualitative composition of the forest litter of young plantations, the dominance of the upper horizon of the inactive fraction, which consisted mainly of needles and branches, was revealed. Here, the share of inactive litter in the conditions of moist poor pine site and moist relatively poor pine site was 8.13 t/ha or 85.1% and 12.54 t/ha or 92.1%, respectively. A large amount of dust, which forms the active fraction, was recorded in the lower horizon. Its stocks were 5.3-5.6 times higher than the reserves of inactive litter. In general, in young pine forests in the conditions of moist poor pine site, the stock of inactive litter is 15.10 t/ha (28.1%), while its presence in of moist poor pine site is 17.91 t/ha, 36.5%. In middle-aged pine forests, the share of the active litter fraction increases, which is a consequence of the active action of its decomposition processes. The share of active litter is 79.3% or 155.29 t/ha in mature stands of the conditions of moist poor pine site. This is evidence of the intensification of the processes of mineralization and activation of the circulation of substances. Three horizons are clearly distinguished in the litter of plantations of older age groups, with a strong connection between them. The lower layer of the forest litter of water conservation plantations is permeated with physiologically active roots, which forms its dense type of structure. Under such conditions, during the separation of the lower layer of litter from the upper one, it does not fall apart and its structure remains dense. The presence of strongly intertwined physiologically active roots in the third horizon of the litter is evidence of the activation of microbiological processes, which are also accelerated by the interception of moisture and the accumulation of humus particles of the soil by the lower layers of the forest litter. To prevent the development of flood processes, the effective performance of water regulation and water purification functions, it is recommended to create water conservation plantations with the formation of the identified type of forest litter

Keywords: active and inactive litter, biometric indicators, dust, litterfall, nutrient turnover

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Introduction

Fortest litter is an important structural and functional component of the forest biogeocenosis, which combines its abiotic and biotic components and forms a cohesive system. Forest litter plays an important role both in the processes of circulation of substances and energy in ecosystems, and in soil formation [1-3].

The forest litter, which is formed under the canopy of the forest plantation, in combination with the rhizosphere of the tree-shrub canopy, significantly changes the water, temperature and air regimes of the soil, accumulates in its layer and in the upper horizon of the soil the biodiversity of microflora and fauna. Enriched with nutrients, the decomposition products of forest litter, penetrating into the soil together with atmospheric precipitation, lead to a change in its structure and properties of soil solutions [4; 5].

The formation of forest litter is understood not only for the accumulation of its phytomass. In the litter there are complex processes of decomposition and transformation of organic compounds, which are completed by their full mineralization [3; 6]. Knowledge of the trend of forest litter development is necessary to evaluate its place and role in the biological circulation of nutrients and nitrogen. With the intensive decomposition and mineralization of the litter, the rapid release of ash nutrients is released, which penetrate into the lower mineral layers of the soil. In the case of accumulation of organic matter in humified or semi-decomposed form, the process of transformation of nutrients and nitrogen is slowed down and sometimes stopped.

Quantitative and qualitative analysis of forest litter contributes to a clearer representation of the dynamics of nutrients in forest ecosystems. The mass, structure and chemical composition of the litter depends on many factors, the most important of which include: site conditions [7; 8], species composition [1; 9; 10], age [11-13], density of the stand [14; 15], health condition of planting [3; 15], origin [4; 5], location [8; 16]. Therefore, an important aspect is the formation of such litter, which would ensure rapid rates of its mineralization and, therefore, the circulation of nutrients in the vegetation-soil system, which is of crucial importance for the productivity of forest ecosystems [2; 3].

Particularly multifaceted is the forest amelioration role of the forest litter, in plantations that determines water regulation, water retention, water purification, soil protection, soil formation, soil erosion control and other purposes [12; 17]. Therefore, it is advisable to consider the study of quantitative and qualitative characteristics, stocks and fractional composition of forest litter as an important dynamic component that ensures effective performance of amelioration functions in water protection plantations.

The purpose of the study was to identify quantitative and qualitative indicators characterizing the structural composition of the forest litter and the peculiarities of its formation in water protection pine plantations of the Ukrainian interfluves of the Dnipro and Desna rivers.

The novelty of the research lies in the revealing of a new type of forest litter, which is formed in the pine plantations in moist poor pine site and relatively poor pine site of floodplain landscapes.

Materials and Methods

The study was carried out in the pine forest stands of the interfluves of the Dnipro and Desna rivers, which grow on a slightly undulating plain dissected by the floodplains of these rivers, which actually determines the landscape structure of this territory. After all, in the valleys of these rivers, marshlands occupy 4.5% of the territory of Chernihiv Polissia. The hydrographic zoning map of Ukraine shows the territory of the Ukrainian interfluves of the Dnipro and Desna rivers, with a total area of about 2 million hectares (Fig. 1). In the landscape structure of the region, the main role belongs to natural complexes dominated by moraine-sand and sandy plains with sod-podzolic soils and pine forests.

Forest coverage of the territory is about 25%. The structure of the forest fund is dominated by pine and oak-pine forests. Forest plantations, in addition to performing important water protection functions, contribute to the accumulation of humus in the soil and form highly productive phytoctnosis, which are characterized by increased water conservation, soil protection, recreational and ecological properties.

The research facilities are located in the State Enterprise "Vyshe-Dubechnia Forestry". Its land fund is located on the second floodplain terrace of the interfluves. Water protection plantings occupy a dominant position. The forest vegetation conditions of the study site are quite favorable for the cultivation of Scots pine, the plantations of which occupy 18,385.0 hectares, which is 68.6% of the total area of the Forestry [13].

The formation and structure of the forest liter was studied on 22 test plots (TP), which were laid out on the first and second terraces of the Desna River, in the most typical for the region plantations with the participation of Scots pine and birch. Test plots were planted in conditions of moist poor pine site (A2) and relatively poor pine site (B2) in plantations of different ages. The terminology of the typology of forest vegetation sites is given in the publication [18].

Figure 1. Geographical location of the Ukrainian interflue of the Dnieper and Desna rivers on the hydrographic zoning map of Ukraine

The age range of the examined plantations ranges from 21 to 117 years. Their average height is 8.2-40.1 m. Productivity corresponds to I^a-II classes of productivity (site index). It is determined by the conditions of forest vegetation and the location of plantations on different terraces of the Desna River.

Field and laboratory methods. Selection of forest litter samples was carried out at the accounting sites laid in pine forests of different age classes within the test plots. Accounting sites in young and middle-aged plantations were placed between rows and in rows. Depending on the age of the plantation and the thickness of the litter, the area of the accounting sites was determined, which was 0.5 m^2 (0.5x1 m) or 1 m^2 (1.0x1.0 m). The litter was cut along the contour of the accounting site and packed in burlap. In the laboratory, litter was divided into fractions and weighed on electronic scales.

The inactive forest litter consists of branches, bark, cones and needles, the period of complete mineralization of which reaches more than 100 years. The active part of litter includes leaves of tree species and bushes, remains of grasses, buds, remains of entomofauna, debris (dust) and roots. This is consistent with the methodological developments of Y. Chornobai & O. Maryskevich [1], I. Bondar [2], V. Maliuha et al. [15].

The distribution of forest litter into fractions was carried out in laboratory conditions. Tree roots were divided into conducting (thickness over 2 mm) and physiologically active (thickness less than 2 mm). Roots of grass plants were counted separately. The debris was divided into two fractions – coarse and fine. Coarse debris was classified as a dust with dimensions from 1.1 mm to 5 mm, and fine debris was classified as a dust smaller than 1 mm. That is, it is the dust sifted through a one-millimeter sieve, which includes particles of vegetation and soil.

Results and Discussion

A number of factors influence the process of forest litter formation in water conservation pine plantations, namely: species composition with an admixture of deciduous species, age of the tree stand, forest vegetation conditions [1; 7; 10]. That is why a study of litter in planted pine forests, which grow in the most common moist poor pine and moist relatively poor pine sites in the Dnipro and Desna interfluves, was conducted.

Peculiarities of forest litter formation in moist poor pine site (A2)
The general view of young (Fig. 2a) and mature (Fig. 2b) pine plantations, in which profiles were laid and litter samples were taken to determine the fractional composition is shown in Fig. 2. The profile of the litter, which was laid on TP 1 in the inter-row of a 21-year-old pine-birch plantation of the Pirnovo Forestry, is shown in Fig. 2c (block (bl.) 540, unit (un.) 2). The thickness of the litter in the interrows is 1.6-2.6 cm, and in the rows 2.8-3.8 cm. A clear distribution of the litter into horizons is not yet observed, although the half-mineralized lower layer is 1.2-2.8 cm. The upper layer of litter consists of fallen pine needles mixed with birch leaves, and its thickness is 1.1-2.0 cm.

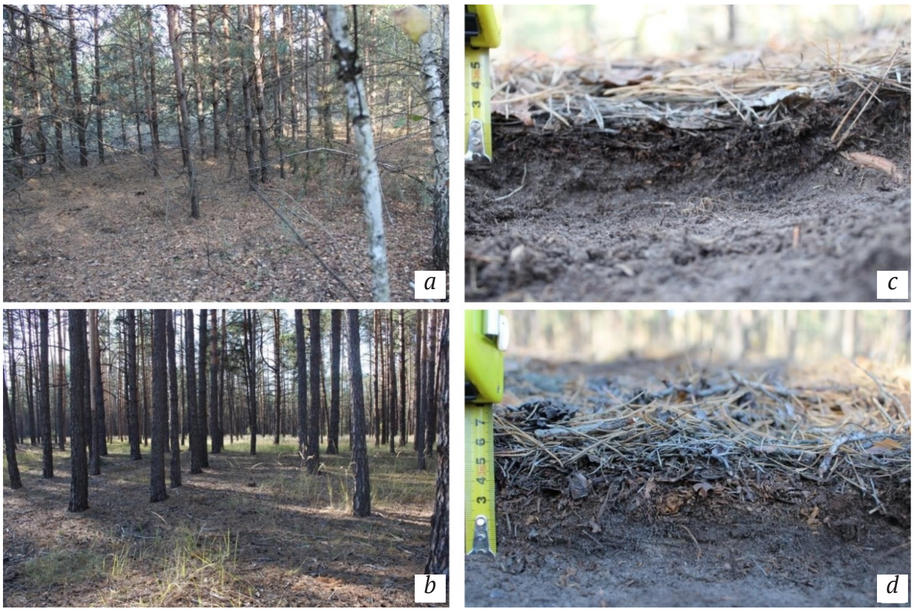

Figure 2. Pine plantations with forest litter profiles: young stand – general view *a*, litter profile *c*; mature stand – general view *b*, litter profile *d*

In the middle-aged pine-birch plantation on TP 6, which is planted in Novosilkiv Forestry in block 795, litter profiles were formed both between rows and in rows. Here, the litter is characterized by clearly defined horizons. In the lower horizon, a semi-decomposed organic mass with a thickness of 1.0-2.6 cm can be traced, and in the middle layer, non-decomposed or half-mineralized remains of needles, birch leaves, and fine pine roots are recorded. The total thickness of this horizon is 1.5-2.3 cm. The upper litter horizon with a thickness of 0.7-2.3 cm is formed by birch, pine needles, and cones. The total thickness of the forest litter in the investigated pine-birch plantation reaches 3.1-4.6 cm.

In the plantations of older age groups, for the study of litter indicators, profiles were laid on TP 3, 8, and 10, which are respectively located in Pirnovo (bl. 579, un. 4), Novosilky (bl. 781, un. 5) and Novosilky (bl. 765, un. 1) forestry's.

The thickness of the forest litter profile is 4.3-5.6 cm in pre-mature pine stands. The bottom layer of litter 1.3-3.2 cm is almost completely decomposed. The middle layer is represented by 1.2-2.2 cm of undecayed twigs, bark, and needles. Fresh annual litterfall from twigs, conifers, and pine cones covers the litter surface with a 1.0-2.0 cm layer.

The litter of a mature pine plantation on TP 10 is represented by well-defined formed layers (Fig. 2d). The thickness of the litter is 4.7-6.6 cm. The profile of the litter shown in Figure 2d, the formed horizons are clearly distinguished. The lower mineralized layer of litter has a thickness of 1.8-3.5 cm. The middle layer of litter is represented by undecayed twigs, needles, bark, remnants of cocoons of entomofauna - pine sawfly, pine silkworm.

Over-mature pine plantations of moist poor pine site accumulate a large layer of litter more than 7.3 cm thick. The lower horizon is clearly defined, mineralized, 1.6-3.7 cm thick. The second semi-decomposed layer of forest litter contains pine roots, conifers, and remains of entomofauna. The upper layer of the litter is the annual litterfall with a small, compared to pines of younger age categories, capacity, which reaches 1.2-2.6 cm.

Generalized data on fractions of forest litter of pine plantations of the II and VI age classes, which grow in A2 site, are given in Table 1. The data of Table 1 indicate that the litter has a two-layer structure in the young plantation. A feature of its structure is the dominant share of dust, which is concentrated in the lower layer of the litter and makes up more than 60% of its capacity. At the same time, the fine part of dust, which is represented by particles smaller than 1.1 mm, exceeds the coarse part of dust by almost two times. The main mass of the litter stock falls on the second layer is 44.13 t/ha. It is more than 4 times greater than the top layer of litter stock (9.55 t/ha).

As the age of the plantations increases, the litter acquires a three-layer structure. This phenomenon is associated with the accumulation of pine needles and cones in the litter. If the stock of cone fraction in young trees was only 0.24 t/ha, then already in middle-aged plantations the stock of cones amounted to 4.01 t/ha, i.e. it was 16.8 times greater. The presence of a significant proportion of cones and needles keeps the bedding substrate in a non coherent and loose state. In general, the litter stock in middle-aged pine stands of moist poor pine site is more than twice the litter stock of young plantation.

Table 1. Fractional composition of forest litter of water protection plantations of moist poor pine sites

Layer	Stock, t/ha	Fractions of forest litter, t/ha												
		Inactive part				Active part								
									Roots			dust		Entomo-fauna
									Tree plants		Herbaceous plants			
		Branches	Bark	Cones	Needles	Leaf	Grass	Buds	Conductive	Physiologically active		Rough part (1-5 mm)	Small fraction (<1 mm)	
Young: Composition* – 8Ps2Bp; Age – 15 years; Test plot 4 (block 795, unit 23)														
1st layer	9.553	0.621	0.707	–	6.797	1.037	–	0.027	–	–	–	0.307	0.054	0.003
2nd layer	44.133	0.320	0.877	0.237	5.539	0.715	–	0.112	0.014	0.584	0.082	12.208	23.387	0.058
∑	53.687	0.941	1.584	0.237	12.336	1.752	–	0.139	0.014	0.584	0.082	12.515	23.441	0.061
Middle-aged: Composition – 10Ps; Age – 56 years; Test plot 2 (block 617, unit 2)														
1st layer	16.816	3.837	2.469	3.267	6.650	–	–	0.022	–	–	–	0.290	0.282	–
2nd layer	19.570	2.341	1.949	0.738	4.640	–	–	0.179	–	0.098	–	4.390	5.226	0.010
3rd layer	77.320	0.626	0.715	0.010	0.408	–	–	0.022	0.061	1.366	–	7.723	66.373	0.016
∑	113.706	6.803	5.133	4.014	11.698	–	–	0.224	0.061	1.464	–	12.403	71.880	0.026
Over-mature: Composition – 10Ps; Age – 111 years; Test plot 21 (block 794, unit 11)														
1st layer	13.112	3.828	1.552	1.994	1.914	–	0.440	0.028	–	–	–	1.647	1.679	0.030
2nd layer	109.031	14.927	7.303	4.198	2.009	–	0.345	0.082	0.003	0.228	0.018	12.494	67.281	0.143
3rd layer	121.590	0.903	0.786	3.084	0.403	–	–	0.010	0.786	2.471	–	8.722	104.319	0.104
∑	243.733	19.658	9.641	9.276	4.326	–	0.785	0.121	0.789	2.698	0.018	22.864	173.280	0.277

***Note:** Ps – *Pinus sylvestris* L.; Bp – *Betula pendula* Roth.; Qr – *Quercus robur* L.

Peculiarities of forest litter formation in moist relatively poor pine site (B2)

The moist relatively poor pine sites differ from the moist poor pine sites by richer growth conditions and phytodiversity, which actually affect the formation of the forest litter. Morphometric parameters of litter were studied in the four age groups: young, middle-aged, pre-mature, mature and over-mature. The locations of laying litter profiles on TP 15 and 12 are shown in the Fig 3. They are located in middle-aged and mature pine plantations.

The view of middle-aged and pre-mature plantations, in which the TP 15 and 12 were laid, is shown in Fig. 3a and 3b respectively. The profiles of forest litter are shown in Fig. 3c and 3d.

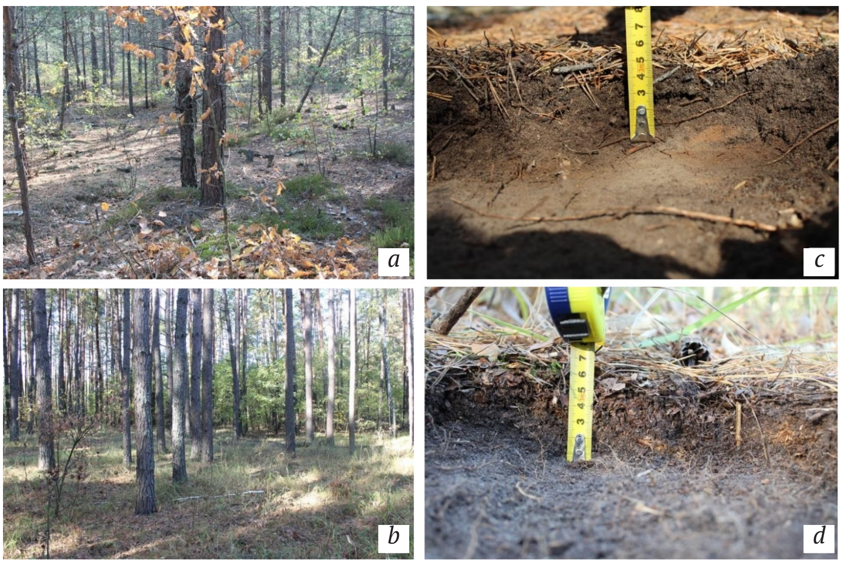

Figure 3. Pine plantations in B2 site with forest litter profiles: middle-aged – general view *a*, litter profile *c*; pre-mature – general view *b*, litter profile *d*

Forest litter of a 26-year-old pure pine plantation growing in moist relatively poor pine site of Novosilky Forestry in the bl. 793, un. 6, reaches a thickness of 2.8-4.7 cm and already forms a thick 1.5-3.4 cm mineralized layer. A more developed living above-ground cover is inherent in a 60-year-old pine planting of the Pirnovo forestry, which grows in the block 539 on the unit 3. Here a layer of litter with a power of 4.8-7.0 cm is accumulated with the formation large thick of stronger annual litterfall, which consists of needles, bark, twigs and cones.

The thickness of the forest litter in the mature 81-year-old pine plantation in the Vyshche-Dubechnia Forestry in block 568, un. 16 was 4.4-7.8 cm with formed three-layer structure. The upper layer up to 2.5 cm is represented by the annual litterfall of woody and herbaceous vegetation with implicit signs of the beginning of the mineralization process. The middle layer consists of semi-decomposed remains of coniferous litter, bark, and twigs with 1.5-3.5 cm thickness. The lowest third layer of litter with a thickness of 1.7-4.0 cm is mineralized organic mass.

Over-mature plantations in Pirnovo Forestry on TP 22 (bl. 562, un. 17) accumulate a thick litter with three-layer structure and the thickness of 8.7-9.8 cm. The thickness of all layers is almost the same and ranges from 2.5 to 4.0 cm.

It is found out a feature of litter formation in water protection plantations between the Dnipro and Desna rivers. It is the fact that the lower horizon, saturated with intertwined fine roots, is characterized by increased density. During separation from the litter of the middle layer, it does not crumble, preserving its structure. Such a phenomenon was not detected in similar forest vegetation conditions of the pine forests of Kyiv Polissia.

The generalized data on the distribution of forest litter by fractions in pine plantations of different age groups of the moist relatively poor pine site are given in Table 2. Qualitative and quantitative indicators of the forest litter of young, pre-mature and over-mature plantations are given below. Such a wide range of research made it possible to determine regularities in the complete cycle of formation of pine plantations in B2 site. Almost the same total mass of litter is accumulated in young pine plantations, the stock of which is 49.098 and 53.87 t/ha, respectively. However, the inactive part of the forest litter in B2 site has more branches and cones in its composition, and in the A2 site the cones was not yet noticeable in the litterfall. This is evidence of the intensive development of young pine plantations in conditions the moist relatively poor pine site. There is a noticeable predominance of root remains in the lower layer in the active part of the litter of young stands of A2 site that indicates the development of the upper soil horizons. The mass of physiologically active roots in the litter of young pine plantations was 0.582 t/ha in A2 site and only 0.162 t/ha in B2 site.

Table 2. Fractional composition of forest litter of water protection plantations of moist relatively poor pine sites

Layer	Stock, t/ha	Fractions of forest litter, t/ha												
		Inactive part				Active part								
									roots			dust		
									tree plants					
		Branches	Bark	Cones	Needles	Leaf	Grass	Buds	Conductive	Physiologically active	Herbaceous plants	Rough part (1-5 mm)	Small fraction (<1 mm)	Entomo-fauna
Young: Composition – 8Ps2Bp;Age – 18 years; Test plot 11 (block 547, unit 5)														
1st layer	13.621	4.566	1.803	0.682	5.491	0.264	–	0.019	–	–	–	0.597	0.198	–
2nd layer	35.477	0.984	1.464	0.128	2.794	0.030	–	0.085	–	0.162	–	4.792	24.786	0.253
∑	49.098	5.550	3.267	0.810	8.285	0.294	–	0.104	–	0.162	–	5.389	24.984	0.253
Pre-mature: Composition – 10Ps+Qr; Age – 60 years; Test plot 12 (block 539, unit 3)														
1st layer	20.032	5.195	1.872	4.987	4.243	0.298	1.382	0.093	–	–	–	1.685	0.275	0.002
2nd layer	13.181	1.187	1.133	1.744	0.570	0.029	0.109	0.078	–	0.042	0.120	5.102	3.038	0.029
3rd layer	90.422	4.162	0.898	3.838	0.208	0.027	0.142	0.066	0.040	0.541	0.643	23.101	56.696	0.061
∑	123.635	10.544	3.902	10.570	5.021	0.354	1.634	0.237	0.040	0.582	0.763	29.888	60.010	0.091
Over-mature: Composition – 10Ps; Age – 101 years; Test plot 22 (block 562, unit 17)														
1st layer	23.874	6.760	3.168	5.502	6.758	0.090	–	0.053	–	–	–	1.165	0.378	–
2nd layer	31.632	4.085	2.846	3.138	1.965	0.029	–	0.232	–	0.155	–	6.427	12.702	0.053
3rd layer	140.242	1.456	1.642	2.834	0.301	–	–	0.070	0.637	4.350	–	15.806	113.067	0.078
∑	195.747	12.301	7.656	11.474	9.024	0.118	–	0.355	0.637	4.506	–	23.398	126.147	0.131

The accumulation of forest litter in middle-aged pine plantations also has a similar pattern, which is characteristic of young plantations. The total stock of litter in middle aged plantations is 2-2.5 times greater than the mass of litter in young plantations, regardless of forest vegetation sites. This is explained by the different intensity of leaf fall, as well as different rates of its mineralization, which is characteristic of pure pine plantations.

Fractional composition of forest litter

In addition to quantified indicators determination of litter distribution by area, aggregation, and fractional composition was studied. It was found that the distribution of litter by area was generally uniform.

Differences in the thickness and stocks of forest litter in rows and between rows of pine plantations are not observed already in pre-mature plantations from the VI age class. The thickness of the litter in the rows exceeds the similar values between rows by 1.0-1.5 cm in young plantations. This is especially clear in plantations with wide (2.0-2.5 m) rows (Fig. 4).

Figure 4. Characteristics of litter profiles in rows (*a*) and between rows (*b*) in pine plantations of the III age class

Thus, in the moist relatively poor pine site, the forest litter of 22-year-old of mixed pine planting (9Ps1Bp) in rows has a thickness of 4.0-5.0 cm, and in the interrows its thickness reaches 3.6 cm (Fig. 4). The composition of the forest litter is marked by a coherent three-layer structure in the older age groups. It consists of the branches, bark, cones, pine needles, leaves, buds, roots, rough and fine dust, entomofauna remains.

The “cones” fraction appears in the middle-aged plantations of the moist poor pine site. It is concentrated in the top layer of litter. Its weight is 4,014 t/ha. The total mass of cones is 10,570 t/ha in the plantations of the moist relatively poor pine site. It is usually almost evenly placed on the separated horizons. This reaffirms the early and intensive reproductive activity of pine plantations of B2 site. The proportion of roots in the litter of A2 site is 5-5.5 times higher than the proportion of roots in the litter of pines growing in B2 site. The content of physiologically active roots in the litter almost doubles their content in the upper 10-centimeter layer of mineral soil, which is respectively 4,506 t/ha and 2,403 t/ha [5].

The small fraction of forest litter, with particles size <1.1 mm, is actively accumulated in the lower layers. If in young plantations it dominates in the second layer of litter, then in the plantations of the older age groups it accumulates in the third layer. Its mass in the forest litter in mature plantations of B2 site is 126,147 t/ha, which is 64.4% of its total mass. This indicates the active course of decomposition processes in the thickness of the litter and intensive mineralization processes in its lower layers. Generalized data of stocks in the forest litter fractions are given in Table 3.

Table 3. Stocks and fractional composition of litter of water protection plantations

Age groups and composition of plantations	Layer of litter	Litter stock, t/ha	Fractions of litter, t/ha				
			Branches	Bark	Cones, needles	Leaf, grass, buds	Roots, dust, entomofauna
Plantations of moist poor pine site (A2)							
Young stand: 8Ps2Bp; A–15 years; TP 4	1st layer	0.955	0.62	0.71	6.80	1.06	0.36
	2nd layer	44.13	0.32	0.88	5.78	0.83	36.33
	∑	53.69	0.94	1.58	12.57	1.89	36.70
Middle-aged stand: 10Ps; Age – 56 years; TP 2	1st layer	16.82	3.84	2.47	9.92	0.02	0.57
	2nd layer	19.57	2.34	1.95	5.38	0.18	9.72
	3rd layer	77.32	0.63	0.72	0.42	0.02	75.53
	∑	113.71	6.81	5.14	15.72	0.22	85.82
Over-mature stand: 10Ps; Age – 111 years; TP 21	1st layer	13.11	3.83	1.55	3.90	0.47	3.36
	2nd layer	109.03	14.92	7.30	6.21	0.43	80.17
	3rd layer	121.59	0.90	0.79	3.49	0.01	116.40
	∑	243.73	19.65	9.64	13.60	0.91	199.93

Age groups and composition of plantations	Layer of litter	Litter stock, t/ha	Fractions of litter, t/ha				
			Branches	Bark	Cones, needles	Leaf, grass, buds	Roots, dust, entomofauna
Plantations of moist relatively poor pine site (B2)							
Young stand: 8Ps2Bp; A–15 years; TP 4	1st layer	13.62	4.57	1.80	6.17	0.28	0.80
	2nd layer	35.48	0.98	1.46	2.92	0.12	29.99
	∑	49.10	5.55	3.27	9.09	0.40	30.79
Pre-mature stand: 10Ps+Qr, Bp; A – 60 years; TP 12	1st layer	20.03	5.20	1.87	9.23	1.77	1.96
	2nd layer	13.18	1.19	1.13	2.31	0.22	8.33
	3rd layer	90.42	4.16	0.90	4.05	0.24	81.08
	∑	123.64	10.54	3.90	15.59	2.22	91.37
Over-mature stand: A – 101 years; 10Ps; TP 22	1st layer	23.87	6.76	3.17	12.26	0.14	1.54
	2nd layer	31.63	4.08	2.85	5.10	0.26	19.34
	3rd layer	140.24	1.46	1.64	3.13	0.07	133.94
	∑	195.75	12.30	7.66	20.50	0.47	154.82

The analysis of the active and inactive litter fractions showed that the upper layer of the litter of young pine plantations the inactive component of the litter is dominated, which contains a large proportion of branches and needles. Their share in the A2 site and B2 site is 8.13 t/ha (85.1%) and 12.54 t/ha (92.1%), respectively. In the second layer of the litter, in young plantations, the active part with a large amount of dust is already dominant, which is 5.3-5.6 times greater than the inactive part of the forest litter. The trend towards an increase in the active part of the litter is confirmed by the research of C. Prescott [19], which indicates the possible humification of the litter in suboptimal conditions (low temperatures or excessive humidity).

In general, the stock of inactive litter in the young plantations of A2 and B2 sites is 15.10 t/ha or 28.1% and 17.91 t/ha or 36.5% respectively. It is noted that a significant mass of the inactive part of the litter accumulates in the upper layer. Moreover, the share is greater in plantations of B2 site due to the more active course of growth and development processes. At the same time, in young pine plantations of A2 site, the inactive part of the forest litter of the second layer already dominates this indicator in the litter formed under conditions of B2 site, which indicates the activation of microbiological processes and its accelerated decomposition.

An increase in the active part of the litter can be achieved by introducing it to pine plantations of deciduous species. This is confirmed by the research of P. Sewerniak [3] and other scientists. It is known that pure conifer monocultures are much more likely than broad-leaved or mixed forests to be affected by factors such as fires, pathogens, pests, and windstorms. This thesis is confirmed by the research conducted in the pure coniferous forests of the Dolomites, in Gallio, Asiago and Cansiglio. In particular, P. Sewerniak [3] recommends converting pine monocultures into mixed forests by conventional planting of deciduous species into middle-aged monocultures. The problem of rational management of clean coniferous plantations is currently urgent and important. After all, the frequency of forest damage has increased in recent decades [20]. It is also predicted that in the future, ongoing climate changes may cause a serious loss of the economic value of European forests.

In pine stands of the VI age class, the litter accumulation and its fractional composition is similar general regularity to that of young stands. However, the tendency to increase the fraction of active litter is clearly visible It indicates the active processes of mineralization.

With age, stocks of active litter increase (Table 4). In mature stands of A2 site, its share reaches 82.4%, which is 200.82 t/ha. Somewhat lower values of the share of active litter were recorded in B2 site – 79.3% or 155.29 t/ha, which is explained by the acceleration of the processes of mineralization and circulation of substances.

Table 4. Distribution of stocks of active and inactive litter in water protection pine plantations

Age group	Layer of litter	Litter stock, t/ha	Fractions of litter			
			Inactive		Active	
			t/ha	%	t/ha	%
Plantations of moist poor pine sites						
Young	1st layer	9.56	8.13	85.1	1.43	14.9
	2nd layer	44.13	6.97	15.8	37.16	84.2
	∑	53.69	15.10	28.1	38.59	71.9
Middle-aged	1st layer	16.82	16.22	96.5	0.60	3.5
	2nd layer	19.57	9.67	49.4	9.90	50.6
	3rd layer	77.32	1.76	2.3	75.56	97.7
	∑	113.71	27.65	24.3	86.06	75.7

Age group	Layer of litter	Litter stock, t/ha	Fractions of litter			
			Inactive		Active	
			t/ha	%	t/ha	%
Over-mature	1st layer	13.11	9.29	70.8	3.82	29.2
	2nd layer	109.03	28.44	26.1	80.59	73.9
	3rd layer	121.59	5.18	4.3	116.41	95.7
	∑	243.73	42.91	17.6	200.82	82.4
Plantations of moist relatively poor pine sites						
Young	1st layer	13.62	12.54	92.1	1.08	7.9
	2nd layer	35.48	5.37	15.1	30.11	84.9
	∑	49.10	17.91	36.5	31.19	63.5
Pre-mature	1st layer	20.03	16.30	81.4	3.73	18.6
	2nd layer	13.18	4.63	35.2	8.55	64.8
	3rd layer	90.43	9.11	10.1	81.32	89.9
	∑	123.64	30.04	24.3	93.60	75.7
Over-mature	1st layer	23.87	22.19	92.9	1.68	7.1
	2nd layer	31.63	12.03	38.0	19.60	62.0
	3rd layer	140.24	6.23	4.4	134.01	95.6
	∑	195.74	40.45	20.7	155.29	79.3

A similar trend regarding the layer-by-layer accumulation of forest litter can be seen in middle-aged and mature water protection plantings. The ratio of litter in young, pre-mature and over-mature stands of B2 site is 1:2.5:4.0 or 49.10, 123.64 and 195.74 t/ha, respectively. With age, there is an increase in the mass of litter, which at the maturing of pine stands is 4 times greater than the litter stocks of young plantations. The same regularity was found in the distribution of litter fractions. In particular, the share of active litter increases with age and reaches 79.3% in over-mature stands. In pre-mature and over-mature pine plantations, the active litter of the third layer is 89.9% and 95.6%, respectively, which indicates active processes of its mineralization.

Conclusions

The distribution of forest litter within the pine plantations of water protection purposes is quite uniform in terms of area. The difference in its thickness and stocks in rows and between rows of artificial pines is not observed after the VI age class. The thickness of the litter in the rows exceeds the similar indicators between the rows by 1.0-1.5 cm only in young plantations. This is especially clear in plantations with 2.0-2.5-meter rows.

In terms of composition, the studied forest litter is coherent with a three-layer structure in older age groups. The litter of over-mature pine plantations of a moist relatively poor site is characterized by a large thickness (8.7-9.8 cm) with a clearly defined lower mineralized layer 2.5-4.0 cm thick. The second semi-decomposed layer of the litter is saturated with small pine roots, needles, and remains of entomofauna. The annual litterfall has a much lower capacity than in the plantations of younger age groups.

A feature of litter formation in water protection plantations is the fact that its lower horizon, saturated with small roots, has a dense structure. During separation from the litter of the middle layer, it does not crumble, and its structure is not destroyed. This phenomenon was not detected in pine plantations growing in similar forest vegetation conditions of the Kyiv Polissia.

The presence of a significant proportion of physiologically active roots in the third layer of litter indicates the active course of microbiological processes in it. The content of physiologically active roots in the litter almost doubles their content in the upper 10-centimeter layer of mineral soil, which is respectively 4.5 t/ha and 2.4 t/ha.

For an in-depth study of the water regulation and water purification functions associated with the formation of forest litter in pine plantations of floodplain landscapes, a perspective trend is the analysis of the chemical composition of the litter in dynamics to complement the mechanism of its mineralization.

References

[1] Chornobai, Y., & Maryskevich, O. (1992). Organic composition of litter in phytosenosis of the Ukrainian Carpathians. *Ukrainian Botanical Journal*, 49(3), 20-25.

[2] Bondar, I. (2000). Quantitative and qualitative indicators of precipitation in different types of growth conditions of forest stands of Kyiv Polissia and their impact on the soil. *Bulletin of the National Agrarian university,* 27, 94-103.

[3] Sewerniak, P. (2020). Plant species richness or soil fertility: Which affects more the productivity of Scots pine in Central Europe? *Annals of Forest Research*, 63(2), 57-73. https://doi.org/10.15287/afr.2020.2003.

[4] Hagvar, S. (2016). From litter to humus in a Norwegian spruce forest: Long-term studies on the decomposition of needles and cones. *Forests*, 7(186), article number 186. https://doi.org/10.3390/f7090186.

[5] Zhang, D., Hui, D., Luo, Y., & Zhou, G. (2008). Rates of litter decomposition in terrestrial ecosystems: Global patterns and controlling factors. *Journal of Plant Ecology.* 1(2), 85-93. https://doi.org/10.1093/jpe/rtn002.

[6] Hättenschwiler, S., Tiunov, A., & Scheu, S. (2005). Biodiversity and litter decomposition in terrestrial ecosystems. *Annual Review of Ecology, Evolution, and Systematics,* 36, 191-218. https://doi.org/10.1146/annurev.ecolsys.36.112904.151932.

[7] Berg, B., & Meentemeyer, V. (2001). Litter fall in some European coniferous forests as dependent on climate: A synthesis. *Canadian Journal of Forest Research,* 31, 292-301. https://doi.org/10.1139/cjfr-31-2-292.

[8] Margesin, R., Minerbi, S., & Schinner, F. (2016). Litter decomposition at two forest sites in the Italian Alps: A field study. *Arctic, Antarctic, and Alpine Research,* 48(1), 127-138. https://doi.org/10.1657/AAAR0015-012.

[9] González-Rodríguez, H., Ramírez-Lozano, R., Cantú-Silva, I., Gómez-Meza, M., Estrada-Castillón, E., & Arévalo, J. (2018). Deposition of litter and nutrients in leaves and twigs in different plant communities of northeastern Mexico. *Journal of Forestry Research,* 29(5), 1307-1314.

[10] Jasinska, J., Sewernial, H., & Puchalka, R. (2020). Litterfall in a Scots pine forest on inland dunes in Central Europe: Mass, seasonal dynamics and chemistry. *Forests,* 11(6), article number 678. https://doi.org/10.3390/f11060678.

[11] Levchenko, V. (2009). Parameters of forest litter in fresh forests of the northern part of the Right-Bank Forest-Steppe of Ukraine. *Bulletin of the National University of Life and Environmental Sciences of Ukraine,* 135, 78-84.

[12] Voron, V., Sydorenko, S., & Tkach, O. (2018). Structure of forest litter as an indicator of potential fire risk in the pine forests of Polissya, Ukraine. *Forestry and Forest Melioration,* 132, 115-123. https://doi.org/10.33220/1026-3365.132.2018.115.

[13] Golovetskyi, M., Urliuk, Y., & Yukhnovskyi, V. (2021). Water protection pine plantations of the Ukrainian confluence of the Dnieper and Desna rivers. Kyiv: Condor Publishing House.

[14] Krynytska, O., Bondarenko, T., Capuliak, J., & Trenciansky, M. (2017). Quantitative analysis of litter-fall in hornbeam-oak-pine stands in the Lviv Roztoche region. *Central European Forestry Journal*, 63(1), 35-41. https://doi.org/10.1515/forj-2017-0004.

[15] Maliuha, V., Khryk, V., Minder, V., Kimeichuk, I., Raduchych, M., Rasenchuk, A., Brovko, F., & Yukhnovskyi, V. (2021). Fractional composition and formation of forest litter in Scots pine plantations on ravine-gully systems and the plain of the central part of Ukraine. *Forest Ideas,* 27(1), 89-100.

[16] Ivanenko, Y., Lobchenko, G., Maliuha, V., & Yukhnovskyi, V. (2022). Spruce forest litter structure, distribution, and water retention along hiking trails in Ukrainian Carpathians. *Journal of Forest Science*, 68(7), 241-252. https://doi.org/10.17221/12/2022-JFS.

[17] Finér, L. (1996). Variation in the amount and quality of litterfall in a *Pinus sylvestris* L. stand growing on a bog. *Forest Ecology and Management,* 80(1-3), 1-11. https://doi.org/10.1016/0378-1127(95)03652-0.

[18] Tkach, V., Buksha, I., Slych, O., & Pasternak, V. (2021). Optimization of maturity age for coppice oak forests within Left-Bank Forest-Steppe in Ukraine. *Central European Forestry Journal,* 67(3), 181-186. https://doi.org/10.2478/forj-2020-0026.

[19] Prescott, C. (2010). Litter decomposition: What controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry*, 101, 133-149. https://doi.org/10.1007/s10533-010-9439-0.

[20] Gregow, H., Laaksonen, A., & Alper, M. (2017). Increasing large scale windstorm damage in Western, Central and Northern European forests, 1951-2010. *Scientific Reports,* 7(1), article number 46397. https://doi.org/10.1038/srep46397.

Особливості формування лісової підстилки водоохоронних соснових насаджень Українського межиріччя Дніпра і Десни

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Анотація. Ефективне виконання меліоративних функцій водоохоронними насадженнями значною мірою визначається розвитком лісової підстилки, її структурою, потужністю, якісним складом, ступенем мінералізації. Тому метою дослідження стало виявлення особливостей формування лісової підстилки соснових насаджень Українського межиріччя Дніпра та Десни. Дослідження лісової підстилки проведено на облікових майданчиках у всіх вікових групах насаджень, у яких закладено 22 пробні площі. Зразки підстилки відбирали у міжряддях і в рядах лісових культур. Під час аналізу якісного складу лісової підстилки молодняків виявлено домінування верхньому горизонті неактивної фракції, яку складали переважно хвоя і гілки. Тут частка неактивної підстилки в свіжих лісорослинних умовах бору і субору становила відповідно 8,13 т/га або 85,1 % і 12.54 т/га або 92,1 %. У нижньому горизонті зафіксовано велику кількість трухи, яка формує активну фракцію. Її запаси у 5,3–5,6 раз перевищують запаси неактивної підстилки. Загалом, у молодих сосняках свіжого бору запас неактивної підстилки становить 15,10 т/га (28,1 %), у той час коли її наявність у насадженнях свіжого субору – 17,91 т/га 36,5 %. У середньовікових сосняках частка активної фракції підстилки збільшується, що є наслідком активної дії процесів її розкладу. У стиглих насадженнях свіжого субору частка активної підстилки становить 79,3 % або 155,29 т/га. Це є свідченням інтенсифікації процесів мінералізації і активізації колообігу речовин. У підстилці насаджень старших вікових груп чітко виділяються три горизонти, із міцним зчепленням між собою. Нижній шар лісової підстилки водоохоронних насаджень пронизаний фізіологічно активним корінням, що формує її щільний тип складання. За таких умов під час відділення нижнього шару підстилки від верхнього він не розпадається і його структура залишається щільною. Наявність сильно переплетеного фізіологічно активного коріння у третьому горизонті підстилки є свідченням активізації мікробіологічних процесів, які також пришвидшуються перехватом вологи і нагромадженням гумусових часток ґрунту нижніми шарами лісової підстилки. Для запобігання розвитку паводкових процесів, ефективного виконання функцій водорегулювання і водоочищення рекомендується створення водоохоронних насаджень з формуванням виявленого типу лісової підстилки

Ключові слова: активна і неактивна підстилка, біометричні показники, труха, опад, кругообіг речовин

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Current state of ornamental arboreal plants in ordinary street tree stands in Kyiv

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Abstract. An increase in anthropogenic load in urban complexes leads to adverse ecological changes in the environment. Urban tree stands can somewhat smooth out these shortcomings by affecting the microclimate within the local territory. According to statistical data, every year the indicator of the provision of green spaces for the residents of Kyiv decreases, which is caused by the unsatisfactory condition of street tree stands. The main purpose of this paper is to highlight the results of the study on the assortment of arboreal plants, to estimate their general condition on the busiest streets and avenues of Kyiv, and to provide recommendations for creating a perspective list of plants for urban street landscaping. The paper analyses the data of the inventory that was performed within ordinary street tree stands in 2021. It was found that the most common street tree stands include *Tilia cordata*, *Aesculus hippocastanum*, and *Populus nigra*. A comparative analysis of the main assortment of plants in the street tree stands of Kyiv for 2009 and 2021 was conducted, and it was established that the number of *Aesculus hippocastanum* and *Populus nigra* decreased, while the percentage of *Robinia pseudoacacia*, *Fraxinus excelsior* increased. The assessment of the general condition of plants indicates that the largest share of plants is in a satisfactory condition – 50%. The best condition was noted in *Robinia pseudoacacia*, *Acer platanoides*, and *Tilia cordata*. Attention is paid to the general condition of arboreal plants by the percentage of inactive photosynthetic surface. High resistance of *Acer platanoides*, *Fraxinus excelsior*, and *Robinia pseudoacacia* to urban conditions is revealed. The analysis of the experimental data provides grounds for determining the main and supplementary assortment of arboreal plant species recommended for use in street landscaping, with further study of their stress resistance

Keywords: dendroflora, general condition, arboreal plants, assortment, defoliation

Introduction

Urbanization of megacities influences changes in the environment, as well as the increase in anthropogenic load. Urban tree canopies provide various ecological and social benefits for urban spaces by reducing local temperatures, energy consumption, and absorbing rainwater runoff. They are one of the closest and familiar green infrastructures to city dwellers [1; 2]. Scientists indicate the importance of street tree stands because they can create a large amount of green cover, especially within dense buildings [3; 4]. Today, Kyiv has the title of "Green Capital" [5], but considering the recreational and anthropogenic load on green areas, the change in microclimate and the outdated range of ornamental arboreal plants and their general condition, every year the indicator of the city's population's provision of green spaces decreases. It is the urban green infrastructure, with a special emphasis on street plantings, that is a sophisticated engineered ecosystem, which plays an important role in the creation of ecosystem services and, if properly managed, can prevent negative and harmful impacts [6]. Street tree stands in Kyiv play a significant role in landscaping and planning structure of the city, which determines their important landscape-architectural, aesthetic, and recreational role [7]. Empirical results of Japanese researchers indicate that increasing the greening ratio of the street landscape improves the residential environment in terms of both the magnitude and saturation level of the tree stand ratio, while increasing the number of urban parks does not [8].

According to urban planner P. Gartner, who studied satellite images using Normalized Difference Vegetation Index, the city of Kyiv was recognized as the greenest capital in Europe in 2017. But not all city residents agree with

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the result of this study, which is caused, in most cases, by the unsatisfactory state of tree stands within the settlement zone. DC Evolution analysts examined the capital's green zones and noted that the total area of Kyiv is 83.4 thousand hectares, and the area of green zones is 16.2 thousand hectares, which is 19.3% of the total [5]. But a significant area of greenery is growing within recreational zones, forest parks, etc.

For Kyiv to become a truly "Green Capital", it is necessary to pay great attention to street landscaping. As A. Ryzhikov, head of the DC Evolution company, says about Kyiv: "Walk through the centre or the neighbourhood – how many trees will you see? They simply do not exist. And it matters not if they got sick and withered, or if they were cut for another kiosk or car park. At the same time, lanscapers plant about 10,000 trees every year… A comfortable city starts small" [5].

One of the effective ways to preserve the quality of the environment is to stabilize the quantity and maintain the quality of green spaces, which must be properly maintained. Trees planted along streets tend to require more maintenance and have a shorter lifespan than those growing in more natural settings. Poor tree growth is often associated with insufficient soil volume for the root system, which limits access to water and nutrients. Tree roots in the urban environment often compete for underground space with urban services and infrastructure, and insufficient space for rooting is one of the factors in the unsatisfactory condition and mortality of street trees in cities [9].

Urban greening encompasses a range of incentives, strategies, and initiatives to green urban landscapes, and often includes urban tree planting programs. The increase of green spaces has both advantages and disadvantages, since the solution to the problem of improving green spaces in an urbanized environment, as well as the increase in green areas, is possible with the use of justifications and scientific recommendations regarding the selection of the assortment of plants and its maintenance, which is based on inventory and assessment of the condition of ornamental tree stands. Only plants in good condition can effectively perform vital functions. Currently, the city of Kyiv does not have comprehensive information on the inventory of street plants, although some plants are already included in the main database of inventory data. Therefore, the purpose of this paper is to establish the main and supplementary assortment of plants for their further use in street landscaping.

Materials and Methods

The study adopted a representative sampling approach. According to the general plan of the city, the experimental area was chosen, where street tree stands are an important green infrastructure with high maintenance needs, namely: Peremohy Avenue, S. Bandery Avenue, Holosiivskyi Avenue, Vernadskyi Boulevard, Velyka Vasylkivska Street, etc. (Fig. 1). For the accuracy of the experiment, the selected streets are located in different parts of Kyiv and differ in the assortment of plants. All trees that grow on the experimental sites are classified as public tree stands, grow in row plantings along the roads, have different ages and composition. From May to November 2021, field research was conducted, 938 trees were examined on 7 streets of the city. To estimate the number of street trees within the selected objects, a preliminary stage of selection took place using Google Earth. The sample survey was designed in such a way as to represent all types of plants under conditions of limitation of more intensive recreational load.

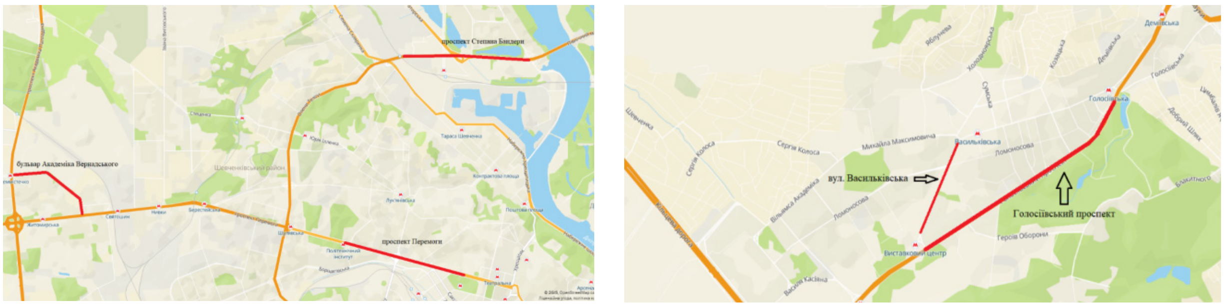


Figure 1. Experimental sites within the districts of Kyiv

To indicate a promising assortment of plants for street tree stands, the main task of the study was to conduct an inventory of tree stands at the experimental sites, to determine and estimate the general condition of the most common arboreal plants. The inventory was carried out according to the "Instructions for the inventory of green spaces in populated areas of Ukraine" [10]. A 5-point scale was also used to detail the assessment of plant condition, according to which the category of plant condition was determined by the percentage of inactive or lost photosynthesizing (leaf) surface. Trees without suppressed growth with a full leaf surface were evaluated at 5 points; trees with growth that generally meets the norm and has about 20-25% of the inactive surface – 4 points; trees with weakened growth, which have about 50% of inactive leaf surface – 3 points; trees with suppressed growth, the growth of the current year is almost absent, have about 75-80% of inactive leaf surface – 2 points; dead and dying, without current tree growth with 100% inactive leaf surface – 1 point [11].

Results and Discussion

The examined 938 trees include 17 species belonging to 13 genera and 11 families (Fig. 2).

Figure 2. The most common types of arboreal plants at experimental sites

According to the inventory data, it was found that the most common species in street tree stands are as follows: small-leaved linden (*Tilia cordata* Mill.), which is 35.8%, horse chestnut (*Aesculus hippocastanum* L.) – 20.3%, and black poplar (*Populus nigra* L.) – 18.9%, which in total makes up 75% of the surveyed tree stands. Black locust (*Robinia pseudoacacia* L.) and Norway maple (*Acer platanoides* L.) have slightly lower figures – 10.4% and 9.6%, respectively, as well as other types of arboreal plants, such as common ash (*Fraxinus excelsior* L.), common oak (*Quercus robur* L.), sugar maple (*Acer saccharum* Marsh.), hybrid plane (*Platanus×hispanica* Mill.), mountain-ash (*Sorbus aucuparia* L.), etc. Comparing the data with the studies of 2008-2009 [12], the percentage of *Aesculus hippocastanum* L. within street tree stands decreased by about 20%, and *Populus nigra* L. by approximately 27% (Fig. 3). Therewith, the number of *Robinia pseudoacacia* L., *Fraxinus excelsior* L. plants is increasing, and the frequency of occurrence of *Platanus×hispanica* Mill. and *Catalpa bignonioides* Walter has increased within the avenues and streets of Kyiv.

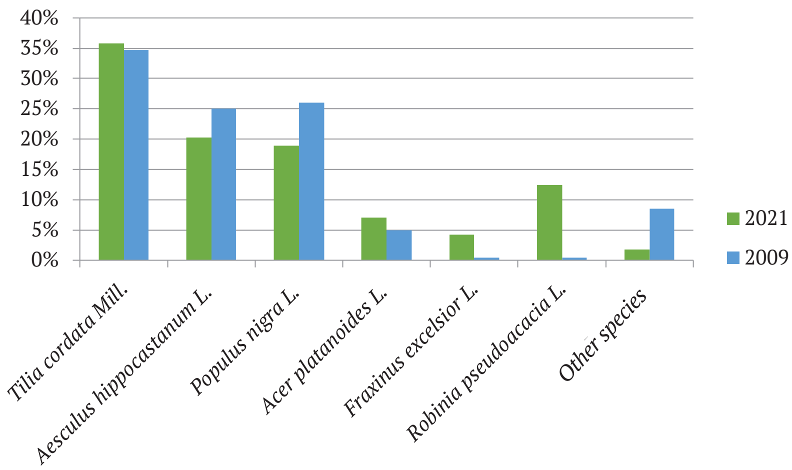


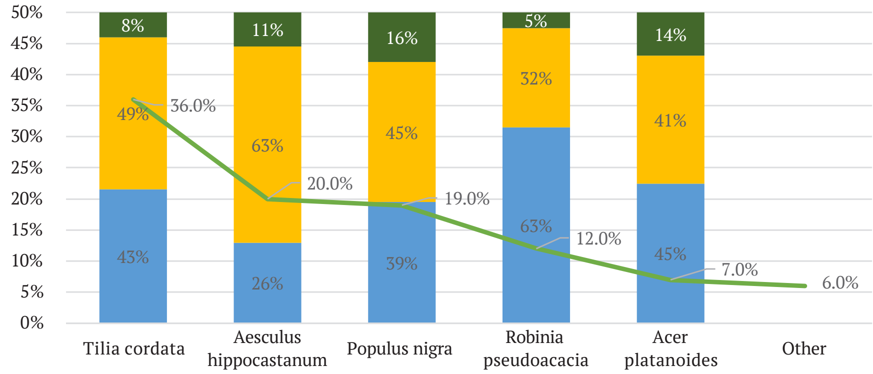
Figure 3. Species composition of street tree stands in Kyiv for 2009 and 2021

The decrease in the number of specimens of *Aesculus hippocastanum* L. is primarily related to the annual damage to the plants by the horse-chestnut leaf miner, which adversely affects the general condition of the plants, starting from June [13]. Moth larvae feed on leaves, which causes their defoliation, and depending on environmental conditions, there can be up to five generations of this pest per year [14]. Combined with anthropogenic load, the weakening of plants is accelerated, the canopy and branches die back, trunk frostbite cracks appear, re-flowering is found in many specimens, etc. (Fig. 4). All the factors listed above have a detrimental effect on the condition of plants, which in the future leads to their death.

Figure 4. *Aesculus hippocastanum* L. in street tree stands in Kyiv: a) canopy defoliation; b) frost cracks; c) repeated flowering; d) defoliation of leaves

The decrease in the percentage of *Populus nigra* L. plants in street tree stands is caused by several factors, namely: short-lived species and the downing of plants during flowering, which causes allergic reactions among the city residents [6]. Furthermore, reaching a critical age barrier and having brittle wood, small gusts of wind lead to branch breaks and falling poplar trees.

During the inventory of tree stands within the streets of Kyiv, the current state of the plants was determined. According to the "Instructions for the inventory of green spaces in populated areas of Ukraine", the examined plants were assigned to three categories according to their general condition: good, satisfactory, and unsatisfactory. As indicated in Fig. 5, the largest share of plants is in satisfactory condition – about 50% of the examined plants, in good condition – within 40%, and in unsatisfactory condition – 10%. Among the most common types of street tree stands, the best condition was noted in *Robinia pseudoacacia* L., *Acer platanoides* L. and *Tilia cordata* Mill., although the percentage of plants in an unsatisfactory condition in these representatives reaches more than 10%. Therefore, it is necessary to analyse the current state of experimental plants and the specific features of their growth in more detail to explain the unsatisfactory state of numerous specimens.



	Tilia cordata	Aesculus hippocastanum	Populus nigra	Robinia pseudoacacia	Acer platanoides	Other
Unsatisfactory	8%	11%	16%	5%	14%	
Satisfactory	49%	63%	45%	32%	41%	
Good	43%	26%	39%	63%	45%	
Species composition	36.0%	20.0%	19.0%	12.0%	7.0%	6.0%

Figure 5. General condition of street tree stands in Kyiv

To estimate the detailed state of street tree stands, several methods were analysed, which included various aspects of plant growth, their condition, appearance, presence of pests and diseases, etc. [7; 4]. The following was highlighted from these methods: during the visual inspection of street tree stands, the researcher pays special attention to the general condition of the plants and the condition of the leaf blade. Therefore, the next step in the research was to determine the category of plant condition based on the percentage of inactive or lost photosynthetic (leaf) surface. It is this indicator that is key in the rating of tree mortality, which is conducted by the Japanese Centre for Research and Development of Greenery and is widely used in scientific research institutions and expert companies in Japan [15]. This method includes 12 parameters, which include plant growth energy, density of branches and leaves, leaf colour, damage to the lower and upper parts of the leaf, damage or rotting of the tree bark, leaf size, presence or absence of sprouts, etc. Therefore, during field surveys, the state of plants was estimated according to the state of the leaf blade in the most common types of street tree stands during May-June 2021 (Table 1).

Table 1. Estimation of the general condition of plants by the percentage of inactive or lost photosynthetic surface

Plant name	Number of trees of each type (pcs/%)						Total number of trees, %
	By status categories, points					Total, points	
	1	2	3	4	5		
1	2	3	4	5	6	7	8
Tilia cordata Mill.	11	19	43	142	122	337	36
	3.3	5.6	12.7	42.1	36.2	100	
Aesculus hippocastanum L.	8	12	42	62	63	187	20
	4.3	6.4	22.4	33.2	33.7	100	
Populus nigra L.	8	9	38	67	56	178	19
	4.5	5	21.3	37.6	31.5	100	
Robinia pseudoacacia L.	2	4	7	29	70	112	12
	1.8	3.6	6.2	26	62.4	100	
Acer platanoides L.	4	5	11	15	30	65	7
	6.1	7.7	16.9	23	46.2	100	
Fraxinus excelsior L.	1	1	3	7	25	37	4
	2.7	2.7	8.1	18.9	67.6	100	
Catalpa bignonioides Walter.	0	0	0	3	8	11	1
	0	0	0	27.3	72.7	100	
Platanus×hispanica Mill. ex Münchh	0	0	1	4	5	10	1
	0	0	10	40	50	100	
Total	34	50	145	329	379	937	100
	3.6	5.3	15.5	35.1	40.4	100	

Estimating the general condition of arboreal plants by the percentage of inactive photosynthetic surface, it was established that a considerable part of the experimental plants is in excellent and good condition precisely in this period of the growing season. However, *Aesculus hippocastanum* L. and *Tilia cordata* Mill. have signs of leaf defoliation for 60% and 45%, respectively, already at the beginning of summer, which further adversely affects the general condition of the plants. *Catalpa bignonioides* Walter. and *Platanus×hispanica* Mill. are represented by a small percentage in street tree stands, but according to the results of research, they have the best rating – over 90% of specimens are in good and excellent condition. Notably, during field surveys in dry weather, the leaves of *Catalpa bignonioides* were flabby, and at that time the decorativeness and general condition of the plants became significantly lower, but when moisture entered the soil, the leaves again had turgor and good condition. According to research data, *Acer platanoides* L., *Fraxinus excelsior* L., and *Robinia pseudoacacia* L. are highly resistant to urban conditions.

Having conducted a detailed inventory of street tree stands and assessing their general condition using two methods, considering the information in literary sources, a description of arboreal plants was compiled, considering their ecological, dendrological, and other features.

***Acer* L.** Three distinct species of the genus Acer are found at the experimental sites in Kyiv: the sharp-leaved maple (*A. platanoides*), the silver maple (*A. saccharinum*), and the ash-leaved maple (*A. negundo*). Maple, in the conditions of Kyiv, has a height of up to 25 m (*A. saccharinum*), 30 m (*A. platanoides*), and 20 m (*A. negundo*). According to the literature, different *Acer* species have different soil requirements [16]: *A. platanoides* grows well on all soils except peat, *A. saccharinum* needs fertile, moist, acidified, and drained soil, while *A. negundo* is the most undemanding. Compared to other species, *A. negundo* has lower frost resistance, a shorter lifespan, is an invasive species, but is characterized by high resistance to air pollution and some decorative forms. *A. saccharinum* can grow in the shade and tolerates soil salinity, which is vital in street tree stands. However, it has many developed superficial lateral roots, which need a large open surface, which cannot always be provided in urban conditions. But considering all the ecological “pros” and decorativeness, *A. platanoides* is more universal, as it can tolerate almost all adverse factors of urban conditions.

***Aesculus* L.** *A. hippocastanum* and its hybrid *Aesculus×carnea* are among the most common trees in street tree stands, dominating due to their crown habit and decorativeness during flowering. *Aesculus×carnea* has better indicators of frost resistance, drought resistance and is less affected by *Cameraria ohridella*, which makes it much more hardy in urban environments [17].

***Tilia* Mill.** In street tree stands, lindens are of immense importance as static plants that create a lot of shade, alley, and park trees. Due to their high regenerative capacity and durability, they are well suited for all types of urban plantings.

T. cordata and *T. platyphyllos* are two species of the genus *Tilia*, which are most often found in the street tree stands of the city of Kyiv, and at the same time differ from each other in their features. *T. cordata* easily adapts and grows well on poor soils, requires less air humidity and nutrients, is wind resistant, less damaged by *Aphidoidea Latreille* compared to *T. platyphyllos*.

T. platyphyllos is light-demanding, frost-resistant, heat-demanding, does not tolerate dryness of the air and soil, creates shade, is sensitive to air pollution and salinity, is damaged by *Panonychus ulmi*, and therefore *T. cordata* has the advantage in outdoor tree stands.

Populus **L.** The genus *Populus* includes three deciduous tree species within the surveyed area, characterized by rapid growth, growing to massive and large trees. It is often used in street landscaping, but it is worth paying attention to the short lifespan and fragility of poplar with age. Their roots are aggressive, spread widely, raising the road surface, and causing damage to underground communications. *Populus nigra* L. and its subspecies *Populus nigra var. pyramidalis* Spach are the most common in landscaping in Kyiv. The main difference between them is the crown shape and the life span since it is much greater in *P. nigra*. Both plants are light-demanding, frost-resistant, wind-resistant, and heat-demanding, but *P. nigra var. pyramidalis* tends to be damaged by diseases and fungal infections, at the age of 40 the tree becomes brittle.

Robinia **L.** *R. pseudoacacia* is very heat-demanding, tolerates heat, drought and salinity well, is undemanding to soils and is well suited for landscaping extreme inner-city facilities. This species is promising in the street tree stands of megacities.

Fraxinus **L.** For landscaping, ash trees are important as a fast-growing and long-lived plant that is used for street landscaping. *F. excelsior* is light-demanding, tolerates light shade and partial shade. Prefers fairly fresh, moist, fertile and well-drained soils, dislikes compacted and too wet soils. Young trees are damaged by late frosts, it is wind-resistant, has a high regenerative capacity, and the top dries up when the groundwater level drops.

Platanus **L.** *Platanus × hispanica* Mill. ex Münchh. is a deciduous tree that grows up to 20-30 m in height, and in recent years has often been planted on the streets of Kyiv. Prefers growth in the sun or light shade. Undemanding to the soil, it grows well on very dry soils if they are not too poor. Features: frost-resistant, heat-loving, smoke- and gas-resistant plant, grows well after shaping and rejuvenating cutting [18].

Catalpa **Scop.** *Catalpa bignonioides* Walter in urban conditions grows to a height of 10-15 m. It has a tap root system and thick, fleshy roots. Prefers the sunny side and a place protected from the wind. It is unpretentious to soils, tolerates dryness well. On dry, not very fertile soils, shoots ripen better, are less damaged by frost, resistant to urban and industrial environments [16].

Based on the study of the current state, ecological and physiological features of the growth of arboreal plants in ordinary street tree stands, it is possible to single out the species that are the main ones, and which can be used as supplementary ones. Some species from the main category will eventually be included in supplementary ones and vice versa (Table 2).

Table 2. Distribution of the assortment of arboreal plants in the street tree stands of Kyiv

Item No.	Plant name	Assortment	
		main	supplementary
1	*Acer negundo*		+
2	*Acer platanoides*	+	
3	*Acer saccharinum*		+
4	*Aesculus hippocastanum*	+ →	→
5	*Aesculus×carnea*	←	← +
6	*Catalpa bignonioides*	←	← +
7	*Fraxinus excelsior*	←	← +
8	*Platanus×hispanica*	←	← +
9	*Populus nigra*	+ →	→
10	*Populus nigra var. pyramidalis*	+ →	→
11	*Quercus robur*		+
12	*Robinia pseudoacacia*	←	← +
13	*Sorbus aucuparia*		+
14	*Tilia cordata*	+	
15	*Tilia platyphyllos*		+

Tree species *Aesculus hippocastanum*, *Populus nigra, and Populus nigra var. Pyramidalis* will eventually *be used* as a supplementary assortment of plants for greening row plantings along the streets, while *Aesculus×carnea, Catalpa bignonioides, Fraxinus excelsior, Platanus×hispanica*, and *Robinia pseudoacacia* are included in the main assortment. The recommended assortment of tree plants for street tree stands in Kyiv will be supplemented as a result of further research among rare species and analysis of the general condition of plants within the entire growing season.

Conclusions

The species composition of street tree stands in Kyiv is represented by about 20 species of arboreal plants, although the most common are five: *Tilia cordata, Aesculus hippocastanum, Populus nigra, Acer platanoides, Robinia pseudoacacia*.

On the streets of the city, over the past decades, there has been a tendency to change the species composition of arboreal plants in ordinary street tree stands. Thus, compared to 2009, the number of *Fraxinus excelsior*, *Robinia pseudoacacia*, *Catalpa bignonioides, Platanus×hispanica* increased on the streets under study. The analysis of the general state of the plants gives reasons to substantiate the replacement of *Aesculus hippocastanum, Populus nigra* with the above-mentioned species.

Characterization of the general state of plants according to the lost photosynthetic surface indicates early defoliation of the leaf surface in *Aesculus hippocastanum* and *Tilia cordata* and points to high positive indicators in *Robinia pseudoacacia, Acer platanoides*.

Based on the results of research, it can be stated that representatives of the family *Robinia* L., *Fraxinus* L., *Platanus* L., *Catalpa* Scop. are those plants that can withstand the urban and anthropogenic load in street tree stands, although without proper agrotechnical measures the plants have fewer opportunities.

A limited number of species of arboreal plants grow in street tree stands, which is associated with special requirements for them, namely: a straight trunk, a high raised dense crown, the possibility of formative pruning, resistance to urbogenic factors. It is these plants that should form the basis for street tree stands, and the rest of the species should be used for addition and accentuation. In the future, it is planned to investigate the stress resistance of street arboreal plants.

References

[1] Riedman, E., Roman, L.A., Pearsall, H., Maslin, M., Ifill, T., & Dentice, D. (2022). Why don't people plant trees? Uncovering barriers to participation in urban tree planting initiatives. *Urban Forestry & Urban Greening*, 73, article number 127597. https://doi.org/10.1016/j.ufug.2022.127597.

[2] Teixeira, C.P., Fernandes, C.O., & Ahern, J. (2022). Adaptive planting design and management framework for urban climate change adaptation and mitigation. *Urban Forestry & Urban Greening*, 70, article number 127548. https://doi.org/10.1016/j.ufug.2022.127548.

[3] Kardan, B. (2015). Haber Etiği ve Bir Siyasi Haber İncelemesi. *İnsan ve İnsan Dergisi*, 2(5), 1-15. https://doi.org/10.29224/insanveinsan.280001.

[4] Laptev, O. (1998). *Ecological optimization of the biogeocenotic cover in the modern urban landscape*. Kyiv: Ukrainian Ecological Academy of Sciences.

[5] Are there enough green zones in Kyiv – research – Building Chamber of Ukraine. (n.d.). Retrieved from http://budpalata.com.ua/informations/chi-dostatno-u-kiievi-zelenih-zon-doslidzhennja/.

[6] Shah, A.M., Liu, G., Huo, Z., Yang, Q., Zhang, W., Meng, F., & Ulgiati, S. (2022). Assessing environmental services and disservices of urban street trees. an application of the emergy accounting. *Resources, Conservation and Recycling*, 186, article number 106563. https://doi.org/10.1016/j.resconrec.2022.106563.

[7] Pikhalo, O. (2014). Peculiarities of the growth of street plantings in urban conditions of Kyiv. *Scientific Bulletin of the National University of Bioresources and Nature Management of Ukraine*, 1(198), 180-185.

[8] Ishikawa, N., & Fukushige, M. (2012). Effects of street landscape planting and urban public parks on dwelling environment evaluation in Japan. *Urban Forestry & Urban Greening*, 11(4), 390-395. https://doi.org/10.1016/j.ufug.2012.08.001.

[9] Mullaney, J., Lucke, T., & Trueman, S. J. (2015). The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees. *Urban Forestry & Urban Greening*, 14(1), 19-29. https://doi.org/10.1016/j.ufug.2014.11.007.

[10] Order of the Ministry of Construction, Architecture and Housing and Communal Services of Ukraine No. 8 "On the Approval of the Amendments to the Instruction on the Technical Inventory of Green Spaces in Cities and Towns of the Urban Type of Ukraine". (2007, January). Retrieved from https://zakon.rada.gov.ua/laws/show/z0082-07#Text.

[11] Kuznetsov, S., Levon, F., Pylypchuk, V., & Shumyk, M. (1998). Environmental prerequisites for optimization of street plantings in Kyiv. *Issues of Bioindication and Ecology*, 3, 57-64.

[12] Pikhalo, O. (2010). Taxonomic analysis of the dendroflora of the historical part of Kyiv. *Scientific bulletin of NULESU*, 147, 56-63.

[13] Konarska, A., Grochowska, M., & Haratym, W. (2020). Changes in Aesculus hippocastanum leaves during development of *Cameraria ohridella*. *Urban Forestry & Urban Greening*, 56(126793). https://doi.org/10.1016/j.ufug.2020.126793.

[14] Ferracini, C., & Alma, A. (2008). How to preserve horse chestnut trees from *Cameraria ohridella* in the urban environment. *Crop Protection*, 27(9), 1251-1255. https://doi.org/10.1016/j.cropro.2008.03.009.

[15] Tan, X., & Shibata, S. (2022). Factors influencing street tree health in constrained planting spaces: Evidence from Kyoto City. *Urban Forestry & Urban Greening*, 67, article number 127416. https://doi.org/10.1016/j.ufug.2021.127416.

[16] Bruns, J. (2013). *Bruns Pflanzen*. Sortimentskatalog: Frese & Wolff Werbeagentur GmbH.

[17] Yevtushenko, Y. (2017). *Biological and ecological features of Aesculus carnea Hayne and prospects for its use in the landscaping of Kyiv* (Doctoral thesis, National University of Life and Environmental Sciences of Ukraine, Kyiv, Ukraine).

[18] Haase, D., & Hellwig, R. (2022). Effects of heat and drought stress on the health status of six urban street tree species in Leipzig. Trees, *Forests and People*, 8, article number 100252. https://doi.org/10.1016/j.tfp.2022.100252.

Сучасний стан декоративних деревних рослин у рядових вуличних насадженнях м. Києва

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Анотація. Підвищення рівня антропогенного навантаження в урбокомплексах призводить до негативних екологічних змін середовища. Міські насадження здатні дещо згладжувати ці недоліки шляхом їх впливу на мікроклімат в межах локальної території. Згідно статистичних даних, щороку показник забезпеченості жителів міста Києва зеленими насадженнями знижується, що, зокрема, викликано незадовільним станом вуличних насаджень. Основною метою публікації є висвітлення результатів дослідження щодо асортименту деревних рослин, оцінки їх загального стану на найбільш навантажених вулицях та проспектах м. Києва та надання рекомендацій щодо створення перспективного списку рослин для міського вуличного озеленення. У статті проаналізовані дані інвентаризації, яка проводилася в межах рядових вуличних насадженнях у 2021 році. Визначено, що найбільш поширеними вуличними насадженнями є *Tilia cordata*, *Aesculus hippocastanum* та *Populus nigra*. Проведений порівняльний аналіз щодо основного асортименту рослин у вуличних насадженнях м. Києва за 2009 та 2021 роки та встановлено, що зменшилася кількість *Aesculus hippocastanum* та *Populus nigra* та збільшився відсоток *Robinia pseudoacacia*, *Fraxinus excelsior*. Оцінка загального стану рослин вказує на те, що найбільша частка рослин знаходиться у задовільному стані – 50 %. Найкращий стан відмічено у *Robinia pseudoacacia*, *Acer platanoides* та *Tilia cordata*. Звертається увага на загальний стан деревних рослин за відсотком недіючої фотосинтезуючої поверхні та виявлена висока стійкість до міських умов *Acer platanoides*, *Fraxinus excelsior* та *Robinia pseudoacacia*. Аналіз дослідних даних дає підстави визначити основний та додатковий асортимент деревних видів рослин, які рекомендовані для використання в озелененні вулиць з подальшим вивченням їх стресостійкості

Ключові слова: дендрофлора, загальний стан, деревні рослини, асортимент, дефоліація

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Analysis of climate changes in the forest fund lands of Boyarka Forest Research Station

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Abstract. The relevance of the study is conditioned upon the predicted changes in the area, as well as the significant narrowing of the zone of optimal growth of Scots pine. These forecasts are based on obtaining data on the ongoing climate changes. A constant decrease in precipitation, along with a gradual increase in temperature levels, will lead to consequences such as uncontrolled changes in ecosystems. Such a substantial change in abiotic factors caused by human activity plays a key role in the formation of forest coenoses. The main purpose of this study was to analyse the change in the average annual temperature, as well as the monthly amount of precipitation observed in the forest communities in the Separated Subdivision of the National University of Life and Environmental Sciences of Ukraine “Boyarka Forest Research Station”. The analysis is performed over decades to obtain data on the level of temperature change in relation to the previous period. This also includes a comparison of monthly precipitation for 2021 relative to 1991-2020, which is set as normal. To obtain indicators of the average annual temperature, the average value method is used, followed by calculating the value of the average annual temperature for each decade. To find the deviation in total precipitation, the method of estimating the moisture conditions according to total precipitation is used. Therewith, the value of a substantial deviation is taken at 20% relative to the precipitation rate. According to the study results, it was established that in 2001-2010 the average annual temperature changed by 0.83°C relative to the previous decade, and in 2011-2020 by 0.74°C relative to the previous period. Such dynamics indicate a gradual increase in the average annual temperature, which is reflected in the forecasts of the world community. During the estimation of moisture conditions, separate months of 2021 with a critical level of precipitation in relation to the normal period were selected. In March, the amount of precipitation was 43% of normal, in June – 32%, in September – 40%, and in October – only 4.3% of normal. The value in November was observed at 63% of the norm. Such a decrease in the amount of precipitation in relation to a gradual increase in the average annual temperature poses a threat of a decrease in the hydrological level of moisture. This leads to a decrease in the radial increment of tree stands, and a gradual shift in the growing area of Scots pine. The obtained analysis results will further be used to conduct dendrochronological studies of tree rings of Scots pine (*Pinus sylvestris L.*) in the tree stands of the Separated Subdivision of the National University of Life and Environmental Sciences of Ukraine “Boyarka Forest Research Station”

Keywords: forest plant community, annual temperature, Scots pine, precipitation, forest fund lands

Introduction

Scots pine is the main forest-forming species in Ukraine. Its main distribution is in Polissia and the northern part of the Forest Steppe. However, since the beginning of the 21st century, the degradation of pine stands has gained considerable momentum not only on the territory of Ukraine, but also on all continents. This is especially noticeable in the forest biocenoses of the temperate climate of the Northern Hemisphere. The loss of one of the main forest-forming species is unacceptable for Ukraine. The mechanisms of investigating the degradation should include the study of its course, as well as the causes and factors of its emergence in forest coenoses. The main reason for this

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phenomenon, as a result, is anthropogenic load, diseases and pests of arboreal plants combined with a set of ecological and climatic factors. Climate fluctuations observed over comparable periods of time, which are directly or indirectly caused by the activities of people on the planet and changes in the climatic conditions of the global atmosphere and are defined as climate change [1].

A substantial change in abiotic factors, because of human activity, plays a major, in some situations, a key role in the formation of forest coenoses. The number, productivity, and distribution of animal and plant communities primarily depends on limiting factors. The global community is on a trajectory that corresponds to a temperature increase of about +4°C by 2100 [2]. This level of temperature increase is catastrophic and will mean the emergence of uncontrolled changes in ecosystems [3]. However, there is also another claim: according to the United Nations, warming by 2100 is projected at 3.2°C [4]. According to the report of the Intergovernmental Group of Experts on Climate Change, scientific studies indicate that since the end of the 19th century, two-thirds of the anthropogenic impact is caused by human activity, namely the increase in the concentration of greenhouse gases in the planet's atmosphere. On the territory of Ukraine, according to the Ministry of Environmental Protection and Natural Resources of Ukraine, the average annual temperature has increased by almost 2°C since the beginning of the 20th century, including by 1.2°C in the past 30 years alone [5]. Based on the results of the World Bank research, the main theses regarding the impact of climate change on the state of forest stands in Ukraine are highlighted. Thus, it was established that the total precipitation will increase annually, but the distribution of precipitation within the year will be uneven. The main increase in precipitation is predicted for the winter period. Prolonged droughts during the growing season will lead to the deterioration of the sanitary condition of forest biocenoses, which in turn will adversely affect the significant increase in the area of forest fires [6]. When investigating the resistance of Scots pine to climatic stress, as well as the reaction to increment in the pine regions of the Czech Republic, the following results of the impact of climate change on stands were obtained: a considerable negative impact of droughts on radial increment over a 30-year period was confirmed, while a positive impact was observed in spring temperatures in February and March, which were higher than normal [7]. Understanding the response of forests to current changes in climate factors is crucial for the implementation of forest management strategies, especially under conditions of expected negative, and even critical climate change [8]. The issue of forest adaptation, as well as its use as an effective means of mitigating global climate change, draws the attention of the scientific community to the key role of forests as one of the most accessible tools for stabilizing the climate and preserving the ecological balance on the planet [9]. According to the authors in [10], the wide ecological range of Scots pine unequivocally demonstrates its ability to adapt to variable environments. The originality of the study lies in the calculation of moisture conditions by the total precipitation using the method of deviation from the norm to determine the months that have deviations from the norm of precipitation.

The purpose of this study was to investigate the issue of changes in the average annual temperature and average annual precipitation in the forest fund of the Separated Subdivision of the National University of Life and Environmental Sciences "Boyarka Forest Research Station".

Materials and Methods

To analyse the general trends, as well as climate patterns in the forest area, the authors used the Separated Subdivision of the National University of Life and Environmental Sciences of Ukraine "Boyarka Forest Research Station" (hereinafter SS NULES of Ukraine "Boyarka FRS").

The forest massifs of SS NULES of Ukraine "Boyarka FRS" are located in the central part of Kyiv region between four administrative districts. Forest stands are in a wide strip, limited to the right bank of the Irpin River – tributaries of the Dnipro and stretch from west to east for 50 km, and from north to south for 35 km [11]. The main type of soil is sod and low-podzolic. According to the forest vegetation zoning of Ukraine, the forest areas of the enterprise, which are located in its northern, western, and eastern parts, belong to the southern zone of the Ukrainian Polissia, the Kyiv-Chernihiv Polissia forestry district, and the forest areas of the southern part of the enterprise belong to the Forest-Steppe zone of the Dniester-Dnipro forest-steppe management district. There are areas that are typical outwash plains of Polissia, as well as clearly defined eroded landforms inherent in the Forest Steppe.

The area of SS NULES of Ukraine "Boyarka FRS" is 17,835 hectares, of which 16,161.5 hectares (92.4%) are forest plots covered with forest vegetation. Of the total amount, the share of Scots pine (*Pinus sylvestris* L.) is 81.6% of forest areas covered with forest vegetation, the share of common oak (*Quercus robur* L.) and common alder (*Almus glutinosa* (L.) *Gaertn*.) is 13.5% and 2.0%, respectively [11]. According to the age indicator, one of the most important forest inventory indicators that characterizes the structure of tree stands [12], medieval plantations predominate and occupy a share of 51.3%. According to the site index classes of forest plots covered with forest vegetation, the share of class I and higher site index classes by age group is 85.5%. Thus, it can be stated that the tree stands of the Boyarka FRS are highly productive. Fresh sudibrovas (mixed oakerys) and subors (mixed pine forests) make up 74.3% and 24.5% of forest areas, respectively. The share of pine forests is 0.7%, and oakerys – 0.5% of forest areas covered with forest vegetation. The most favourable conditions for the growth of highly productive Scots pine stands, as the main forest-forming species, are fresh sudibrova and subor conditions. The forest fund of the enterprise is mainly represented by tree stands with a background portion of Scots pine in the first tier and admixture of common oak in the second tier. In general, the tree stands at the enterprise have a composition of 9Ps1Qr, the average age of the plantations is 74 years, the average site index class is I^a, and the average stand density is 0.63. The distribution of forest land by category was also analysed. Of the total area of the forest fund, 98.1% are forest plots, of which:

– 71.2% – artificial stands;
– 21.2% – natural stands;
– 4.1% – open forest cultures;

– 0.5% – forest nurseries and plantations;
– 0.1% – sparse forests.

Based on the analysis of the distribution of forest fund lands, almost a third of the area comprises artificial tree stands, namely 71.2% of the total amount. The data of the Borys Sreznevsky Central Geophysical Observatory in Kyiv [13] were used. The period 1881-2020 was used to simulate changes in average annual temperatures over a multi-year period. The average annual temperature for each year was determined according to the method of determining the average value, and these data were compiled by decade. For each decade, the average annual temperature was calculated using the method of determining the average value. A graph was drawn based on the obtained values, which made it possible to ascertain the change in the average annual temperature. The value of the temperature change relative to the previous period for each decade was calculated. Data for 1991-2020, which is considered normal, are used to determine the change in precipitation. The estimation of moisture conditions by total precipitation was analysed according to the method of deviation from the norm, and the obtained data are expressed in percentages (%). Indicators are determined for 2021 in relation to the norm period. During the estimation of the moisture conditions according to the amount of precipitation by the method of deviation from the norm, the months that have a substantial deviation from the norm will be determined. A significant deviation is taken at 20% relative to the precipitation norm.

Results and Discussion

Dynamics of changes in the average annual temperature by decade

The factors affecting the radial increment of pine stands were investigated and identified. One of the tasks is the analysis of data on regional climate changes, as one of the possible reasons for the loss of productivity of pine stands [14]. Conducting a retrospective analysis to establish the mechanism, as well as the degree of influence of climate change, to identify the sustainability of Scots pine (*Pinus sylvestris* L.) in the future.

It is necessary to ensure continuous and reliable monitoring of climate impacts, considering special threats to forest ecosystems, to observe changes in the productivity of forests. It is also important to state that an essential component is the monitoring of growth reduction, degradation of stands and soils, as well as loss of biodiversity, and as a result, degradation of coenoses [15].

Data from the B. Sreznevsky Central Geophysical Laboratory in Kyiv were used to analyse changes in general trends, as well as general patterns of changes in the temperature regime and the amount of precipitation in forest areas [13]. Based on data from the Central Geophysical Laboratory, the average monthly air temperatures over a prolonged period were analysed. According to the available monthly average temperature data, the average temperatures over the decade were analysed starting in 1881, which is presented in Figure 1. According to the analysis presented in Figure 1, since 1881 there has been a constant increase in temperature for decades. Using the data of the results obtained during the analysis of archival data, it is also possible to follow the linear trend shown on the graph. The obtained information allows ascertaining that the tendency of the temperature of the environment to increase will only persist in the future.

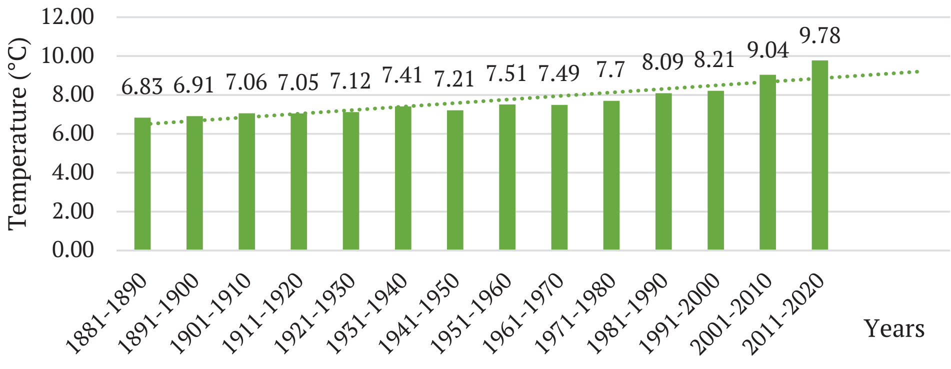

Figure 1. Average annual air temperature by decade (°C) in Kyiv

This was highlighted during the Paris climate agreement [16]. According to the given forecast, it was determined that in 2080-2100 there will be a considerable narrowing of the zone of optimal growth according to the climate humidity indicator [9]. Thus, if one analyses the changes in temperature relative to previous periods, which is presented in the table according to the data of the Central Geophysical Laboratory [13], changes in the average temperature relative to the previous period can be observed.

Table 1. Dynamics of average temperature (t) over decades

Observation period, decades	1881-1890	1891-1900	1901-1910	1911-1920	1921-1930	1931-1940	1941-1950
Indicator t (°C)	6.83	6.91	7.06	7.05	7.12	7.41	7.21
Difference t (°C)	–	0.08	0.15	-0.01	0.07	0.29	-0.2

Table 1, Continued

Observation period, decades	1951-1960	1961-1970	1971-1980	1981-1990	1991-2000	2001-2010	2011-2020
Indicator t (°C)	7.51	7.49	7.7	8.09	8.21	9.04	9.78
Difference t (°C)	0.3	-0.02	0.21	0.39	0.12	0.83	0.74

Having obtained the results, one can ascertain that an increase in the average annual temperature was observed in different specific periods. Thus, temperature increase was recorded in 1891-1900, 1901-1910, 1921-1930, 1931-1940, 1951-1960, 1971-1990, 1981-1990, 1991-2000, 2001-2010, and 2011-2020. A decrease in the average annual temperature was recorded in 1911-1920, 1941-1950, 1961, and 1961-1970. The largest decrease in temperature was recorded in 1941-1950, and was -0.2°C. Since 1971, the average annual temperature has gradually increased in each decade, except for 1991-2000, when the increase was recorded at 0.12°C, but in observations starting from 2001, a significant increase in the average annual temperature was recorded to 0.83°C in 2001-2010 and 0.74°C in 2011-2020.

Considering the obtained indicators, and the research carried out by the scientific community [17], in recent years, in the territory of the forest fund of the SS NULES of Ukraine "Boyarka FRS", atmospheric maximum temperatures have been observed, which can lead to changes in the hydrological level of soil water. Such a scenario can only be considered if the amount of precipitation for the year is studied, as well as for the growing season (April-September). The analysis of average monthly temperatures during the growing season plays one of the key roles in determining the radial increment of trees per year when conducting dendrochronological studies. The radial increment can also be affected by the temperature regime, not only during the growing season, but also during the rest period.

Deviation of climate indicators in 2021 to normal (1991-2020)
The deviation of the indicators of the average monthly temperature and the monthly amount of precipitation in 2021 was analysed according to the accepted norm of indicators of the period of 1991-2020 [13], which is presented in Figure 2.

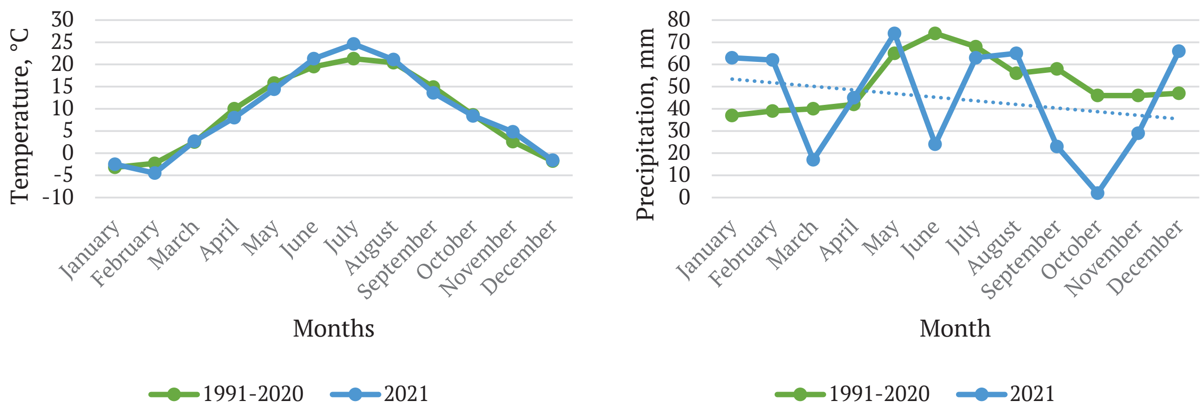

Figure 2. Comparison of average monthly temperature and precipitation in 2021 according to the norm (1991-2020)

It was established that the structure of annual temperatures during 1991-2020 is expressed by smooth changes during the period under study. However, the indicators of 2021 are characterized by lower temperatures at the end of winter and at the beginning of spring, as well as higher indicators in the summer period, respectively. Most of the elevated temperature indicators fall directly on the growing season, namely in June, July and August, an increase in the average temperature by almost 2°C was observed. It is also possible to single out an increase in temperature in October and November, relative to the normal period. However, there is also a decrease in the temperature regime in February, April, and May. The above data on the graph clearly show that in 2021, the period of low temperatures in February-March received a small amount of precipitation – only 17 mm compared to the norm (40 mm). During the following months of the growing season, until June 2021, the amount of precipitation gradually increased and corresponded to the normal indicators, but in June-July, the indicators of precipitation decreased sharply. A significant decrease in precipitation can be observed in June 2021, which was only 24 mm compared to the norm (74 mm). This situation was accompanied by an average temperature of 21.3°C, which is 1.8°C more than in the normal period. This period closely correlated with high summer temperatures that were more in line with the normal period. Such indicators can lead to a violation of the hydrological regime, which can lead to drying out of the forest litter, as well as dehydration of the soil root layers. A decrease in precipitation was observed in September, October, and November against the background of near-normal temperatures. Precipitation indicators during the autumn months amounted to 23 mm for September – 35 mm less than the norm; 2 mm for October, which is less than the norm by 44 mm; and for November – at 29 mm, the difference between the indicators of the normal period was 17 mm. However, the situation improved in December, and the amount of precipitation was 66 mm compared to the normal value of 47 mm. The dependence of radial increment is closely related to the decrease in precipitation during the growing season and is also correlated with fluctuations in average monthly temperatures, high indicators of which, combined with insufficient precipitation, can lead to a decrease in the width of the annual ring.

Estimation of moistening conditions by the total precipitation
Using the data [13], during the research, the moisture conditions were estimated based on the amount of precipitation in 2021 by the method of deviation from the norm (1991-2020). Calculation results are presented in Table 2. Special attention is paid to the estimation of moisture conditions, in line with the statement that the main limiting factor in Ukraine is the hydrological conditions for the existence of living organisms.

The calculations results presented in Table 2 suggest that, in general, during the year, precipitation fell not significantly below the norm, the indicator is 86% of the norm. The significance of the deviation can be asserted only when it exceeds 20%. When analysing individual months of the year, it can be seen that the amount of precipitation was within the normal range in April, May, July, and August; in January, February, and December, their number was significantly higher than normal; however, in March, June, September, October, and November, the amount of precipitation was significantly below normal. The lowest extreme for precipitation was October – 4.3% of the norm, which is catastrophically insufficient for the normal functioning of coenoses. Such indicators, even when the temperature level is close to normal, demonstrate an increase in the expendable part of the water balance in forest areas. And even an increase in precipitation cannot level the moisture supply of coenoses, considering the indicator of the annual amount of precipitation, which is 14% below the norm.

Table 2. Estimation of moistening conditions by the total precipitation in 2021 by the method of deviation from the norm (1991-2020)

Indicator	Period (month)												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
Average long-term precipitation (1991-2020), mm	37	39	40	42	65	74	68	56	58	46	46	47	618
Total precipitation for 2021, mm	63	63	17	45	74	24	63	65	23	2	29	66	533
Precipitation as a percentage of the norm, %	170	159	43	107	114	32	93	116	40	4.3	63	140	86

Having obtained the value of the estimation of the moisture conditions by the total precipitation according to the method of deviation from the norm, where the values of the average multi-year total precipitation were used [13], and considering the earlier studies [18; 19] regarding the influence of temperatures and the hydrological regime, it was determined that with a negative trend of such indicators as a decrease in precipitation, extremely high temperatures during the growing season and low temperature indicators in winter and early spring directly affect the radial increment of tree stands. Furthermore, the limitation of the radial increment of pine in Zhytomyr Polissia is caused by precipitation, relative humidity during the growing season, as well as winter and early spring temperatures. Therewith, it is important to note that different dynamics of dependence of radial growth on precipitation were observed in different periods. With an increase in precipitation, there was an increase in radial growth without a limitation in the form of extreme temperatures during the growing season. It is also worth noting the regression of the radial increment with a decrease in the amount of precipitation and the presence of temperature extremes during the growing season [20].

The data obtained in the study allows comparing it with the research conducted in the territory of Ukraine in the corresponding area. When studying and determining the causes of dieback of pine forests of Volyn Polissia, it was found that there was a moisture deficit in the second half of the growing season. This period was accompanied by the withering and premature termination of vegetation of herbaceous vegetation, and premature shedding of older needles was also observed. Considering the indicators obtained during the research, one can observe an increase in temperature in the middle of the growing season relative to the norm, as well as a large decrease in the amount of precipitation, only 32% relative to the norm in June 2021. Due to such deterioration of the hydrological regime, as one of the phenomena, it is also possible to observe the activation of stem pests. In the forest-steppe zone, temperatures rose especially quickly during the cold period [21]. This led to a decrease in the radial increment of pine due to the disruption of winter rest in trees, while the minimum values of the radial increment are characterized by periods with a considerable decrease in precipitation and an increase in temperatures at the beginning of the growing season, as well as in its second half. When investigating the reaction of the radial increment of Scots pine to climate changes in the stands of the Left-Bank Steppe [22], it was established that the minimum radial increment was found in years characterized by high average annual temperatures and low winter temperatures. The maximum increment was observed at the optimal ratio of precipitation and temperature. However, the increase in temperature with a small amount of received moisture negatively affected the radial increment. The droughts during the growing season, which were accompanied by high early spring temperatures, lead to the weakening of tree stands. The greatest limitation of radial increment is caused by high temperatures during the vegetation period, early spring periods and in winter, as well as an increase in the amount of precipitation during the cold period, which does not contribute to the accumulation of moisture in the soil [23]. A similar increase in precipitation since the winter period is also noted in 2021, in January – 170% relative to the norm, in February – 159%, and in December – 140%, respectively. In the specified months, a considerable deviation from the norm was observed.

Analysing the results obtained during the study, it can be assumed that the reaction of the radial increment in Scots pine stands in the SS NULES of Ukraine "Boyarka FRS" will have a similar value.

Conclusions

The performed analysis suggests that the main limiting factors of the functioning of forest coenoses are the average annual temperature, considering the minimum and maximum temperature extremes during the growing season (April-September). According to the analysis, over the last two decades, the average annual temperature has increased by 0.83°C and 0.74°C, respectively. The average amount of precipitation for a multi-year period, including the precipitation that falls during the growing season, as well as the assessment of moisture conditions by the total precipitation of the specified period according to the method of deviation from the established norm. During the calculation and analysis of the obtained temperatures, it was found that in 2021, in some months of the growing season, there was a significant deviation, and it amounted to a minimum of 39% compared to the period that was considered the norm. The months of 2021 that had a significant deviation from the normal period were noted, some of the lowest indicators were observed at 43% in October, 40% in September, and 43% in March relative to the normal period. In general, based on the assessment of the moisture conditions by the total precipitation using the method of deviation from the norm, it was calculated that in 2021, relative to the normal period, the amount of precipitation amounted to 86%. Such an indicator does not have a significant deviation, but it is an indicator of the occurrence of a climatic signal of the violation of the hydrological conditions in the forest fund of the SS NULES of Ukraine "Boyarka FRS". It has been established that the arid phenomena observed on the territory of the forest fund are undoubtedly of thermal origin. The obtained results will be further used to conduct dendrochronological studies of annual rings of Scots pine trees (*Pinus sylvestris* L.) in the tree stands of the SS NULES of Ukraine "Boyarka FRS".

References

[1] Adamenko, T. (2014). *Agroclimatic zoning of the territory of Ukraine, taking into account climate change*. Kyiv: "RIA" Blitz.

[2] La Querre, C. (2015). *Global carbon budget 2014*. *Earth System Science Data*, 7, 47-55.

[3] Shvidenko, A., Buksha, I., & Krakovska, S. (2018). *Vulnerability of Ukraine's forests to climate change*. Kyiv: Nika-Tsentr.

[4] UN Environment Programme. Emissions Gap Report 2019. (2019). Retrieved from https://www.unenvironment.org/resources/emissions-gap-report-2019.

[5] Ministry of Ecology and Natural Resourses of Ukraine. How the climate is changing in Ukraine. (2020). Retrieved from https://mepr.gov.ua/news/35246.html.

[6] Ministry of Ecology and Natural Resourses of Ukraine. Results of the research of the World Bank, Ukraine. Building climate resilience in agricultural and forestry. (2021). Retrieved from https://mepr.gov.ua/news/38732.html.

[7] Novák, J., Slodičák, M., Kacálek, D., & Dušek, D. (2010). The effect of different stand density on diameter growth response in Scots pine stands in relation to climate situations. *Journal of Forest Science*, 56, 461-473. https://doi.org/10.17221/14/2010-JFS.

[8] Bista, R., Mohr, M., Saldaña, D., Angulo, G., & Chhetri, P.K. (2021). Tree-ring climate response of Jeffrey pine in the Cascade Creek Watershed, Northern California. *Journal of Forest Science*, 67, 285-297. https://doi.org/10.17221/191/2020-JFS.

[9] Shvidenko, A., Lakyda, P., Schepaschenko, D., Vasylyshyn, R., & Marchuk, Y. (2014). *Carbon, climate, and land-use in Ukraine: Forest sector*. Korsun'-Shevchenkyvskiy: NULES.

[10] Kovalevskii, S., Krol, A., Myroniuk, V., Kovalevskyi, S., Vysotska, N., Khromulyak, O., & Yurchenko, V. (2022). Growth of Scots pine (*Pinus sylvestris* L.) stands on soils with close bedding of crystalline parent rocks in Central Polissya, Ukraine. *Central European Forestry Journal*, 68(2), 72-77. https://doi.org/10.2478/forj-2021-0026.

[11] Fuchylo, Y., Irkliyenko, S., Sbytna, M., & Ivanchenko, V. (2009). Scots pine forest crops in the south of Kyiv Polyssia: Features of creation and cultivation. Kyiv: Logos.

[12] Kashpor, S., & Strochynskiy, A. (2013). Reference book of forest assessment. Kyiv: Publishing house "Vinichenko".

[13] Kutsyi, A. (Ed.). (2022). *Proceedings of the Central geophysical observatory named after Borys Sreznevsky* (18th ed.). Kyiv: Bussinespolygraph.

[14] Buksha, I.F., Bondaruk, M.A., Tselyshchev, O.G., Pyvovar, T.S., Buksha, M.I., & Pasternak, V.P. (2017). Vitality forecasting for Scots pine and English oak in condition of climate change in the lowland of Ukraine. *Forestry and Forest Melioration,* 130, 146-158.

[15] Shvidenko, A., Buksha, I., Krakovska, S., & Lakyda, P. (2017). Vulnerability of Ukrainian forests to climate change. *Sustainability*, 9(7), article number 1152. https://doi.org/10.3390/su9071152.

[16] Conference on climate change in Paris (2015). Retrieved from https://www.cop21paris.org/knowledge-centre/reports/.

[17] Getmanchuk, A., Kychylyuk, O., Voytyuk, V., & Borodavka, V. (2017). The regional changes of climate as primary causes of strong withering of pine stands in Volyn Polissya. *Scientific Bulletin of UNFU*, 27(1), 120-124. https://doi.org/10.15421/40270127.

[18] Koval, I.M. (2011). Response of pine radial growth to change of climate and recreational load in forest-steppe of Ukraine. *Scientific Bulletin of UNFU*, 21(2), 63-70.

[19] Koval, I.M., Bräuning, A., Melnik, E., & Voronin, V.O. (2017). Dendroclimatological research of Scots pine in stand of the left-bank forest-steppe of Ukraine. *Man and Environment. Issue of Neoecology*, 28 (3-4), 66-73. https://doi.org/10.26565/1992-4224-2017-28-07.

[20] Zhukovskiy, O.V., & Zborovska, O.V. (2015). Annual increment of pine plantations on the different mother rocks in Zhytomyr. Retrieved from http://eztuir.ztu.edu.ua/123456789/741.

[21] Koval, I., & Sydorenko, S. (2019). The influence of surface fire on radial and height growth of *Pinus sylvestris* L. in forest-steppe in Ukraine. *Folia Forestalia Polonica*, 61(2), 123-134. https://doi.org/10.2478/ffp-2019-0012.
[22] Koval, I.M., & Voronin, V.O. (2019). Response of *Pinus sylvestris* L. radial growth to climate change in stands in Left-Bank Forest-Steppe. *Forestry and Forest Melioration*, 135, 140-148. https://doi.org/10.33220/1026-3365.135.2019.140.
[23] Koval, I.M., Bologov, O.V., Nusbaum, S.A., & Juzvinsky, G.A. (2018). Radial increment of Oak and Ash trees as indicator of forest ecosystems conditionin Novograd-Volynsky physiographic region. *Forestry and Forest Melioration*, 126, 202-211.

Аналіз кліматичних змін на території лісового фонду Боярської лісової дослідної станції

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Анотація. Актуальність дослідження зумовлена прогнозованими змінами ареалу, а також значним звуженням зони оптимального росту сосни звичайної. Дані прогнози ґрунтуються на отриманні даних щодо змін клімату які зараз відбуваються. Постійне зменшення кількості опадів разом із поступовим збільшенням рівня температури призведе до таких наслідків як некеровані зміни у екосистемах. Така істотна зміна абіотичних факторів причиною яких є діяльність людини становить ключову роль у формуванні лісових ценозів. Основною метою дослідження було проведення аналізу зміни середньорічної температури, а також місячної кількості опадів, що спостерігались в лісових угрупуваннях у Відокремленому підрозділі Національного університету біоресурсів та природокористування України «Боярська лісова дослідна станція». Аналіз проводиться по десятиріччях для отримання даних щодо рівня зміни температури по відношенню до попереднього періоду. А також співставлення кількості опадів по місяцях за 2021 рік відносно до періоду 1991–2020 років, який встановлений за норму. Для отримання показників середньої річної температури використовується метод середнього значення, з подальшим обрахуванням значення середньої річної температури для кожного десятиріччя. Для визначення відхилення сум опадів використовується метод оцінки умов зволоження за сумою опадів. При цьому за значення суттєвого відхилення приймається на рівні 20 % відносно показника норми опадів. За результатами отриманих даних в ході проведення дослідження, встановлено, що за період 2001–2010 років середня річна температура відносно попереднього десятиріччя змінилась на 0,83 градуси за Цельсієм, а за період 2011–2020 років на 0,74 градуси відповідно до попереднього періоду. Така динаміка свідчить про поступове збільшення середньої річної температури, що і відображено в прогнозах світової спільноти. Під час проведення оцінки умов зволоження виділено окремі місяці 2021 року з критичним рівнем опадів по відношенню до періоду норми. В березні кількість опадів становила 43 % до норми, червень – 32 %, вересень – 40 % та жовтень лише 4,3 % до норми. Значення у листопаді спостерігалось на рівні 63 % до норми. Таке зменшення кількості опадів у співвідношенні із поступовим підвищенням рівня середньої річної температури становить загрозу зменшення гідрологічного рівня вологи, і як наслідок зменшення радіального приросту деревостанів, та поступове зміщення ареалу сосни звичайної. Отримані результати аналізу в подальшому будуть використані для проведення дендрохронологічних досліджень деревних кілець дерев сосни звичайної (*Pinus sylvestris* L.) в насадженнях Відокремленого підрозділу Національного університету біоресурсів та природокористування України «Боярська лісова дослідна станція»

Ключові слова: лісове угруповання, річна температура, сосна звичайна, опади, землі лісового фонду

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